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Article

Build-Up/Wash-Off Monitoring and Assessment for Sustainable Management of First Flush in an Urban Area

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Abstract: The characterization of stormwater runoff on urbanized surfaces by means of comparison between experimental data and simulations is a strict requirement for a sustainable management of urban sewer systems. A monitoring campaign was carried out within a residential area in Puglia (Southern Italy) in order to collect and evaluate quantity and quality data. A strong correlation was observed between COD (Chemical Oxygen Demand) and TSS (Total Suspended Solid) concentrations, whose values exceed water quality standards. TSS was used for calibration of Storm Water Management Model (SWMM) which was then validated with reference to the pollutograph's shape and the peak-time. The first flush phenomenon occurrence was also investigated by looking at the distribution of pollutant mass *vs.* volume in stormwater discharges, using the so-called "M(V) curves". Results show that on average the first 30% of that washed off carries 60% of TSS and provides important information for the design of efficient systems for first flush treatment.

Keywords: calibration; first flush; monitoring; residential area; SWMM

1. Introduction

Urban drainage is one of the most important issues for sustainable use of the environment in heavily anthropized areas [1]. During a rainfall event of particular duration and intensity, especially following a dry period, the first and faster runoff contribution washes away impervious surfaces, generating wastewater that is more concentrated in pollutants. In recent years, the so-called "first flush" has been recognized and investigated as a typical phenomenon of areas heavily populated and urbanized. In fact, runoff on urban surfaces carries into drainage systems pollutants including mainly settleable solids (organic and/or inorganic), nutrients, bacteria, oil, grease and heavy metals (Cu, Zn, Cd, *etc.*), in concentrations depending on land use. This contaminated flow rate if delivered, without treatment, through the drainage system outlet can be one of the major causes of quality deterioration of streams.

Based on these considerations, several researchers have studied the "first flush" phenomenon (e.g., [2–5]) which is usually identified by its intensity rather than its volume. In literature, different criteria have been proposed for the evaluation of a load threshold over which the first flush is considered significant and no attempt has been made to provide a unique definition. Helsel *et al.* (1979) [6], followed by Geiger (1984) [7] and Sansalone and Buchberger (1997) [8], proposed to simply define the first flush as when the mass/volume M(V) curve is above the bisector (45° diagonal), meaning that the fraction of pollutant load in the first part of the storm is greater than the corresponding fraction of runoff volume. Saget *et al.* (1996) [9] define the first flush to be significant when at least 80% of the load is transferred in the first 30% of the storm, represented by Zone 1 of the M(V) curve. Bertrand-Krajewski *et al.* (1998) [10] admits that the selection of the 30/80 criterion is useful to quantify precisely the first flush phenomenon, but it is arbitrary; they believe that it is possible to choose other pairs of values to define first flushes. They consider that there is a substantial first flush if the maximum difference between the dimensionless cumulative pollutant mass and the dimensionless cumulative runoff volume is greater than 0.2. Doyle (2008) [11] states back that any storm pollutant plot falling above the diagonal (the $m(t) = v(t)$) of the M(V) curve exhibits a flushing effect.

A limited number of works is based also on monitoring campaigns [12–16]. Each of these campaigns contributes methodologically to the characterization of the quality of stormwater runoff of urbanized areas and the study of build-up/wash-off and transport phenomena of pollutants during wet periods.

Such studies reveal the need for suitable modeling tools aimed at prediction of quantity and quality of drainage water which is necessary for proper design of sustainable sewer systems. The problem is even more complex in combined sewer systems where storm-water is mixed with wastewater from residential, commercial, and industrial areas. In such a case, a proper design needs to evaluate the effects in the receiving water body of the discharge overflowing the wastewater treatment capability [17]. Several simulation models have been developed for this purpose in latest years. We used the Storm Water Management Model (SWMM version 5.0), whose main features are briefly described in Section 2, as it is one of the most complete and widely used throughout the world (e.g., [18]).

Based on these considerations, we present the data collected during a brief monitoring campaign carried out within a residential area in Sannicandro di Bari (Puglia, Southern Italy). Data and analyses focus on Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), Nitrogen (N), Phosphorus (P), Copper (Cu) and Lead (Pb). In urban areas, where vehicular traffic is prevalent, high concentration values of heavy metals are observed, including usually also Zinc (Zn) (e.g., [19]), nevertheless in this experimental campaign, the available economic budget allowed to monitor only Cu and Pb. During the field campaign, carried out from November 2006 to January 2007, three rainfall events were observed. We exploited such data in order to calibrate and validate SWMM by means of quality experimental data. In fact, one purpose of this paper is to describe how the quality and quantity pollution data, obtained by field experiments, may be used for model calibration and validation, showing that even a minimum amount of experimental observations, may provide important information necessary to enhance design procedures and to improve the efficiency of systems aimed at first flush separation, storage and treatment.

Main aims of the study are:

- report the field campaign observations,
- evaluate the occurrence of the first flush phenomenon,
- calibrate and validate the SWMM model with reference to the build-up/wash-off processes, exploiting a minimum amount of experimental data, in order to assess model performances and suitability on ungauged basins.

2. The Storm Water Management Model (SWMM Version 5.0)

SWMM allows the simulation of flow and polluting load of urban runoff as well as their conveyance through a combined sewer system. The model is suitable for evaluating a single rainfall event, and also for continuous simulation of a long period including dry and wet spells. It offers several options in order to simulate build-up and wash-off of the pollutants in the catchment area, and different conditions in the combined sewer system too [20].

SWMM evaluates quantity and quality of runoff within a catchment, in particular: flow rate, flow depth and pollutant concentration in each channel during the simulation period.

SWMM is able to represent the various hydrological processes responsible of runoff production: rainfall losses are subtracted from precipitation to produce rainfall excess. Losses include evaporation, depression storage and infiltration.

In the evaluation of a single rainfall event the infiltration process represents the greatest amount of losses and it is modeled evaluating, for each subcatchment, the percentage of pervious and impervious area obtained from the land use map. The infiltration model used in this study is based on the Horton's equation. Horton's parameters values, as well as depression storage, have been chosen according to the typical values tabulated in technical handbooks, in relation to soil type (maximum infiltration rate = 76 mm/h; minimum infiltration rate = 13 mm/h; decay constant = 4.14). The flow routing is based on kinematic wave model and on Manning's equation.

Quality Module of SWMM

SWMM allows evaluating the pollutants buildup process on the basin surface, all processes involving solids transportation by runoff and their transport through the drainage system.

Pollutant buildup within a land use category is described by a mass per unit of subcatchment area. The amount of buildup is a function of the number of dry weather days antecedent to the rainfall event.

In this study, following the Alley and Smith [3], the buildup function follows an exponential growth curve that approaches a maximum limit asymptotically as in:

$$M_a(d_{ts}) = \left(\frac{Accu}{Disp}\right) \cdot A \cdot P_{imp} \cdot \left(1 - e^{-(Disp \cdot d_{ts})}\right) \quad (1)$$

where

$M_a(d_{ts})$	is the pollutant buildup during the antecedent dry days [kg/ha];
$Disp$	is a parameter that identifies the disappearance of accumulated solids due to the action of wind or vehicular traffic [1/d];
$A \cdot P_{imp}$	represents the impervious area percentage;
$Accu$	is a parameter that characterize the solids buildup rate [kg/(ha·d)];
$\left(\frac{Accu}{Disp}\right) \cdot A \cdot P_{imp}$	represents the maximum asymptotical limit of the buildup curve.

Previous experiments show that Disp typically takes a constant value equal to 0.08 [1/d] in urban basins of the same region [21]. Instead, the solid buildup rate has great variability depending on the activities locally carried out: generally its value ranges from 5 kg/(ha·d) in sparsely populated residential areas, to 35 kg/(ha·d) for industrial areas [2]. According to these considerations, in Sannicandro di Bari, DISP was assumed equal to the regional value of 0.08 [1/d] while Accu was used as a calibration parameter of the buildup model.

The Pollutant wash-off over different land-uses takes place during wet periods and it is described by the Jewell and Adrian [22] exponential function:

$$\frac{dM_d(t)}{dt} = -Arra \cdot i(t)^{wash} \cdot M_a(t) \quad (2)$$

where

$\frac{dM_d(t)}{dt}$	represents the wash-off load in units of mass per hour;
Arra	is the wash-off coefficient [mm^{-1}];
i(t)	is the runoff rate;
wash	is the wash-off exponent, a numerical parameter that controls the influence of rainfall intensity on the amount of leached pollutants.

Following the results of several experiments carried out in different Italian urban basins [21,23], the wash off coefficient was set equal to 0.18 mm^{-1}. On the other hand the wash-off exponent can assume values in the range 0/3, and was considered as a calibration parameter of the wash off model.

The software SWMM calculates the spatial and time trend of pollutant concentrations in the drainage network assuming that the conduits behave as a Continuous-flow Stirred-Tank Reactor (CSTR). It is an ideal continuous reactor consisting of a reservoir powered by a constant flow of material and equipped with a stirring system (Figure 1).

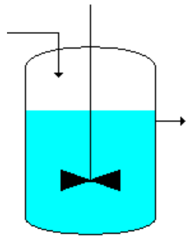

Figure 1. Synthetic depiction of a CSTR (Continuous-flow Stirred-Tank Reactor) reactor.

The reference system is the reactor volume, which coincides with the conduit volume. The mathematical balance inside the reactor is obtained from a macroscopic material balance. In reference to the substance involved in the reaction, a perfect and ideal mixing is assumed, and the universal law of material balance is applied:

$$\text{Accumulation} = \text{Input-Output} + \text{Generation} \quad (3)$$

then:

$$\frac{d(V\,x)}{dt} = Q_{ING}\,x_{ING} - Q\,x + V\,r_c \quad (4)$$

in which:

$V\,[m^3]$	is the water volume in the conduit (reactor), calculated at each time step;
$Q_{ING}\,[m^3/s]$	is the inflow in the conduit;
$Q\,[m^3/s]$	is the outflow to the conduit;
$x\,[mg/L]$	is the solute concentration in the volume V (assumed homogeneous) at the outlet of the conduit;
$x_{ING}[mg/L]$	is the solute concentration at the inlet of the conduit;
$r_c\,[L/s]$	is the solute “reaction rate”.

The parameter r_c is identified in SWMM by the constant k (called “first order decay constant”, expressed in [1/year]), which depends on the sedimentation velocity of the transported material and average height of the water table in the pipe.

3. Experimental Section

3.1. Case Study

The experimental study area is sited in Sannicandro di Bari, a small town in Puglia (Southern Italy). The drainage area (with surface equal to 31.24 ha) covers approximately 60% of the total urban area and is characterized by 21.87 ha (70%) of impervious surface. In particular, the land use thematic map, extracted from the regional geographical information system (SIT Puglia), shows that the entire area is exclusively residential and only 3.8% of the basin (1.2 ha) is covered by urban-green. The drainage basin has an average slope of 1.56%. The drainage network, used only for stormwater, has a total length of 1.96 km and collects water into a concrete rectangular (1.20 m wide, 1.70 m high) channel [21].

The measurement of the rainfall input was carried out through a rain gauge installed close to the outlet of the drainage network. Water quality was measured with samples collected by an autosampler provided with 24 bottles of 0.5 L each.

Figure 2 shows an aerial photo of the study area with indication of the drainage basin, the drainage network and the gauged section.

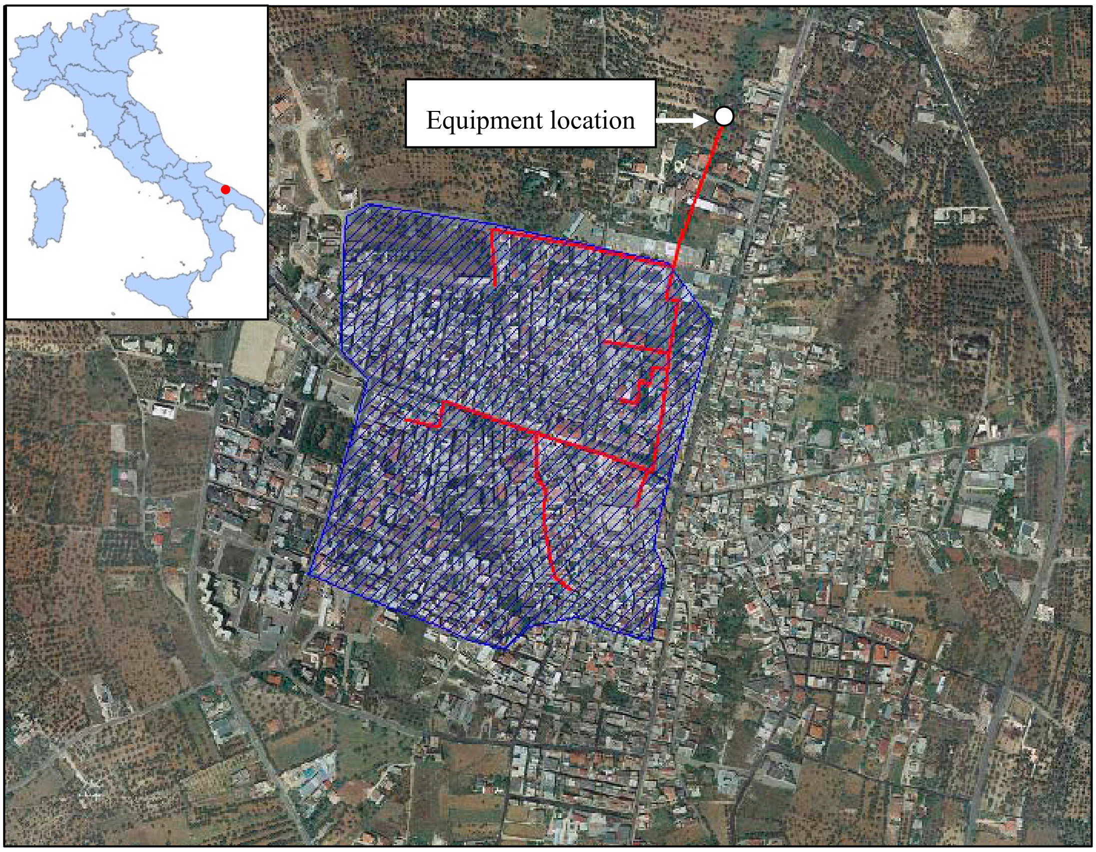

Figure 2. Sannicandro di Bari, drainage network (**red line**) and drainage basin (**in blue**).

Figure 3 shows the SWMM scheme of the basin including five sub-catchments and a drainage network with 20 nodes (black dots) and 20 channels (black solid lines).

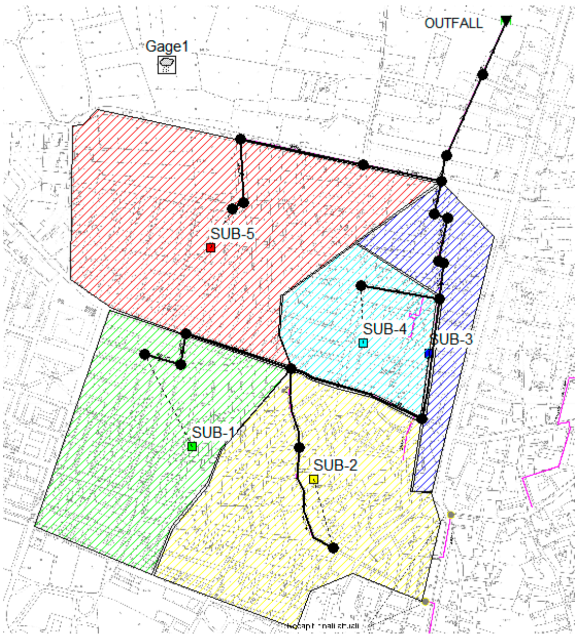

Figure 3. SWMM depiction of the drainage network with 20 nodes, 20 channels and five sub-catchments.

3.2. Equipment

The equipment is composed (see Figure 4) by a rain-gauge, a bubble level meter and a refrigerated autosampler installed at the outlet of the drainage network. Figure 5 shows pictures of the rain-gauge and the autosampler while installed at a different site.

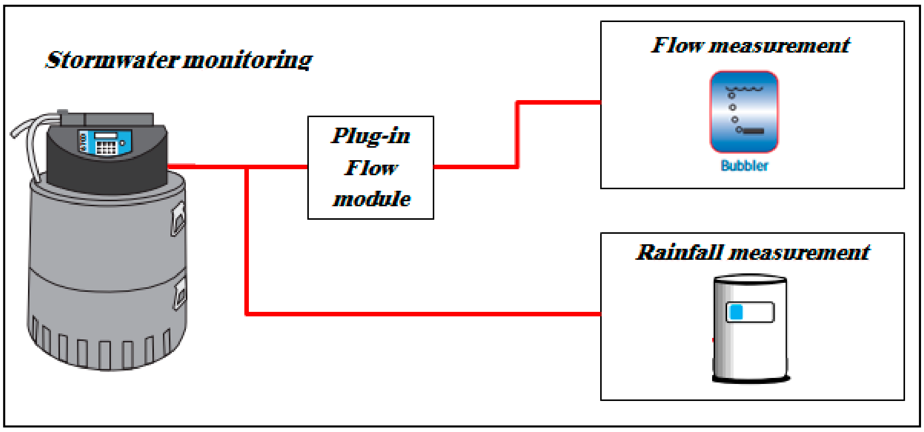

Figure 4. Scheme of the equipment used for the monitoring campaign: autosampler, rain gauge and bubble level meter for flow data.

Figure 5. Rain-gauge and autosampler.

A meter bubble was used for the measurement of discharge. The module uses a differential pressure transducer and a flow of bubbles to measure liquid levels up to ten feet. The bubbler is unaffected by wind, fluctuations of air or liquid temperatures, turbulence, steam, foam on the surface, corrosive chemicals, debris, oil, floating grease, or lighting.

For quality water monitoring a sampler ISCO 6700 FR was installed, *i.e.*, a stationary refrigerated sampler. Operationally, the model installed allows to take 24 samples of 0.5 L each, according to the set programming. The sampling phase starts when a predetermined runoff threshold value is exceeded and it consists of runoff sampling with a fixed frequency, which is selected considering the catchment extension and rainfall characteristics of the investigated area. We used a sampling frequency of three minutes.

The samples were subjected to laboratory analysis to determine the concentration of a number of benchmarks: COD, BOD_5, Total Suspended Solids, Total Nitrogen, Phosphorus, Copper and Lead.

3.3. Experimental Data

The monitoring campaign in Sannicandro di Bari, provided records of rainfall and flow for only three rainfall events occurred, respectively on: 10 November, 2006, 22 November, 2006 and 24 January, 2007.

For each storm event monitored, the samples analysis was conducted for the determination of the content of: Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand in five days (BOD_5), total Nitrogen and Phosphorus (whose presence is mainly due to the possible use of fertilizers in urban green areas), and some heavy metals, such as Lead and Copper, whose presence is mainly due to vehicular traffic and combustion residues.

In the following tables and figures (Tables 1–3, Figures 6–8), the quality-quantity data relating to the three rainfall events are summarized and represented; in particular, Tables 1–3 show the maximum, minimum and average values of the investigated parameters, as well as the duration (day) of antecedent dry weather, the rainfall event duration and the total rainfall depth (mm). Figures 6–8 show a comparison of the observed discharge and the monitored TSS and COD values for the three rainfall events investigated. It is worth noting that TSS and COD values are very high compared to thresholds provided by the Italian National Legislation [24].

Table 1. Quality-quantity data for the event of 10 November 2006.

a

Quantity Data 11/10/2006	
Total rainfall (mm)	2.4
Event duration (min)	50
Antecedent dry period (days)	6
Runoff volume (m^3)	113.5
Runoff peak (m^3/s)	0.042

b

Quality Data 11/10/2006	BOD_5	COD	TSS	Ntot	P	Pb	Cu
Maximum Value (mg/L)	15	223	420	8.3	1.00	0.03	0.06
Minimum Value (mg/L)	3	150	224	7.0	0.70	0.02	0.04
Mean Value (mg/L)	8	186	305	7.5	0.83	0.03	0.05

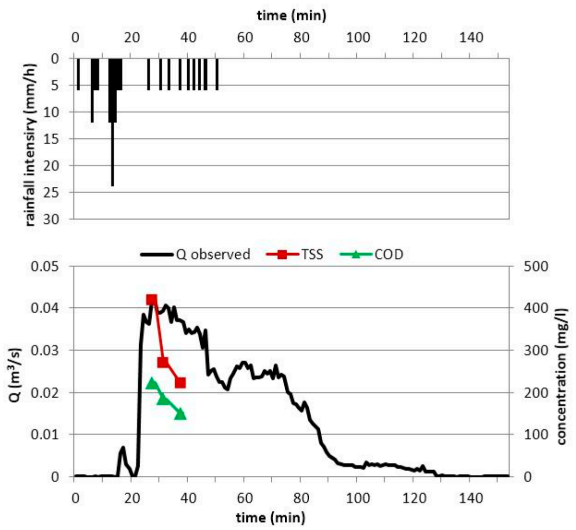

Figure 6. Hyetograph, hydrograph and pollutograph for the event of 10 November 2006.

Table 2. Quality-quantity data for the event of 22 November 2006.

a

Quantity Data 11/22/2006	
Total rainfall (mm)	4.3
Event duration (min)	113
Antecedent dry period (days)	11
Runoff volume (m^3)	148.9
Runoff peak (m^3/s)	0.039

b

Quality Data 11/22/2006	**BOD_5**	**COD**	**TSS**	**Ntot**	**P**	**Pb**	**Cu**
Maximum Value (mg/L)	51	296	2160	14	2.96	0.13	0.15
Minimum Value (mg/L)	15	44	124	3.6	0.24	0.01	0.04
Mean Value (mg/L)	24	120	716	7.53	1.74	0.07	0.10

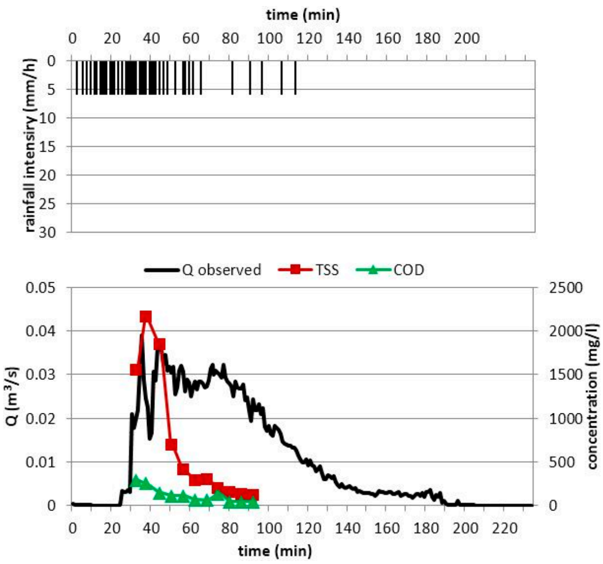

Figure 7. Hyetograph, hydrograph and pollutograph for the event of 22 November 2006.

Table 3. Quality-quantity data for the event of 24 January 2007.

a

Quantity Data 01/24/2007	
Total rainfall (mm)	1.6
Event duration (min)	39
Antecedent dry period (days)	19
Runoff volume (m^3)	111.6
Runoff peak (m^3/s)	0.050

b

Quality Data 01/24/2007	**BOD_5**	**COD**	**TSS**	**Ntot**	**P**	**Pb**	**Cu**
Maximum Value (mg/L)	44.9	360	807	10.3	0.99	0.019	0.062
Minimum Value (mg/L)	23.5	106	177	5.4	0.65	0.011	0.033
Mean Value (mg/L)	31	188	383	7.7	0.82	0.015	0.048

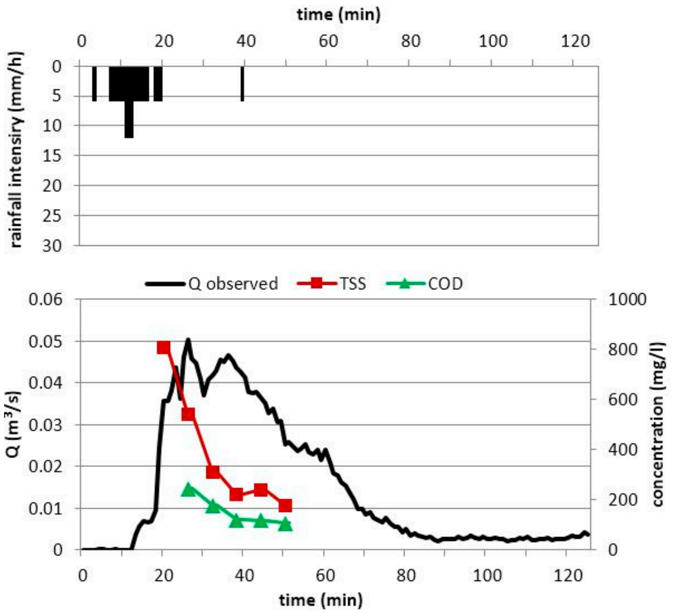

Figure 8. Hyetograph, hydrograph and pollutograph for the event of 24 January 2007.

Several works in literature (e.g., [25,26]) consider TSS as a synthetic index of the general level of pollution in urban areas. In fact, suspended solids are often used in mathematical models that simulate the dynamics of pollutants in runoff; therefore, it is extremely important to detect the correlation between suspended solids and other parameters' indicators of pollution [14]. Analyzing the quality data for the three monitored events, it is possible to realize that TSS is closely related to other pollutants and in particular to COD; then we choose the TSS as pollutant reference value. The correlation between the TSS and COD values sampled during the events observed was evaluated: it is very high and, in particular, the R^2 is equal to 0.928, 0.6949 and 0.977, respectively, for the events of 10 November, 2006, 22 November, 2006 and 24 January, 2007. Since the first event is characterized by only three values sampled, in order to make its R^2 more effective, the analysis of the correlation between TSS and COD relied on data from different events: Figure 9a shows the R^2 obtained from the records of the events 10 November, 2006 and 24 January, 2007 was evaluated. Figure 9b points out the R^2 for the event 22 November, 2006. The R^2 obtained from the overall records of the three events drops to 0.36.

Probably, this is due to the different characteristics of the rainfall space-time distribution. In fact, comparing the quality-quantity data observed in the three cases, the event of November 22nd, 2006 shows a lower and constant rainfall intensity and a longer rainfall duration. As a consequence, also the discharge hydrograph is less variable and, then, the maximum water velocity is lower and produces a differentiated capacity of transport with respect to materials of different particle sizes. Moreover, the organic substances are not generally present in amounts proportional to the particle size classes and may be an object of different transport processes and velocity.

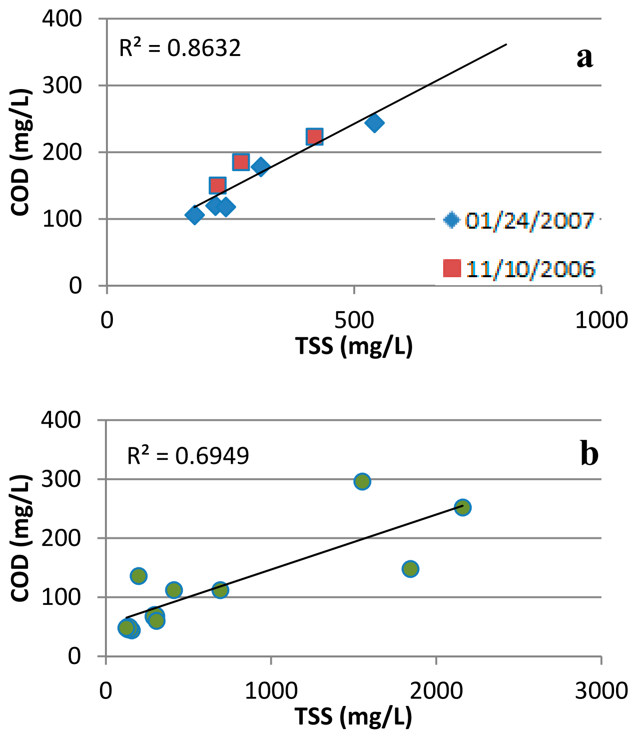

Figure 9. Correlation between TSS and COD measured during the events: (**a**) 11 November 2006 (red squares) and 24 January 2007 (blue rhombuses); (**b**) 22 November 2006.

4. Results and Discussion

4.1. Model Calibration and Validation

A model provides reliable results, in accordance with any recorded data, identifying appropriate parameter values that ensure an overall good agreement between recorded and simulated data. This process in principle should include independent phases of "calibration" and "validation", in order to provide a model able to predict the quality-quantity response of basin for any flowed rainfall.

Nevertheless, the comparison between the flow rates simulated by the SWMM model and flow rates measured at the drainage system's outlet for the three monitored events provided unexpected results after the calibration/validation procedure.

The parameters of the hydraulic model are: depth of depression storage on the impervious (Dstore-Imperv) and pervious (Dstore-Perv) portion of the subcatchment, Manning's coefficient for overland flow over the impervious portion of the subcatchment (N-Imperv), Manning's coefficient for overland flow over the pervious portion of the subcatchment (N-Perv), Percent of the impervious area with no depression storage (%Zero Imperv) and the characteristic width of the overland flow path for sheet flow runoff (Width) [27]. Their range of variation (e.g., [28,29]) and the values chosen for these parameters in this paper are shown in Table 4.

In particular:

- the values of Dstore-Imperv and Dstore-Perv, were fixed near the lower bound of the respective intervals, because in a urban basin we expect that the runoff value is quite high; for the same reason we chose a mean-low value of the %Zero Imperv.

- the value of N-Imperv was fixed equal to 0.012 s/m$^{1/3}$, being the impervious surface characterized by smooth concrete material; moreover, the value of N-Perv was fixed equal to 0.15 s/m$^{1/3}$ being the pervious area characterized by grass short and prairie;
- the value of the Width of the overland flow path for sheet flow runoff, was evaluated taking into account the following [30] formula valid for irregular shape basins:

$$W = (2 - S_k) \cdot l \quad (5)$$

where W is the Width of the overland flow path [m], S_k is the skew factor, l [m] is the overland flow path.

To evaluate the S_k value ($0 < S_k < 1$), we used the following equation:

$$S_k = \frac{A_2 - A_1}{A_{tot}} \quad (6)$$

Where A_1 is the portion of area on one side of the overland flow path; A_2 is the portion of area on the other side; A_{tot} is the total area.

Table 4. Parameters of the hydraulic-hydrological model.

Parameters	Description	Range	Value	
Dstore-Imperv	Depth of depression storage on the impervious portion of the subcatchment [mm]	1.27–2.54 *	1.30	
Dstore-Perv	Depth of depression storage on the pervious portion of the subcatchment [mm]	2.54–5.08 *	2.60	
N-Imperv	Manning's coefficient for overland flow over the impervious portion of the subcatchment [s/m$^{1/3}$]	0.011–0.024 **	0.012	
N-Perv	Manning's coefficient for overland flow over the pervious portion of the subcatchment [s/m$^{1/3}$]	0.15–0.41 **	0.15	
% Zero Imperv	Percent of the impervious area with no depression storage [%]		45	
Width	Characteristic width of the overland flow path for sheet flow runoff [m]		Subcatchment 1	335
			Subcatchment 2	717
			Subcatchment 3	527
			Subcatchment 4	378
			Subcatchment 5	483

* [28]. ** [29].

Initially, we tried to use the first of the three observed events for calibration and the others for validation. Nevertheless, based on the contemporary measures of rainfall and discharge, and even after different choices for the calibration event, we found a poor agreement as shown in Figure 10. The simulated flow rates are always higher than the measured, unless we use some parameter values that are outside their suitable physical range. As shown in Figure 10, the observed peak discharge assumes values close to 0.04 m^3/s (in the events of 10 November 2006 and 22 November 2006) and 0.05 m^3/s (event of 24 January 2007) which is totally uncorrelated with either rainfall depth or peak of rainfall intensity. These observations proves that the drainage system was unable to capture the entire generated runoff probably because of a shortage, wrong position, obstruction of inlet catch basins or due to losses in the network. As a matter of fact, the sewer system has been object of works to improve its drainage efficiency in 2008.

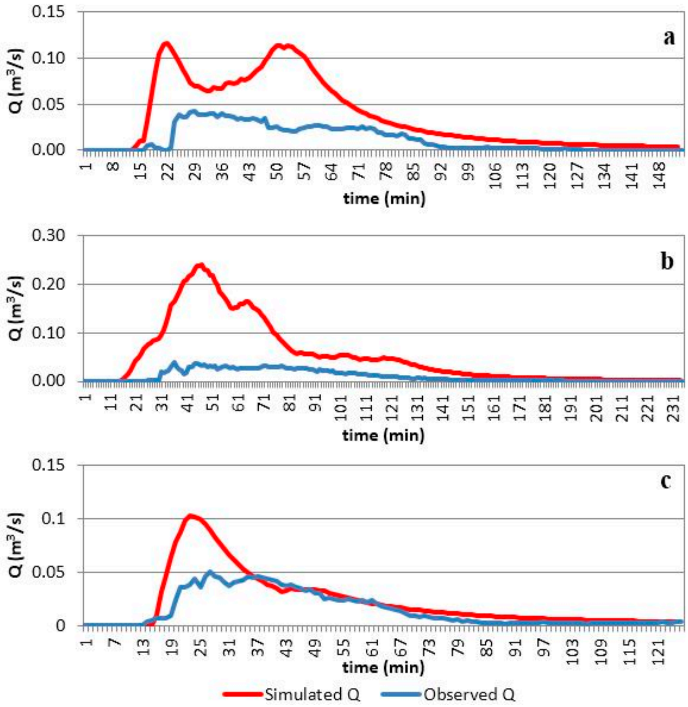

Figure 10. Comparison between observed flow rates (**blue line**) and simulated ones (**red line**) for the event (**a**) 10 November, 2006; (**b**) 22 November, 2006; (**c**) 24 January, 2007.

In order to preserve and exploit the scientific value of the pollutant sampling, we performed a sensitivity analysis of the parameter r_c which settles the characteristics of the pollutant transport into the sewer system. Considering the rainfall input of the three observed events we found that for r_c values within the typical range of literature for urban areas, the pollutant concentrations at the inlet of the drainage network remains practically unaffected by processes that develop within the drainage network. In other words, the transport process in this drainage system does not alter significantly the TSS concentration, which depends substantially on the washoff and build up phenomena, for rainfall events of characteristics (antecedent dry period, intensity, duration, *etc.*) similar to those observed.

Following these considerations and assuming that the flow conveyed in the drainage network, is a part of the hydrological flow, we performed the model calibration and validation with reference to the TSS concentration data measured at the drainage system's outlet, during the three rainfall events monitored. As mentioned before, most of the surface is intended for residential use and is impervious, while only 3.8% of the basin is covered by urban-green. We observed that varying parameters of the buildup and wash-off model of the latter land use and TSS concentration measured at the drainage system's outlet does not change; therefore, urban-green land use does not affect the model calibration process.

During the field campaign only three events were observed then, the first one (November 10^{th}, 2006) was used to calibrate model parameters while the other two events were used for model validation. Considering the very limited number of observed events assumed for most of the model parameters some reference literature values are detailed in Section 2. Thus, we reduced as much as possible the number of calibration parameters. Quality-parameter values obtained in the calibration event are presented in Table 5.

Table 5. Parameter used for the quality calibration of the model.

Parameters		Range	Value
Buildup	Accu [kg/(ha·d)]	10/25 *	13.143
	Disp [1/d]	0.08 **	0.08
Wash off	Arra [1/mm]	0.11/0.19	0.18
	Wash	0/3	2.35

* For highly populated residential areas. ** Italian residential basin typical values.

The calibration was made by means of an iterative process of trial and error, by adjusting the parameters in Table 5. Working within the established range, and comparing (numerically and graphically) the simulation with the measured pollutograph, the calibration was worked on until a good fit was obtained. The numerical comparison was made by evaluating RMSE and R^2 per each rainfall event (Table 6).

Table 6. Numerical comparison between the simulated and measured pollutographs for each rainfall event.

Events	RMSE	R^2
Calibration: 11/10/2006	30.92	0.994
Validation: 11/22/2006	663.30	0.670
Validation: 01/24/2007	57.48	0.967

As we can see in Figure 11, the simulated pollutographs very well interpolate the values of TSS concentration measured during the calibration event of 10 November 2006 and also during the validation event of 24 January 2007. A still fair comparison is obtained for the second validation event of 22 November 2006 which provides a high value of RMSE which seems mainly due to a shift in the peak time; in fact, the maximum observed value (2160 mg/L) is not far from the simulated peak value (2231 mg/L).

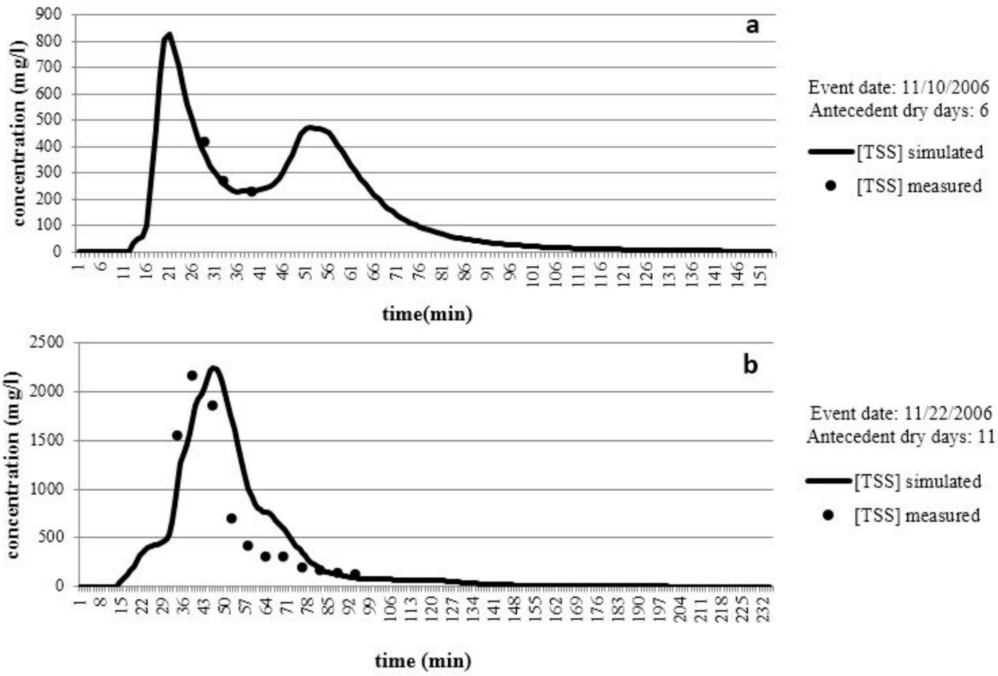

Figure 11. *Cont.*

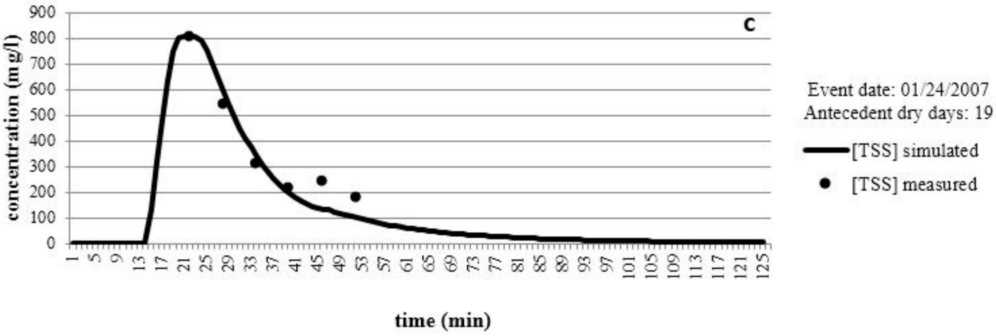

Figure 11. Comparison between TSS concentrations of measured and simulated data of the calibration event: (**a**) 10 November 2006; and validation events: (**b**) 22 November 2006; (**c**) 24 January 2007.

4.2. Analysis of the First Flush Occurrence

The monitoring process conducted in this study, allowed the analysis of the distribution of pollutant mass *vs.* volume in stormwater discharges in dimensionless terms by using the so-called "M(V) curves" [10]. This representation provides the variation of the cumulative pollutant mass divided by the total pollutant mass in relation to the cumulative volume divided by the total volume. If the concentration remains constant during the storm event, the pollutant mass is proportional to the volume and the M(V) curve is merged with the 1:1 line. When the M(V) curve is above the 1:1 line, the first-flush is noticed and the extent of the phenomenon increases with the slope of the curve for small values of volume.

The M(V) curves obtained from TSS data processing of the three events recorded in Sannicandro di Bari are shown in Figure 12.

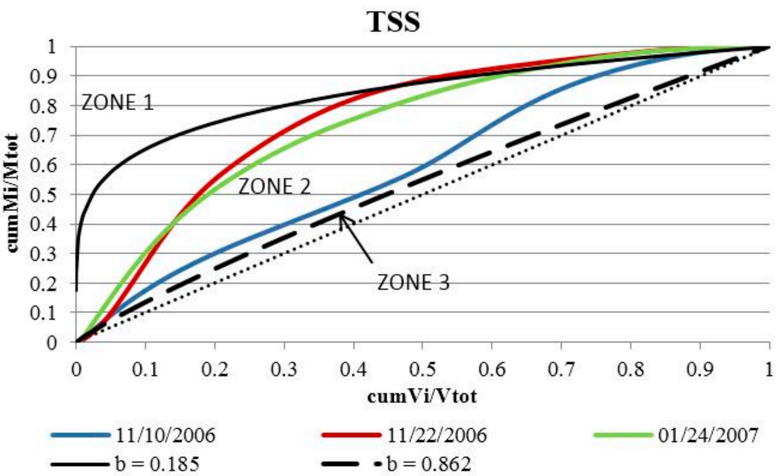

Figure 12. M(V) curves for TSS relating to the three events recorded in Sannicandro di Bari.

Comparing the three events, which differ mainly in terms of antecedent dry period (Table 7), we observe the expected dependence of the first flush phenomenon on this factor.

Every M(V) curve can be fitted approximately by a power function [10]:

$$F(x) = x^b \tag{7}$$

The value of the parameter b characterizes the gap between the M(V) curve and the 1:1 line. The numerical analysis conducted on the parameter b indicates that it varies significantly from one event to another. It should also be noted here that the lower the value of b, the more pronounced is the first flush, being a high fraction of the total pollutant load transported during an early stage of the rainfall event.

Table 7. Characteristics of three events in Sannicandro di Bari.

Events	Antecedent Dry Period (d)	Qmax (m^3/s)
11/10/2006	6	0.04
11/22/2006	11	0.04
01/24/2007	19	0.05

The parameter b allows the upper part of M(V) graph to be divided into three zones, delimited in Figure 12 by a black solid line with b = 0.185 and a dotted black line with b = 0.862.

Zone 1 represents a phenomenon of a very pronounced first flush, with about 75% of pollutant mass and about 20% of runoff volume. Zone 2 represents the situations in which during the rainfall event the discharged concentration decreases (first flush phenomenon). Zone 3 is close to the 1:1 line, representing the zone where the pollutant mass concentration is more or less constant during the event. The curves representing the three events are in zone 2.

Furthermore, we know that the first flush phenomenon implies that most of the pollutant mass is washed off by the first inputs of a rainfall event. In fact, analyzing the M(V) curves for the three events examined, we can see that the first 30% of the volume of washed off water carries a quantity of TSS respectively equal to:

- 40% for the 10 November 2006 event;
- 70% for the 22 November 2006 event;
- 65% for the 24 January 2007 event.

Such results are in accordance with Lee *et al.* [31] who stated that first flush occurs strongly when the proportion of impervious area increases, considering the high proportion of impervious area (70%) of the catchment.

An alternative way to assess the occurrence of the first flush phenomenon is a comparison between the normalized pollutant mass emissions *vs.* the normalized flow volume as shown in Figure 13, where the normalized TSS mass emission rate is plotted for each normalized runoff volume ranging from 10%–100% with intervals of 10%.

From Figure 13, we evaluated the mass first flush ratio (MFF) [32] which is defined as the ratio between the pollutant mass with respect to runoff volume [33], used to characterize and quantify the magnitude of first flush.

For example, Figure 13c shows that the first 10% of the runoff (V10) discharge has a mean value of pollutant mass equal to 0.08. This means that 8% of TSS mass was washed off by V10. If the MFF ratio is the normalized pollutant mass divided by the normalized pollutant volume, in this case: MFF10 = 0.8.

With regard to the first volumetric contributes, a greater dispersion of data related to the washed off mass compared to the average value is manifested. It is reasonable to assume that this is due to the temporal discontinuous trend of these contributions.

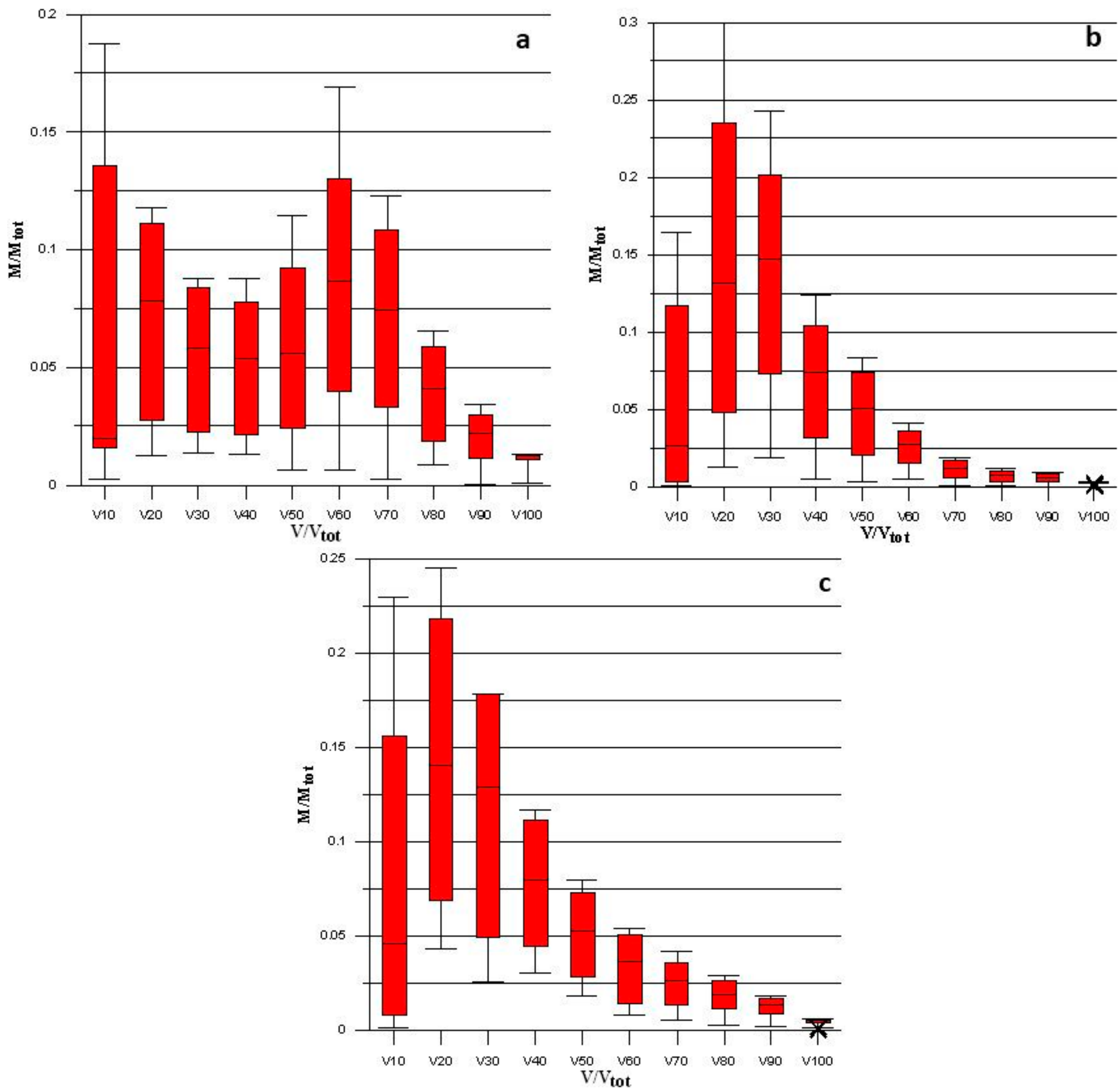

Figure 13. Notched bar graphs for MFF ratios (10%–100%) for TSS for the three events: (**a**) 10 November 2006; (**b**) 22 November 2006; (**c**) 24 January 2007.

5. Conclusions

The characterization of the quality of stormwater runoff from impervious surfaces is a complex task that has assumed growing importance with the growth of urbanization. One of the main problems in modeling stormwater pollution loads is the lack of event water quality data and the large variability in the pollutant concentration data.

Between 2006 and 2007, a monitoring campaign in the urban basin of Sannicandro di Bari was conducted with the aim of increasing the availability of experimental data on the quality of stormwater runoff. Although only three events were observed during the field campaign, they were used to calibrate the parameters of the SWMM model in order to simulate observed pollutographs and to extend application to ungauged basins.

It is certainly true that with reference to the general assessment of the first flush phenomenon, this limited number of events may be considered an insufficient dataset. Nevertheless, it is necessary to remark that the purpose of this paper is to describe the field experiments conducted during the monitoring campaign, and to show how the collected data may be exploited for validation and calibration of the first flush phenomenon. It is also useful to point out that neither the technical engineering practice nor the technical legislation actually consider that even a brief field survey may provide strong enhancements in the efficiency of structures for separation, storage and treatment of first flush; thus, we believe that it is important to demonstrate the value of these data as well as to enhance the quality and quantity of the data measurements.

After the calibration of the SWMM model, able to simulate polluting loads during wet periods in the separate sewer system at the outlet of a catchment area in the city of Sannicandro di Bari, the following general conclusions can be drawn:

- The expected flow data results are much higher than the ones observed. This is probably due to the characteristics of the basin–drainage network interface, and in particular due to an unsuitable spatial distribution and/or quantity of the inlet catch basins. It has been proved, however, that processes that may alter the pollutants concentration within the drainage network does not occur until the discharge point. As a consequence, it was reasonable to assume that, since the hydraulic flow carried through the network is a portion of the hydrological flow, the respective concentrations are about equal. Therefore, it was possible to go ahead with model calibration and validation at least from a quality point of view.
- Simulations performed with SWMM show their rather good correlation with the measured values of TSS concentration for single events.
- The M(V) curves (see Figure 12) relating to three monitored rainfall events are above the 45° diagonal, showing a significant first flush phenomenon, according to the main definitions provided by the scientific community and reported in the introduction. Moreover, observing the three pollutographs, reported in Figures 5–7, a flushing effect is evident within each rainfall event, due to the decrease of the pollutant concentration. The characteristics of the M(V) curves depend on the pollutant, the site, the rainfall event and the overall operation of the sewer system. No clear and general linear multi-regression relationship can be established to explain their shape and their variability. These observations are probably due to the complexity of the phenomena involved and to the multiplicity of influencing factors and parameters. Analyzing the M(V) curves for the three events examined, we observe that, on average, the first 30% of washed off water carries 60% of TSS.

Author Contributions

The presented research was conjointly designed and elaborated. The discussions were realized conjointly by all authors and all authors contributed equally in the writing of this paper. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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