An investigation of wash-off controlling parameters at urban and commercial monitoring sites

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Abstract The relationship between the parameters of the wash-off function and the controlling hydrologic variables are investigated in this paper, assuming that the pollutant generation process basically depends on the watershed rainfall-runoff response characteristics. Data collected during an intense monitoring program carried out by the Department of Environmental Engineering of the University of Genova (Italy) within a residential area, an auto dismantler facility, a tourism terminal and a urban waste truck depot are used to this aim. The observed runoff events are classified into different TSS mass delivery processes and the occurrence of the first flush phenomenon is also investigated. The correlation between the mathematical parameters describing the exponential process and the hydrological parameters of the corresponding rainfall-runoff event is analysed: runoff parameters and in particular the maximum flow discharge over the time of concentration of the drainage network are proposed as the controlling factor for the total mass of pollutant that is made available for wash-off during each runoff event

Keywords First flush; pollution; storm water; TSS, wash-off, urban hydrology

Introduction

In this work, empirical relationships are sought between the hydrologic characteristics of storm events and their potential in mobilising pollutants from the impervious surfaces of the urban landscape. To this aim, a set of rainfall/runoff events monitored at various residential, commercial and production sites were investigated, and results then compared in terms of their mass delivery behaviour. The mass transport analysis concentrated on total suspended solids (TSS), as these usually act as a carrier for other more dangerous constituents (such as metals) and their behaviour is more easily correlated with the wash-off process operated by storm waters.

The solid particles accumulated on impervious areas (street, kerbs, roofs) are washed off during storm events, with many variables contributing to the dynamics of this phenomenon: rainfall intensity, rain depth and duration, runoff peak and volume, topography, particles characteristics (Bertrand-Krajewski *et al.*, 1993). The wash off is triggered by rain drop impacts, thus the relevance of the rain intensity and particles are then transported into the stormwater drainage system by the overland flow (Young and Wersma, 1973; Deletic *et al.*, 1997). The traditional modelling approach focuses on the Antecedent Dry Weather Period (ADWP) – namely the number of dry days between two subsequent rain events – as the key variable to quantify the mass accumulation phase at urban surfaces. The hypothesis behind this is that the amount of mass that a given rainfall event will be able to mobilise equals the total amount available at the surface at the beginning of the rain event. The evolution of the wash-off process will follow a suitable depletion law, and the hydrologic characteristics of the events are only able to modulate the form of such a curve, thus influencing in any case the actual mass that is mobilised in the end.

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In the present work we assume that the pollutant generation process basically depends on the watershed rainfall-runoff response characteristics, rather than on the availability of constituents at the surface as a result of some accumulation process occurring during dry weather periods (Sartor *et al.*, 1974; Alley and Smith, 1981; Bujon and Herremans, 1990). This means that the amount of water that is made available for wash-off is only asymptotically equal to the accumulated mass on a specific impervious surface, and its actual value is prominently a function of the hydrologic characteristics of the event. The results of the analysis performed on various test sites, although the number of the monitored events is still limited and will require further investigation, seem to confirm this hypothesis and lead to significant correlations as described in the paper. These first results are intended as the basic experimental evidence required to drive the present analysis toward singling out more precisely the various emerging dependencies and to get rid of the noise, which is coming out from the extreme variability of rainfall events, site specific characteristics, sampling and monitoring problems, etc.

Experimental sites and equipment

Since January 2002 the Department of Environmental Engineering of the University of Genoa has carried out an intense monitoring program for sampling runoff quality parameters at urban, commercial and industrial areas. In the present paper, rainfall-runoff data collected at a residential area, an auto recycler/dismantler facility, a tourism terminal and a urban waste truck depot were respectively examined. Each monitoring station was basically equipped with an automatic sampler (24 PVC bottles with 0.5 L capacity for the residential area, 12 glass bottles with 0.95 L capacity for the other sites) for water quality aspects and with a system for continuous flow monitoring designed according to the specific site characteristics. Each experimental site was also equipped with a tipping bucket rain gauge (20 gr bucket capacity). The first experimental catchment was located in Villa Cambiaso, at the Faculty of Engineering of Genoa. The monitored site was an asphalt paved parking lot with an extension of approximately 1,000 m^2. The sampling station is located just upstream of the inflow into the municipal stormwater drainage system (Gnecco *et al.*, 2005). The second pilot site was installed within an auto recycler and dismantler facility located in Chiavari, in the vicinity of the town of Genova. The study area was about 4,500 m^2 and consisted of an external area, totally paved, used for the storage of scrap vehicles and various metallic matters. The sampling station was installed inside the initial sedimentation chamber of a first flush tank (Gnecco *et al.*, 2006). The third experimental site, located within the car ferries terminal of the Port of Genoa, included the access road for private and commercial vehicles to/from the car ferries embarkation point and the parking lot for vehicles and trucks before embarkation. The monitored area was a concrete paved surface with an extension of approximately 5 ha and the sampling station was installed in the terminal section of the stormwater drainage pipeline. The last pilot site was an apron located within the municipal depot in Chiavari; the monitored area was employed for parking and maintenance of dumpers and trucks collecting urban solid wastes. The instrumented catchment was an asphalt surface of approximately 1,500 m^2 and the gauge station was installed at the outlet section of the stormwater system.

Data and results

The following data are provided for each sampling station: one minute rainfall and runoff data obtained from continuous measurements and runoff water samples automatically collected at 5–10 min intervals. General water quality parameters are investigated: total suspended solids (TSS), chemical oxygen demand (COD), or total organic carbon (TOC) and pH. In addition, aqueous heavy metals were examined in each gauge station while particulate fraction analyses were performed only for the tourism terminal and the waste truck depot. The total and linear aliphatic hydrocarbons were investigated (Hc_{tot}) only for the production site. At the Villa Cambiaso site, 12 rainfall-runoff events were monitored during the period 2002–2003 and 11 rain events were monitored at the auto dismantler facility in the period from February to December 2004. At both the tourism terminal and the urban waste truck depot sites, data from five rainfall-runoff events were collected; these monitoring campaigns are still in progress. In order to compare the overall runoff quality associated with each rainfall event, the event mean concentration (EMC – flow-weighted average of constituent concentration) was evaluated. In Table 1 the EMC values (mean and standard deviation) corresponding to the urban and commercial sites are summarised for each parameter. By comparing water quality data, the relevance of the pollutant load associated with stormwater discharges at the auto dismantler site clearly emerges: in particular, the concentration of TSS and COD significantly exceeds the quality standards for direct outflows into the receiving water bodies, respectively equal to 80 and 160 mg/L (Annex 5 – Italian Decree by Law 152/2006 according to the EC Dir. 91/271). In addition, it can be observed that among heavy metals, Cu, Zn and Pb showed significant concentrations at each site of concern as both aqueous and particulate fractions according to the American and European case studies reported in the literature (Barrett *et al.*, 1995; Gromaire-Mertz *et al.*, 1999, etc.): such metals are indeed considered as the typical pollutants connected to vehicular traffic (Ball *et al.*, 2000).

In order to examine the mass delivery behaviour across the whole monitoring campaign and to compare the different experimental catchments, the wash-off process was analysed using the dimensionless *M(V)* representation (reporting the cumulative fraction of total pollutant mass *M* vs. the cumulative fraction of total runoff volume *V*). A quantitative measure of the first flush phenomenon is provided through the first flush index *FF* (Berretta *et al.*, 2007) calculated as the ratio between the areas subtended by the *M(V)* curve and by the bisector in the same graph: the first flush occurs when *FF* is greater than 1 ($0 \leq FF \leq 2$).

Table 1 Event mean concentration values (mean and standard deviations) of water quality data for the rainfall-runoff events monitored at the urban and commercial sites in the province of Genova. Subscript 'd' refers to the dissolved fraction of metals, while subscript 'p' refers to the particulate-bound fraction

	Residential site		Auto dismantler site		Tourism terminal site		Urban waste trucks depot site	
	Mean	SD	mean	SD	Mean	SD	Mean	SD
TSS (mg/L)	140	115	378	207	163	96	99	37
COD (mg/L)	129	79	634	286	25[b]	15[b]	58[b]	14[b]
pH (–)	n.a.	n.a.	n.a.	n.a.	7.2	0.2	7.05	0.2
HC_{tot} (mg/L)	n.a.	n.a.	12	9	–	–	–	–
Cu_d (μg/L)	19.4	20	63.8	37	9.8	4.1	37.1	15.2
Cu_p (μg/L)	n.a.	n.a.	n.a.	n.a.	148.2	157.6	120.3	60.2
Pb_d (μg/L)	13.2	6	29.6	30	7.2	8.1	3.2	2.3
Pb_p (μg/L)	n.a.	n.a.	n.a.	n.a.	265.1	457.4	42.6	20.1
Zn_d (μg/L)	81.1	33	283.8	144	103.9	63.8	128.5	48.3
Zn_p (μg/L)	n.a.	n.a.	n.a.	n.a.	677.2	840.0	325.4	201.1
Cr_d (μg/L)	–	–	5.9	6	n.a.	n.a.	1.6	0.4
Cr_p (μg/L)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	19.3	8.5
Ni_d (μg/L)	–	–	24.8	17	n.a.	n.a.	5.7	4.0
Ni_p (μg/L)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	28.3	35.7
Cd_d (μg/L)	–	–	0.5	0.1	0.03	0.02	0.63	0.27
Cd_d (μg/L)	n.a.	n.a.	n.a.	n.a.	1.64	1.99	0.73	0.17

n.a. = not available

The elaboration of experimental data generally reveals a remarkable occurrence of the first flush for TSS. In particular, the occurrence of the phenomenon was observed both at the auto dismantler facility and the residential area, respectively covering 80 and 70% of the rainfall-runoff monitored events. In spite of the limited data set available at the tourism terminal and the urban waste trucks depot, three over five events confirm such mass delivery behaviour for TSS. Regarding COD, the first flush phenomenon was only observed at the residential site. No clear behaviour emerges from the *M(V)* curves of Cu, Zn and Pb at all experimental sites.

Wash-off process analysis

The pollutant mass transport associated with storm runoff is a dynamic process affected by several factors including hydrologic parameters, catchment characteristics and the nature of pollutants. In spite of its variability, it was observed in a previous study (Sansalone and Cristina, 2004) that rainfall-runoff events can be generally classified in two different pollutant mass delivery behaviour: mass-limited and flow-limited events. Mass-limited events are characterised by high runoff volumes and disproportionately high delivery of mass in the early event, on the contrary flow-limited events are characterized by low runoff volumes and a more proportionate mass delivery with respect to the runoff hydrograph across the event (Sansalone *et al.*, 1998; Cristina and Sansalone, 2003). Following this approach, the monitored events at each site of concern were examined in order to point out the mass-limited and flow-limited behaviour, and assuming that the first class is characterised by an exponential relationship between delivered mass and runoff volume while a linear relationship is typical of the second class of runoff events.

Regarding both the residential and production site, it was observed that the most suitable parameter to discriminate between the different classes of mass transport is the maximum value of the average flow-rate Q calculated over a time window corresponding to the time of concentration t_c of the specific drainage system, indicated as $Q_{max}(t_c)$. Such criterion confirms that the mass delivery behaviour is strongly related to the rainfall runoff response of the specific watershed while the single rainfall characteristics may not be comprehensive in describing the complexity of factors affecting both the build-up and wash-off processes. In particular, in the case of the auto dismantler facility, it is evident that the specific land use (such as the storage of various metallic materials) has a strong influence on the hydrologic response and thus on the mass delivery behaviour. As for the tourism terminal and the urban waste trucks depot, the observed events were divided into exponential and linear in terms of their mass delivery with respect to the runoff volume. However, it was difficult to single out a precise classification criterion due to the limited data set available. After evaluating the eleven rainfall events monitored at the auto-dismantler site, five were classified as mass-limited processes and the threshold value of the maximum flow-rate over the time of concentration, $Q_{max}(t_c = 15\,\text{min})$, was assumed equal to 2 L/s. As for the residential site, six events were classified as mass-limited process and the classification was based on the maximum value of the average flow-rate calculated over the time of concentration, $Q(t_c = 10\,\text{min})$, with a threshold equal to 0.5 L/s. Regarding the tourism terminal and the waste trucks depot, three rainfall runoff events revealed an exponential mass delivery behaviour with respect to the runoff volume and were therefore classified as mass-limited events.

Figure 1 illustrates the *M(V)* curves corresponding to the rainfall runoff events characterized by a mass limited behaviour; in addition the calculated first flush index is reported. At all monitoring sites, mass-limited events generally exhibited a pronounced first flush phenomenon: the mean *FF* value is equal respectively to 1.4 for the waste trucks depot and 1.3 for the other sites. It can be observed that the *M(V)* curves show a

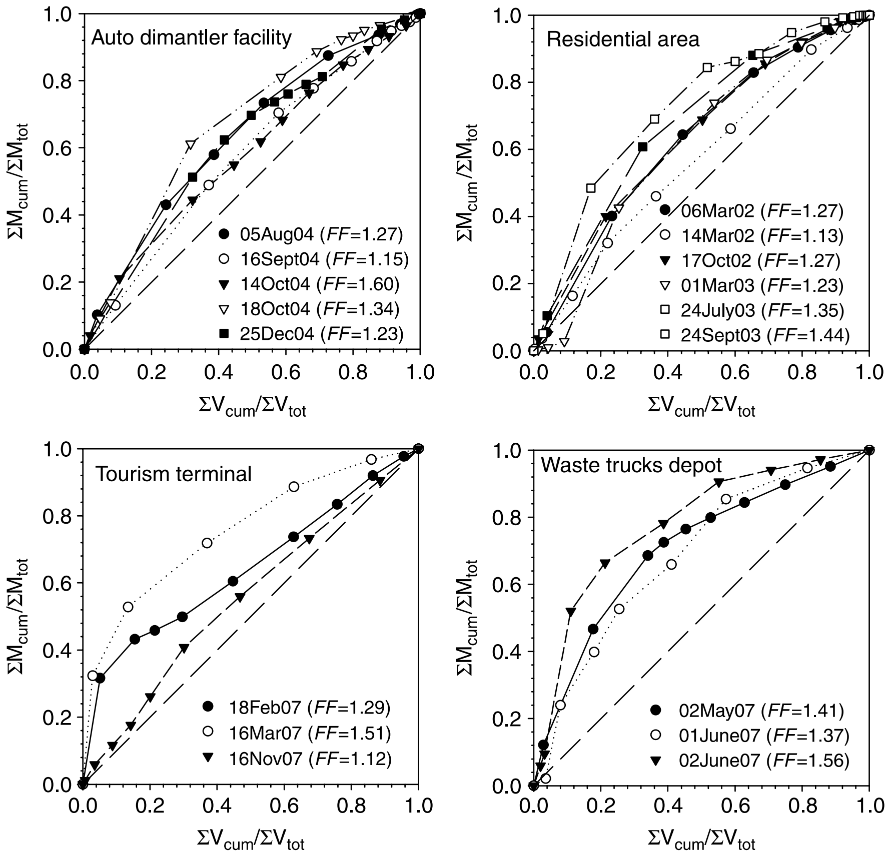

Figure 1 M(V) curves for TSS corresponding to the mass-limited events at the auto dismantler facility, the residential site, the tourism terminal and the urban waste trucks depot. For each monitored event, the first flush index *FF* is also indicated in brackets

marked variability at the tourism terminal site: the different site characteristics in terms of the drained area could mask the occurrence of the first flush phenomenon due to the combined effect of the wash-off process at the surface level and the re-suspension process into the pipeline system (thus partially diminishing the first flush effect when compared to other monitored sites). On the other hand, the urban waste trucks depot was characterised by a fairly small experimental catchment and a well distributed drainage system; such characteristics minimise the effects of the pipeline network thus enhancing the evidence of the first flush phenomenon.

Mass-limited events can be described by an exponential law in terms of mass delivery as a function of the runoff volume, in the form:

$$M_t = M_0(1 - e^{-k_1 V_t})$$

where M_t is the cumulative mass delivery, V_t the cumulative runoff volume, k_1 the first order wash-off coefficient and M_0 the mass limiting parameter. In the present study it is assumed that M_0 actually accounts for the maximum mass available for detachment and transport by runoff during each specific rainfall event. This parameter does not represent the total mass of pollutant accumulated on the surface with time during the antecedent dry weather period (ADWP) as employed in traditional studies. Indeed, the observed correlation between M_0 and the ADWP is very scarce. The M_0 parameter therefore depends on the specific rainfall characteristics and is the actual limiting factor of the

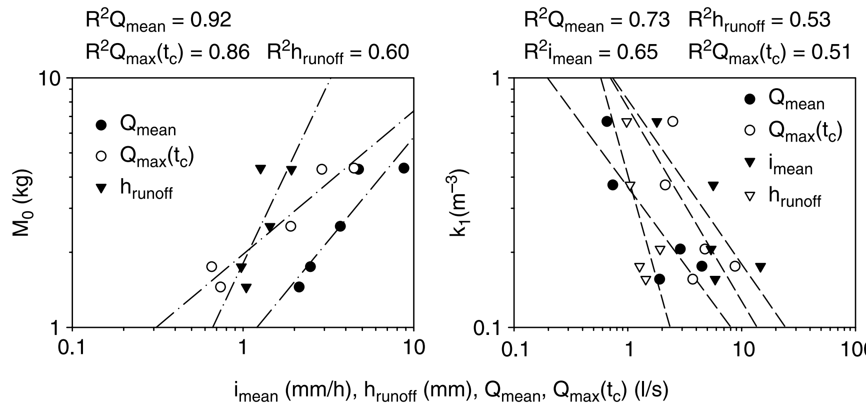

Figure 2 Correlation between the M_0 and k_1 parameters and the rainfall-runoff characteristics at the auto dismantler site

wash-off process for this class of events. The exponential parameters M_0 and k_1 were calculated for all mass-limited events at all experimental sites. In order to investigate the correlation between the mass-limited events and the hydrologic characteristics, a simple regression analysis was carried out for the following hydrologic parameters: average and maximum rainfall intensity, total rain depth, total runoff depth, mean runoff flow rate, maximum value of the average flow-rate over the time of concentration and antecedent dry weather period. Figures 2–5 illustrate the results of the elaboration with respect to M_0 and K_1 for each experimental site.

The M_0 coefficient provided good correlation with rainfall and runoff characteristics; the exception occurs for the auto-dismantler site which reveals good correlation solely with the runoff parameters, and in particular with respect to the flow rate (Q_{mean} and $Q_{\mathrm{max}}(t_c)$). This different observed behaviour can be related to the influence of land use on the rainfall-runoff response: at the auto-dismantler facility the hydrological response and the corresponding pollutant load delivery strongly depends on the specific conditions of the watershed in terms of the total amount and the type of stored material respectively, thus masking the influence of the rainfall characteristics. At the same time, the residential site, the tourism terminal and the waste trucks depot whose main pollutants source is constituted by vehicular/trucks traffic show significant correlation respectively with the

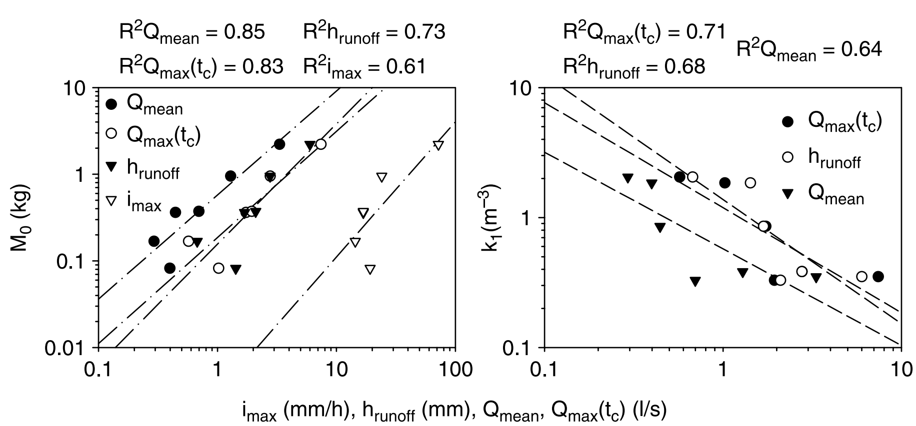

Figure 3 Correlation between the M_0 and k_1 parameters and the rainfall-runoff characteristics at the residential site

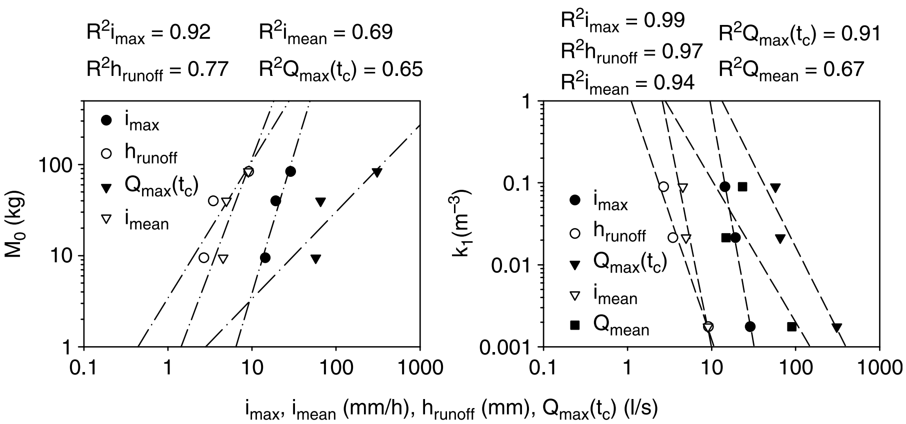

Figure 4 Correlation between the M_0 and k_1 parameters and the rainfall-runoff characteristics at the tourism terminal site

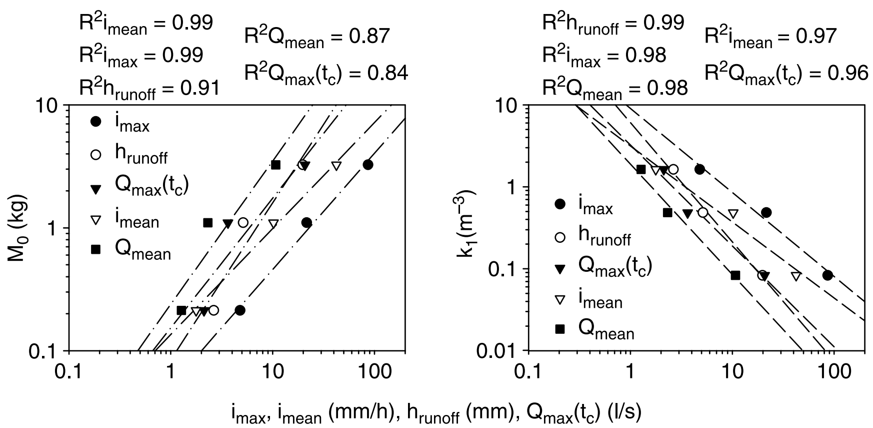

Figure 5 Correlation between the M_0 and k_1 parameters and the rainfall-runoff characteristics at the urban waste trucks depot site

maximum rainfall intensity, the flow rate ($Q_{\max}(t_c)$) and the runoff depth. In particular, at the waste truck depot, the strongest correlations emerge due to the specific site characteristics as mentioned before. As for the k_1 coefficient, correlations seem less remarkable, in particular at the auto dismantler site, even if a correlation with the mean flow rate was observed at all instrumented sites. On the contrary, at the tourism terminal and the waste trucks depot, strong correlations (in the range between 0.91–0.99) emerge with the average/maximum rainfall intensity and with runoff characteristics in terms of maximum flow rate and runoff depth.

Conclusions

Runoff quality data collected at four monitoring stations located within urban and commercial areas were examined to investigate their suitability to fit the two main classes of flow-limited and mass-limited wash-off processes as recently proposed in the literature. Due to the predominance of the exponential mass delivery behaviour with respect to the runoff volume (mass-limited), a first attempt was made to correlate parameters deriving from the mathematical description of such a class of processes with suitable hydrologic variables. It was found that the value of the average maximum flow discharge calculated over the time of concentration of the drainage basin, which is a measure of the hydrological response of the system, provides good correlation at all experimental catchments with M_0, the total mass of pollutant that is made available for wash-off at the paved surface of each site. On the contrary, the influence of rainfall parameters depends on the specific characteristics and land-use of the watershed. Less homogeneous results were observed between the first-order wash-off coefficient k_1 and the investigated hydrological parameters, even if a correlation with the mean flow rate was observed at all instrumented sites. Despite the preliminary promising results, the data set available to the present study was limited in various aspects. First, due to the limitation in time of the monitoring campaign at the auto-dismantler and residential sites, the class of monitored events in terms of their hydrological characteristics was confined at quite short duration events – the range of runoff responses is therefore far from being comprehensive. Furthermore, the monitored rainfall-runoff events were limited in number at the tourism terminal and the waste trucks depot, since the monitoring campaigns are still in progress. The above considerations stimulated the need for improved monitoring capabilities within the urban environment, with special interest on production sites of various characteristics.

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