Long term simulation analysis under two different rainfall regimes as an aid to gully pot management

Aide à la gestion des avaloirs par l'analyse de simulations sur le long terme sous deux régimes de précipitations différents

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RÉSUMÉ

Un avaloir en bord de route est le composant le plus superficiel d’un système d'assainissement urbain. En tant que point de connexion entre la surface et le réseau sous-jacent, cela implique des aspects hydrauliques et de qualité des eaux, ainsi que des problèmes de gestion et d'entretien. Les avaloirs sont supposés piéger les matériaux solides entrainés à la surface du bassin versant, mais aussi de collecter et canaliser les eaux de ruissellement. L’accumulation de particules réduit progressivement la capacité hydraulique des avaloirs et de ce fait, augmente la probabilité d’inondations urbaines au cours d’évènements pluvieux. Ceci soulève des questions sur la nécessité de travaux d'entretien et leur programmation. Des études de laboratoires ont analysé les phénomènes de décantation dans les avaloirs au moyen d’expressions analytiques pour estimer l'efficacité de piégeage. Sur la base d’observations expérimentales, l’objectif de cette étude consiste à évaluer le comportement à long terme d’un seul avaloir au moyen d’une modélisation numérique. Cette analyse a utilisé deux séries de pluies sur le long terme, représentatives de régimes hydrologiques relativement différents (Milan et Palerme, en Italie). Les modèles d’accumulation et de lessivage inclus dans le programme SWMM 5 de l’EPA ont été envisagés. Les valeurs des paramètres ont été échantillonnées de manière aléatoire par distribution uniforme et non-uniforme dans les plages normales mentionnées dans la littérature. A partir des résultats de simulation sur le long terme, on peut estimer la probabilité de distribution de la masse de solides annuellement retenue dans un avaloir et étudier la relation entre cette masse et les principaux paramètres impliqués dans les équations d’accumulation et de lessivage.

ABSTRACT

A roadside gully pot is the most superficial component of the urban drainage system. Being the connection point between the street surface and the network below, involves both hydraulic and water quality aspects, as well as associated management and maintenance problems. Gully pots are supposed to trap solids material washed off the catchment surface, but also to collect and convey the stormwater network. The continuous accumulation of particulate matter brings to a progressive loss of the gully pot hydraulic conveyance, then increasing the probability of urban flooding problems during rainstorm events. This raises questions about maintenance needs and scheduled maintenance timing. Previous laboratory studies have analyzed the settling phenomena inside gully pots, developing and validating also analytical expressions for estimating the trapping efficiency. Based on experimental findings, the present work aims to assess the long-term behaviour of a single gully pot by means of numerical simulation modelling. The analysis made use of two long term rainfall series representative of fairly different hydrological regimes (Milan and Palermo, Italy). The widely known build-up and washoff models included in EPA SWMM 5 have been considered. Their parameters values have been randomly sampled by uniform or non-uniform distributions within the normal ranges reported in literature. From long-term simulation results it is possible to estimate a probability distribution of solids mass annually retained in the gully pot as well as to study the relationship between such mass and the main parameters involved in the build-up and washoff equations.

KEYWORDS

Gully pot; Long-term simulation; Runoff quality models; Sensitivity; Maintenance

1 INTRODUCTION

Roadside gully pots are a relevant component of the drainage system, as they form the connection between the drained catchment and the drainage network. However, gully pots have a dual function: to collect and convey storm water into the network and to retain particulate matter washed off from paved surfaces, therefore protecting the whole drainage system from an excess load of solids. According to previous field and laboratory studies (Bolognesi et al., 2008; Butler and Karunaratne, 1995; Butler and Memon, 1999; Deletic et al., 2000; Memon and Butler, 2002; Silvagni and Volpi, 2002) a continuous feed of solids to a device supposed to trap them, leads unavoidably to gradual silting and eventually to clogging problems. This brings to a progressive loss of the gully pot hydraulic efficiency, then increasing the probability of urban flooding problems during rainstorm events.

The above issue is mostly true in cities served by combined sewer systems (the majority, in Italy) where trapped gullies (Figure 1) are required to prevent the exit of bad odour and animals, being then particularly subject to clogging problems. A regular maintenance of gully pots is therefore essential to ensure their proper functionality. Many municipalities (or stakeholders) do not have an actual predetermined cleaning plan. Maintenance is therefore often limited to cope with emergency situations (severe clogging and/or flooding) when they occur.

Experimental studies carried out in the past led to a better understanding of trapping phenomena within single manholes. In this work, these results will be applied to two different long term rainfall series, belonging to two fairly different climatic locations (Milan and Palermo). The study will also analyze the effects of common build-up and washoff models, considering the uncertainty of their parameters.

Rainfall data consist in ten years extracted from Milan series and eight years from Palermo series. Build-up and washoff models are chosen among SWMM 5 ones, details concerning their formulations as well as parameters range and distribution will be given in the following paragraphs.

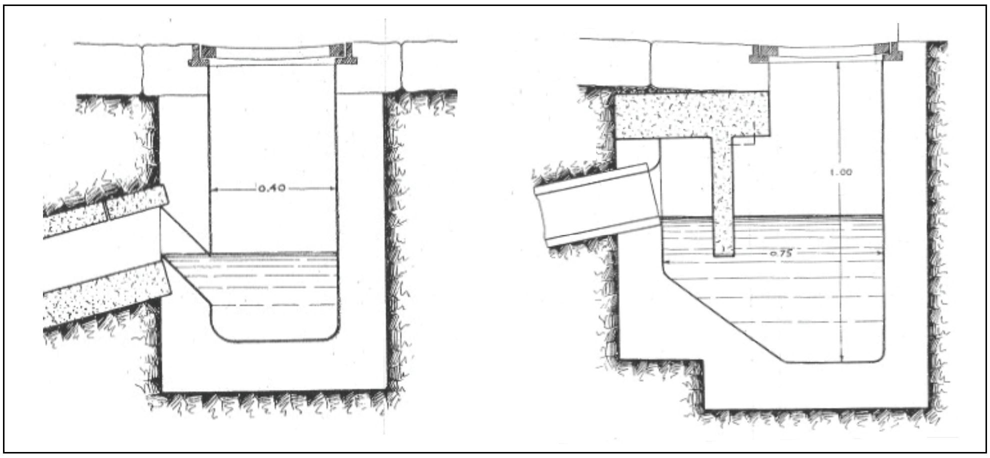

Figure 1 – Typical cross sections of trapped gully pots adopted in Italian cities.

2 DATA AND MODELS CONSIDERED

Rainfall-runoff as well as build up washoff phenomena have been simulated by means of SWMM 5 (EPA Storm Water Management Model), a widely known freely available hydraulic and water quality model, developed in 1969-1971 by three groups: Metcalf & Eddy, University of Florida and Water Resources Engineers.

The simulations aim to assess long-term effects on a ordinary roadside gully pot. Since the analysis wants to be as close as possible to the physical conditions actually existing, both geometrical and hydrological input data have been chosen to be representative of a typical portion of urban street drained by a single gully pot. Considering the way SWMM describes the catchment, the following values were adopted:

- Subcatchment area drained by single gully pot = 100 m^2

- Percent of impervious area = 100%
- Subcatchment width (average distance between gully pots) = 20 m
- Subcatchment slope (Street transverse slope) = 2%
- Street surface roughness = 0.013 s/m$^{1/3}$
- Depth of depression storage = 0.001 m

The goal is to perform a series (Monte Carlo like) of long term simulations, each of which is based on some fixed parameters (e.g. geometry) and some (build up, washoff) sampled from given distributions.

2.1 Rainfall series

Rainfall data consist in ten years extracted from Milan series and eight years from Palermo series.

Milan is located in northern Italy and has a humid subtropical climate (Köppen Cfa, according to Peel et al., 2007), characterized by hot, humid summers and cool winters. Palermo, about 1000 km South of Milan has a mediterranean climate (Köppen Csa, according to Peel et al., 2007), characterized by warm to hot, dry summers and cool, wet winters. The characteristics of both climate, with special reference to the rainfall series here adopted, are represented in figure 2 and synthesized in Table 1.

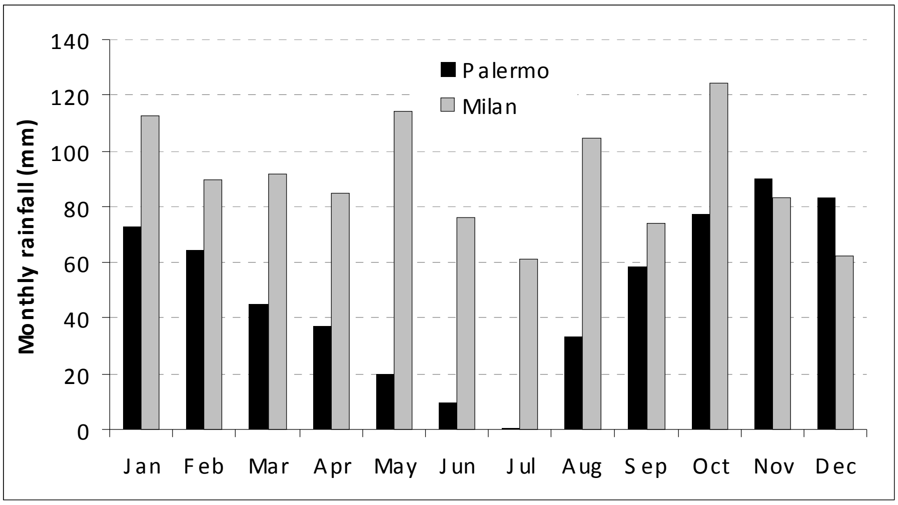

Figure 2 – Average monthly rainfall for the two long-term series considered

	Milan	Palermo
Mean annual rainfall (mm)	1078.8	592.3
Event mean Intensity (mm/h)	21.1	19.7
Event Volume (mm)	21.8	14.2
Inter Event Time (hours)	188.9	224.4
Event Duration (hours)	18.4	16.7
Number of Events per year	46.2	38.6

Table 1 – Main hydrological values for the two long-term series considered

2.2 Build up

The accumulation of solids on the street surface can be modelled in SWMM by means of four possible empirical laws. This study considers two of them: the exponential and the linear one, both frequently adopted in literature to represent build-up experimental data. The following (1) represents the exponential formula (Huber and Dickinson, 1988), while (2) is the linear one:

$$M_a(t_s) = \frac{Accu}{Disp}\left(1 - e^{-Disp \cdot t_s}\right) \tag{1}$$

$$M_a(t_s) = \min\left(\frac{Accu}{Disp};\ Accu \cdot t_s\right) \tag{2}$$

where M_a is the specific mass accumulated on the catchment surface at time t_s (kg); *Accu* is the solids build-up rate (kg/ha/day); *Disp* is the dispersion coefficient (1/day); t_s antecedent dry weather period (day). In both cases the ratio *Accu*/*Disp* represents the limit value for the specific mass accumulated on the basin.

Accu and *Disp* parameters can assume quite different values. While *Disp* has basically a role of calibration parameter, the value of *Accu* is usually associated in the international literature with the land use type (Table 2):

Land Use	*Accu* (kg/ha/day)
High density residential areas	10-25
Low density residential areas	5-6
Commercial areas	15
Industrial areas	35

Table 2 - Build-up rate as a function of land use (Alley and Smith, 1981; Bujon and Herremans, 1990)

The range definition and a proposal for the distribution of *Accu* and *Disp* values was mainly based on experimental data collected in Italy (Maglionico, 1998; Maglionico and Pollicino, 2004; Bolognesi et al., 2008) as well as considering the ranges proposed in literature

In particular, once the range for *Accu* (5-35 kg/ha/day) and *Disp* (0.08-0.30 1/day) are set, such values can be uniformly or non-uniformly distributed. In case of non-uniform distribution, a normal distribution was assigned to *Accu* having mean equal to 20 and standard deviation equal to 5; while the *Disp* parameter was assigned a log-normal distribution (Figure 3).

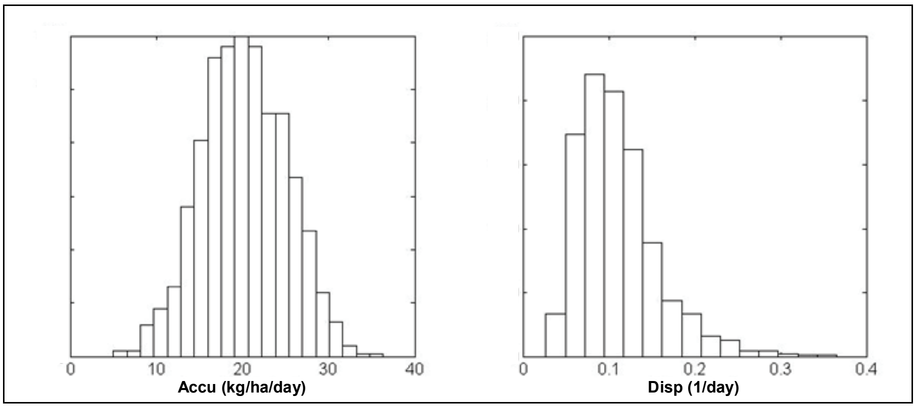

Figure 3 - Examples of probability distribution assigned to *Accu* (left) and *Disp* (right).

2.3 Washoff

Washoff modelling comes from the integration of the equation given in the current version of SWMM and due to Huber (1986):

$$\frac{dM_a}{dt} = -Arra \cdot P^{wash} \cdot M_a \qquad (3)$$

Where M_a is the mass of solids on the catchment when the event starts (kg); *Arra* the washoff coefficient ($mm^{-wash}\ h^{(wash-1)}$); *wash* the washoff exponent which has the function to increase the effect of rain intensity; *P* the net rainfall intensity (mm/h).

Also in this case there are two parameters for which range limits have to be defined: *Arra* and *wash*. If the second does not present particular problems, being a dimensionless parameter, the first requires some additional explanation, especially in order to facilitate comparison with previous studies. In the original formulation of SWMM the parameter *Arra* had the dimension of the inverse of a length. With the introduction of the *wash* exponent, the value of *Arra* becomes linked to *wash* itself, as well as to rainfall intensity. This obviously affects the *Arra* units. Many references in the literature indicate for those parameters values expressed in US customary units. However, in this study SWMM simulations and results are based on the International System, so it is important to remember that, *Arra* (S.I.) is equal to *Arra* (U.S.) times 25.4^{-wash}. The importance of this conversion emerges also when the range limits and a probability distribution has to be defined for *Arra*, since it would be obviously uniform in one case, exponential in the other. The range of variation for *Arra* was then based on the limits suggested by Ammon (1979) for settleable solids (2.9 - 9.3). These values are expressed in U.S. units and are supposed uniformly distributed. The assumption of *wash* parameter uniformly distributed between 1 and 2 allows for the final conversion of *Arra* in SI units. The range limits of *Arra* in S.I. units are in line with those proposed by Sonney (1980) (0.002 to 0.260) and with those experimentally obtained by wash-off laboratory tests (Simone et al., 2004).

2.4 Gully pot efficiency model

The gully pot trapping efficiency formula has been taken from the experimental results of a previous work (Bolognesi et al., 2008). Laboratory tests carried out on a traditional gully pot confirmed those obtained by other authors (Lager, 1977; Grottker, 1990, Butler and Karunaratne, 1995) and extended their validity to a wider range of conditions. In summary:

1) the efficiency (capability of retaining solid material) of a single gully pot is inversely proportional to the inflow and to the specific weight of sediment, while is directly proportional to their size, according to the following law:

$$\varepsilon = \frac{w_s}{w_s + Q/A} \qquad (4)$$

where ε is the trapping efficiency, w_s is the particulate matter settling velocity (m/s) which depends on particle size and density; *Q* is the liquid flow entering the gully (m^3/s); *A* is the gully pot cross sectional area (m^2).

2) the efficiency does not depend on the incoming solids concentration;

3) solid mass contribution due to erosion and re-suspension of bed sediments is not quantitatively significant, and is limited to short transient periods (first 20-40 seconds of the event).

Laboratory tests have verified the applicability of (4) also in case of non monodisperse samples. In such cases, the efficiency is determined by applying (4) to each size fraction and then calculating the weighted average, on a mass fraction basis. According to the above, assuming a particle size distribution for the incoming sediment and given the internal dimensions of the gully pot, it is possible to develop inflow-efficiency curves, similar to the empirical ones by Grottker (1990).

3 INFLUENT SOLIDS CHARACTERIZATION

In terms of mass, solids are the most relevant potential pollutant conveyed by rain water. Various experiments designed to determine the characteristics of the material accumulated on the road surface (Sartor and Boyd, 1972; Ellis and Harrop, 1984; Sansalone and Ying, 2008) have shown these sediments to be well assorted in terms of size, with particle diameters ranging from a few microns to some millimetres and d_{50} often between 100 and 300 μm. As far as specific gravity is concerned, Chebbo et al. (1990) found that it tends to exceed 2.4 for particles with diameters of 100-250 μm and then to decrease with increasing particle size, while Butler et al. (1992) determined the range of the particles specific gravity to be 1.89 to 2.78 (mean value 2.35), but without showing any clear relationship with sediment particle size. According to many authors (Chebbo et al., 1990; Michelbach and Wöhrle, 1992; Stahre and Urbonas, 1990) the coarser are the particles, the higher is the organic fraction. Moreover several studies prove that most pollutants are associated with smallest particles: according to Ellis and Revitt (1982) 70% of metals are attached to particles smaller than 100 μm; Xanthopoulos and Hahn (1993) set in 60 μm the value below which the highest correlation between heavy metals concentration and particle size is present. In present work, two different kind of particulate matter, both result of street sampling, were considered. Figure 4 shows the two particle size distributions sampled along Via Togliatti (Maglionico and Pollicino, 2004), and Via del Lazzaretto (Bolognesi et al., 2008). The first is a highly trafficked road with three lanes for each carriageway, while the second is a low to medium trafficked road, in the immediate outskirts of Bologna. Particle size distributions are consistent with those found in the literature.

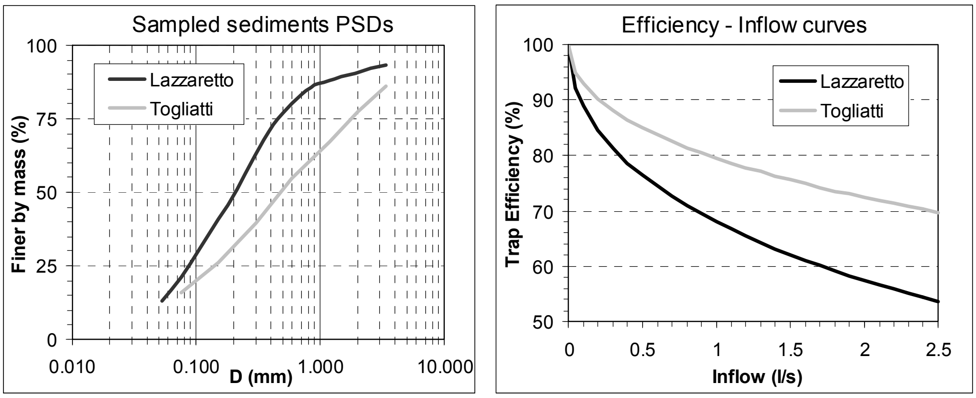

Figure 4 – Particle Size Distribution (PSD) of street samples collected during previous studies (Maglionico and Pollicino, 2004; Bolognesi et al., 2008) (left) and here adopted for numerical simulations; Efficiency-inflow curves for different incoming sediment types and for a 40 cm square gully pot (right).

Using the PSDs of figure 4 and equation (4), it is possible to calculate the gully pot efficiency as a function of the selected material (PSD) and of the liquid inflow rate, thus defining the curves of Figure 5. Thanks to those curves, given (by SWMM) the solids mass washed off and entering the gully, and given the particulate matter PSD it is possible to quantify the fraction retained.

4 SIMULATIONS AND RESULTS

On the basis of the above hypotheses, particularly concerning:

- simulation model, hydrological and geometrical parameters of the catchment;
- long term rainfall series;
- build-up and washoff models: parameters range limits and distributions;
- trapping efficiency model for the gully pot;
- characteristics of particulate matter sampled on the street surface;

several numerical simulation have been eventually carried out. Once the build-up and washoff models have been defined, how their parameters are distributed and the type of street sediment considered, a series of MonteCarlo-like simulations is performed on both rainfall series. For each run, the surface quality models parameters are sampled from the assigned distributions. Each simulated configuration thus provides two distinct groups of results: the first is relative to the yearly solids mass trapped in the gully pot, expressed in terms of probability distributions. The second shows the relationship between the main surface quality modelling parameters and the amount of solids retained in the gully pot. Figures 5 and 6 show respectively for Milan and Palermo series the cumulated distribution of mass yearly trapped in the gully, allowing to assess how models and parameters considered for the simulations affect the resulting retained mass. In synthesis, the following possible alternatives have been tested:

- Build-up model: Exponential (*Exp*) or Linear (*Lin*);
- Distribution of Parameters: Uniform (*Uni*) or Non-Uniform (*Non*);
- Particle size distribution of particulate matter: Lazzaretto (*Laz*) o Togliatti (*Tog*).

	Exp-Uni-Tog	*Exp-Uni-Laz*	*Lin-Uni-Laz*	*Exp-Non-Laz*
	Mean (St. Dev.)	Mean (St. Dev.)	Mean (St. Dev.)	Mean (St. Dev.)
Milan	22.4 (11.8)	20.5 (10.7)	25.5 (14.2)	26.7 (9.1)
Palermo	14.8 (8.8)	13.4 (7.6)	17.4 (10.0)	21.1 (7.9)

Table 3 - Statistical indicators of mass trapped yearly in gully pot, for each configuration modelled.

According to figure 5 and 6, the estimate for retained mass seems to be more dependent on the build-up model or on the parameters distribution, rather than on particle size distribution. The relationship analysis between SWMM surface quality parameters and trapped mass (qualitatively illustrated in figure 7 and thoroughly presented in table 4) clearly identifies *Accu* as the most highly correlated parameter, while *Disp* exhibits weaker negative correlations. Washoff coefficients, especially *wash*, do not seem to have significant relationship with solids mass retained in the gully pot.

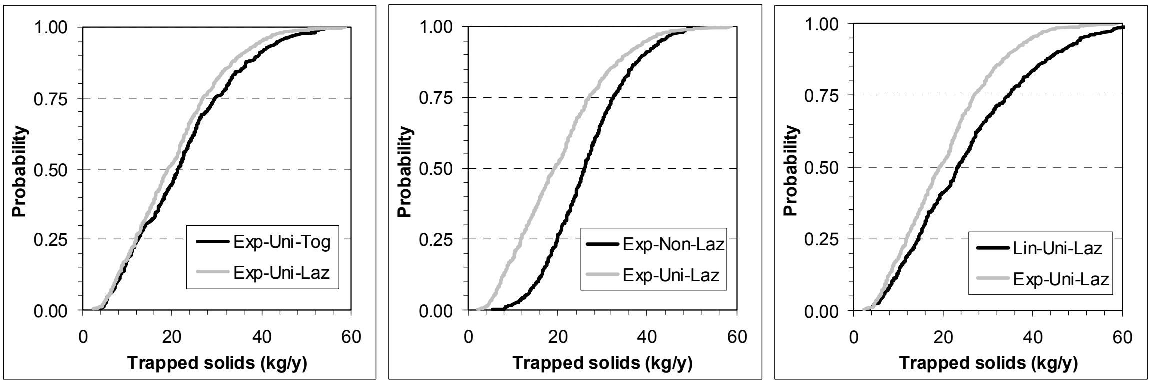

Figure 5 - Cumulative distributions of sediment mass trapped yearly in gully pot based on all Milan series simulations: in each plot two variables are fixed, while the third is compared.

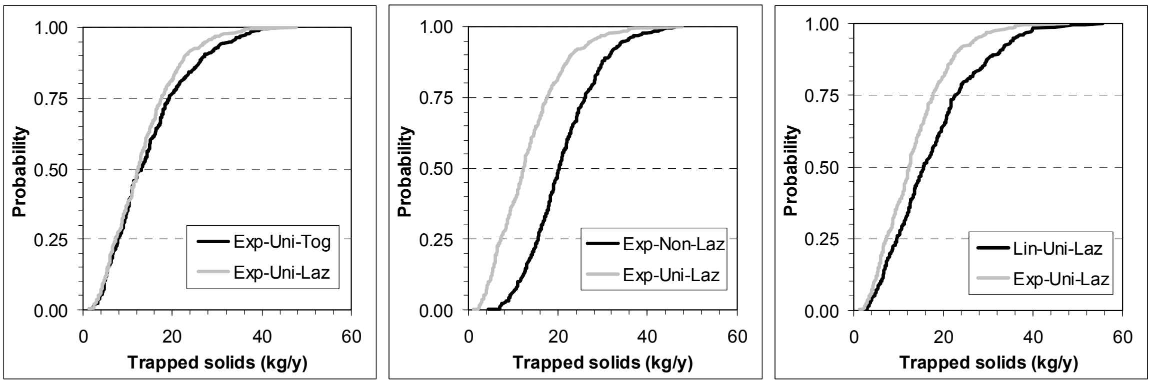

Figure 6 - Cumulative distributions of sediment mass trapped yearly in gully pot based on all Palermo series simulations: in each plot two variables are fixed, while the third is compared.

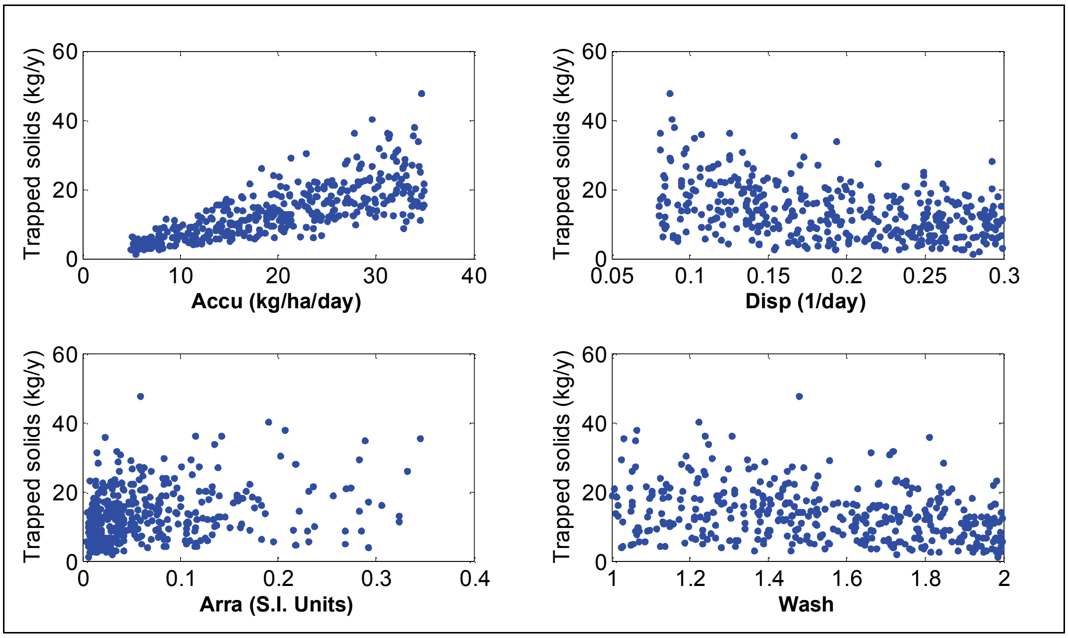

Figure 7 - Correlations between build-up/washoff parameters and solids trapped yearly in gully pot: example based on 50 long term simulation on Milan series, configuration Exponential-Uniform-Lazzaretto.

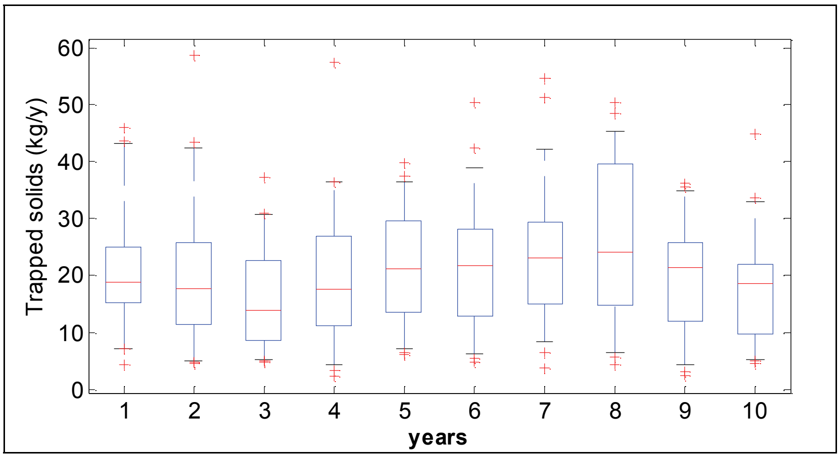

Figure 8 - Solids trapped in gully pot for each simulated year: example based on Milan series, configuration Exponential-Uniform-Lazzaretto (outliers represent values outside 5th and 95th percentile).

		Exp-Uni-Tog	*Exp-Uni-Laz*	*Lin-Uni-Laz*	*Exp-Non-Laz*
Milan	*Accu*	0.831	0.794	0.800	0.710
	Disp	-0.327	-0.436	-0.454	-0.513
	Arra	0.245	0.248	0.242	0.290
	Wash	-0.259	-0.270	-0.253	-0.272
Palermo	*Accu*	0.773	0.763	0.743	0.631
	Disp	-0.414	-0.399	-0.434	-0.522
	Arra	0.309	0.274	0.274	0.302
	Wash	-0.257	-0.297	-0.300	-0.275

Table 4 – Correlation coefficient between build-up/washoff parameters and solids trapped yearly in gully pot for both rainfall series and each simulated configuration.

5 CONCLUSIONS

The objective of this work was to assess the long-term behaviour of a generic gully pot with specific attention to the capability of retaining particulate matter. Numerical simulations were conducted using the EPA SWMM 5 build-up and washoff models, analyzing two rainfall series belonging to two different climate regime (Milan and Palermo, Italy).

The gully pot trapping efficiency was considered on the basis of laboratory experimental results and analytical formulations developed in a previous work. From the results of Monte Carlo-like simulations two sets of conclusions may be drawn: firstly, the choice of build-up model and the runoff quality parameters assigned distribution seem to have a greater influence on the amount of solids retained inside the gully pot, while the sediment particle size distribution appears less important. Secondly, concerning the relationship between the main runoff quality parameters and the trapped solids annual estimate, it is quite clear that sediment surface accumulation *Accu* exhibits significant direct correlations, while *Disp* shows weaker inverse correlations. Washoff parameters, instead, do not present significant correlations in any sense. The above conclusions apply to both rainfall series analyzed. Milan series resulted in higher mean values for retained mass, probably not just for the almost doubled annual rainfall volume, but also for to the greater number of annual rainfall events.

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