



Proceeding Paper

Assessing the Environmental Impact of Combined Sewer Overflows through a Parametric Study [†]

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Abstract: Design and management of combined sewer overflows (CSOs) have been, so far, mainly based only on complying a fixed dilution rate of wastewater in stormwater during rain events. This poses serious environmental issues, since the definition of the acceptable dilution does not consider the characteristics of the upstream urban catchment, nor the climatic features, nor those of the receiving water body. Overflows are usually designed for activation when the mixed discharge reaches about five-times the mean wastewater discharge (though it may vary, depending on country regulations), the latter being the mean dry weather wastewater discharge. Accordingly, recent regulations started enforcing limits also on the frequency of overflows. Overflow activation frequency and discharged volumes of pollutants may depend on the upstream catchment features as well as on the precipitation regime. The great variability in these factors could make the impact on the receiving water body of similarly designed overflows quite different. In this study, the behavior of a CSO placed at the outlet of urban catchments with the same size but different characteristics was simulated with SWMM. The considered hydrological parameters were catchment imperviousness, width and slope, Manning coefficient and depression storage. Served population characteristics affecting the combined sewer hydraulic regime were studied by changing the population density and the mean wastewater discharge per capita. After defining realistic ranges for each parameter, the time series of discharged overflows were calculated for all the combinations of the variable catchment parameters, corresponding to 20-year-long precipitation series from a single rain gauge. The obtained results, although preliminary, indicate that CSOs' impact on the receiving water body strongly depends on the characteristics of the upstream urban catchment. Therefore, such characteristics should be considered in CSO design and management.

Keywords: CSO; SWMM; urban hydrology; water quality; parametric analysis



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1. Introduction

Environmental and health issues arising from the combined sewer overflows (CSOs) are of great concern in urban drainage, as most of the sewer systems in cities are combined [1]. Combined sewer systems (CSSs) are designed to convey both wastewater and stormwater during rain events. Especially during the latter, the combined water flow can increase to the extent that the operation of the downstream wastewater treatment plant (WTP) can be affected [2] or floods may occur along the drainage system [1]. To remedy to this, it is common to place one or more overflow discharge structures at convenient locations along the drainage system, so that they are activated at a certain flow rate or water level. The exceeding water is then diverted to a receiving water body with the assumption that an acceptable dilution rate is achieved by the mixing of the foul water with the storm water [3]. However, it is well known that CSOs may determine uncontrolled amounts of pollutants to be discharged into the water body, so have a strong negative impact on the

environment [4]. Moreover, emerging pollutants (e.g., microplastics [5–9]) can find their way in water bodies through CSOs.

The assumption about wastewater dilution in stormwater results in the common practice of using a fixed dilution rate C between the generic wet weather flow Q at the overflow location and the mean wastewater discharge Q_{mw} in dry weather conditions, to assess whether the free discharge in the water body can take place or not through CSOs:

$$C = \frac{Q}{Q_{mw}} \quad (1)$$

Different values for C can be found in the literature, e.g., in the UK, $C = 6$ was used until 1970 [1] or an Italian law in 1996 [10] set $C \geq 3$. In Italian technical literature, the dilution rate is often assumed equal to 5, where this value is obtained as the ratio of the plausible biochemical oxygen demand after five days (BOD_5) concentration of the wastewater by the threshold imposed by an old Italian law [11] for treated water to be freely discharged into water bodies:

$$C = \frac{200 \frac{mg}{L}}{40 \frac{mg}{L}} = 5$$

For instance, the same coefficient $C = 5$ was also adopted by Lazio regional government (Italy) in 2018 [12].

Although regulations have changed over the years, it was clear in 1970 [13], as well as today, that a fixed CSO setting does not seem to be sufficient to prevent environmental pollution. For this reason, some regulators are trying to enforce enhanced rules to prevent pollution from CSOs [14] (e.g., maximum frequency of spills).

More realistically, the rainfall regime and its modification over decades [15] and the hydrological and water consumption characteristics of urban catchments, also changing in many cases, may have an influence on CSO behavior, namely the frequency of activation of the overflow and the discharged volumes. The latter, when coupled with knowledge on the characteristics of pollutants, give the amount of pollutants disposed into water bodies.

Hydrological simulation at urban catchment scale is a useful tool to study urban drainage phenomena and a rich literature exists on different hydrological models to suit different simulation needs [16]. So far, many works have approached the problem of the behavior of CSOs through software modelling, experimental setups or hybrid approaches [4,17], but few have extensively tackled the great uncertainty in modelling CSOs resulting from different parametrization of catchment models.

To give a contribution on this aspect, in this study, a method to assess CSOs variability, based on these latter characteristics, was developed through hydrological simulations in SWMM within a Python 3 software framework.

2. Methods

A simplified method to assess CSOs' uncertainty was developed, taking advantage of a software framework written for the purpose.

2.1. Model Input Parameters

A lumped urban catchment with an area $A = 1 \text{ km}^2$ was considered (Figure 1). For the sake of focusing on how different hydrological and urban characteristics affect CSOs, the drainage network was here neglected.

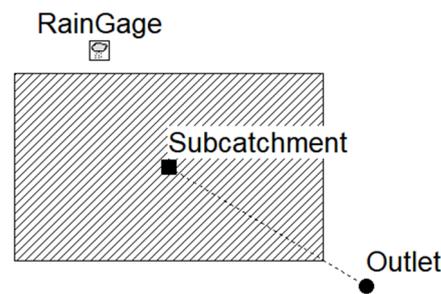


Figure 1. Scheme of the urban catchment simulated in SWMM 5.1.

In order to characterize the impact of the CSOs on receiving water bodies, it is important to assess some key variables, such as:

- The number of activations of overflows, namely the spills in a year;
- The volume of polluted water discharged in a year.

Aiming at a better understanding of CSO events, this work dealt with these two variables, defined as follows:

$$F^y = \sum_{i=1}^N f_i^y \tag{2}$$

$$V^y = \sum_{i=1}^N D_i^y \Delta t \tag{3}$$

being:

F^y the number of overflow events expressed in $[year^{-1}]$ relevant to the y^{th} year;

V^y the volume of water discharged expressed in $[\frac{mm}{year}]$ relevant to the y^{th} year;

where:

$$f_i^y = \begin{cases} 1, & D_i^y > 0 \wedge D_{i+\frac{t}{\Delta t}}^y = 0 \\ 0, & D_i^y = 0 \end{cases} \tag{4}$$

and:

$$D_i^y = Q_i^y + Q_{mw} - CQ_{mw} \geq 0 \tag{5}$$

$N = \frac{\Delta T}{\Delta t}$ is the number of Δt time steps in the interval $\Delta T = 1 \text{ year}$;

$\Delta t = 10 \text{ min}$ is the time step resolution of the results of the simulations;

Where t is the inter-event time, that is the interval of time defining two different events of overflow, considered equal to $t = 10 \text{ minutes}$ in this study and where D_i^y is the discharged flow at the i^{th} time step relevant to the y^{th} year, calculated as the difference between the resulting runoff Q_i^y plus the mean wastewater discharge Q_{mw} and CQ_{mw} , the latter being the setting threshold of overflow activation.

In this study we investigated the case corresponding to $C = 5$. To identify the ranges of hydrological and urban characteristics to be investigated (Table 1), the 50 most densely populated Italian cities were considered. The daily water use per capita (DWC) [18] and the population density (PD) were made available from ISTAT. The percentage of the impervious surfaces (I) was implied from Di Fabbio et al. [19], the ISPRA [20] and the SWMM user manual [21,22]. The width (W) parameter was calculated assuming different shapes for the catchment. Slope (S) is subject to specific site orography: as per the current study, flat urban environments were considered. For the Manning roughness coefficients (n_{imp} , n_p) and the depression storage (d_s), references were made to SWMM user manual [21] and to Yen (2001) [23].

Table 1. Ranges of investigated hydrological and population parameters: 6 values are attributed to each parameter, linearly sampling them between a minimum and a maximum value.

Parameter	Values
Daily Water use per Capita $DWC \left[\frac{L}{p \cdot day} \right]$	[100, 180, 260, 340, 420, 500]
Population Density $PD \left[\frac{p}{km^2} \right]$	[1000, 2400, 3800, 5200, 6600, 8000]
Impervious surface $I[\%]$	[10, 24, 38, 52, 66, 80]
Width $W[m]$	[250, 1000, 1750, 2500, 3250, 4000]
Average Slope $S[\%]$	[0.1, 0.18, 0.26, 0.34, 0.42, 0.5]
n Manning of impervious surfaces $n_{imp} \left[\frac{s}{m^{\frac{1}{3}}} \right]$	[0.01, 0.012, 0.014, 0.016, 0.018, 0.02]
n Manning of pervious surfaces $n_p \left[\frac{s}{m^{\frac{1}{3}}} \right]$	[0.03, 0.04, 0.05, 0.06, 0.07, 0.08]
Depression Storage of impervious surfaces $d_s [mm]$	[0.5, 0.8, 1.1, 1.4, 1.7, 2]

Under the assumption that densely populated cities are also highly urbanized, the parameters DWC , DP and I were considered as linearly dependent from each other: the first two were integrated into the Q_{mw} expression:

$$Q_{mw} = (\varphi \cdot PD \cdot DWC) \sim I \tag{6}$$

where $\varphi = 0.8$ was assumed as the ratio of the water being conveyed to the CSS after use by the water distributed in the water distribution network (WDN). Equation (6) expresses the production of sewage per unit surface. This assumption led to a significant reduction in the computational time required to run all the simulations, since the eight parameters investigated would have resulted in 6^8 scenarios, while aggregating DWC , PD and I resulted in the number of simulations being reduced to 6^6 , with a 36-times reduction.

2.2. Rainfall Input Data

The rainfall time series registered by a rain gauge in Ercolano, an Italian city near the coast in the province of Naples, were used as input (Figure 2): they had a resolution of 10 min and covered the period from 2002 to 2021 (included). A simple pre-processing of the data was carried out to remove outliers.

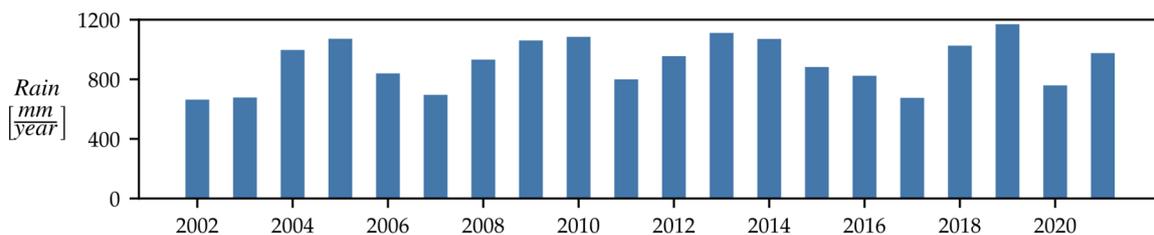


Figure 2. Yearly rain in Ercolano. <http://centrofunzionale.regione.campania.it/#/pages/sensori/archivio-pluviometrici> (accessed in 1 April 2022).

2.3. Software Framework

From Equation (6) and Table 1, it follows that the total number of parameter combinations to be simulated was:

$$n = 6^6$$

To evaluate F^y and V^y corresponding to all the combinations of the parameters, a software framework for the hydrological simulations was set up and it consisted of:

- (a) SWMM 5.1 [24] as the core simulation software for each single run that covered 20 years of rainfall events;

- (b) A Python 3 program written for the purpose, also taking advantage of multiprocessing to substantially reduce the remarkable amount of time needed for the simulations.

Since SWMM itself does not allow one to run multiple models simultaneously, the Python program embedded two packages:

1. “pyswmm 1.1.1” [25]: it has been employed to run the engine of SWMM;
2. “swmm-api 0.2.0.16” [26]: it has been employed to generate the 6⁶ scenarios as different input files to be run, as well as to read the output files.

3. Results

After running the simulations, the total number of results for F^y and V^y was, respectively, $20 \cdot 6^6$, corresponding to the case of $C = 5$. Histogram plots (Figure 3) highlight the high variability in the variables with respect to all the investigated scenarios.

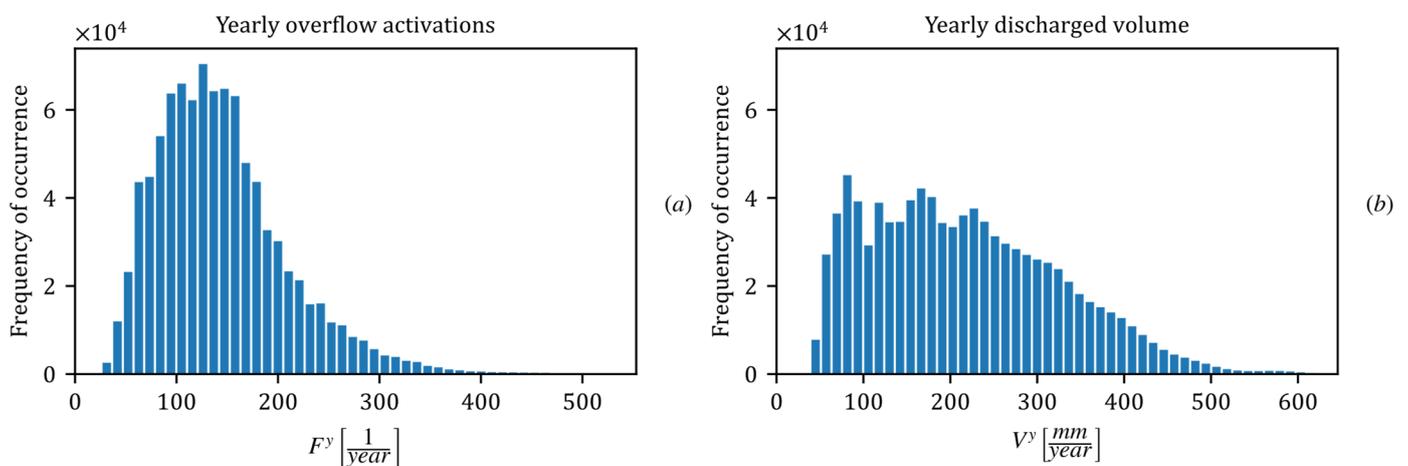


Figure 3. Histogram plots for F^y (a) and V^y (b): each variable, respectively, covers $20 \cdot 6^6$ values from the output results while 50 bins are shown.

F^y may vary between 26 year^{-1} and 553 year^{-1} with a variability of 21.27 times, while V^y may vary between $38.98 \frac{\text{mm}}{\text{year}}$ and $645.75 \frac{\text{mm}}{\text{year}}$ with a variability of 16.57 times. Average values, standard deviations and interquartile ranges for F^y and V^y are given in Table 2.

Table 2. Average values, standard deviations and interquartile ranges for F^y and V^y .

	Mean μ	Standard Deviation σ	Interquartile Range IQR
$F^y \text{ [year}^{-1}\text{]}$	145	64	[98;178]
$V^y \text{ [}\frac{\text{mm}}{\text{year}}\text{]}$	215.80	108.45	[126.85;290.51]

To evaluate the influence of the yearly rainfall in Ercolano on CSOs, the average values of F^y and V^y were plotted against the yearly rainfall in Ercolano. Figure 4 shows how CSOs are directly proportional to yearly rainfall.

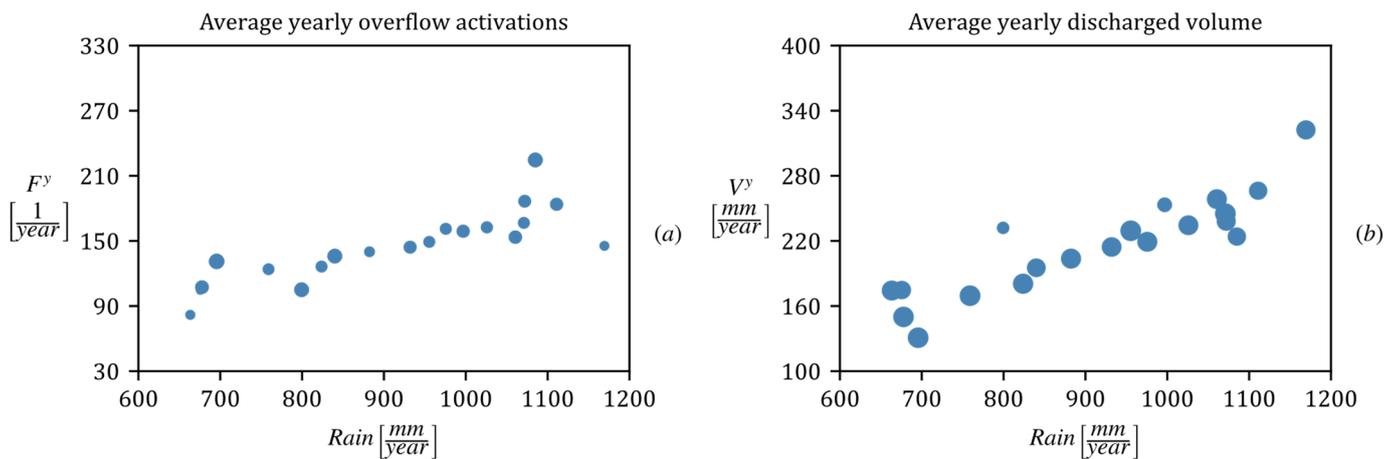


Figure 4. Influence of annual rainfall on F^y (a) and V^y (b).

Correlations between the output data from the 6⁶ simulated models for a period of 20 years and the input parameters were searched for, giving the trends shown in Figure 5. In particular, the charts represent the influence of each parameter on the average of F^y and on the average of V^y , defined as follows:

$$F = \sum_{y=2002}^{2021} \frac{F^y}{20}; \quad V = \sum_{y=2002}^{2021} \frac{V^y}{20} \tag{7}$$

The most influential parameters on F and V are summarized in Table 3.

Table 3. Most influential parameters on F and V: the ranges are intended with respect to the mean values of F and V as in Table 2.

	$F [year^{-1}]$	$V [\frac{mm}{year}]$
Increase	$W : [-45\% \div +28\%]$	$Q_{mw} \sim I : [-63\% \div +57\%]$
Decrease	$Q_{mw} \sim I : [+47\% \div -25\%]$	$n_{imp} : [+5\% \div -5\%]$

It is worth noting that with the same assumed dilution coefficient $C = 5$ for the activation of the CSO, greater sewage production leads to less frequent activations, but to greater discharged volume. The sewage production is, in turn, due to *DWC* and *PD*, as expressed by Equation (6).

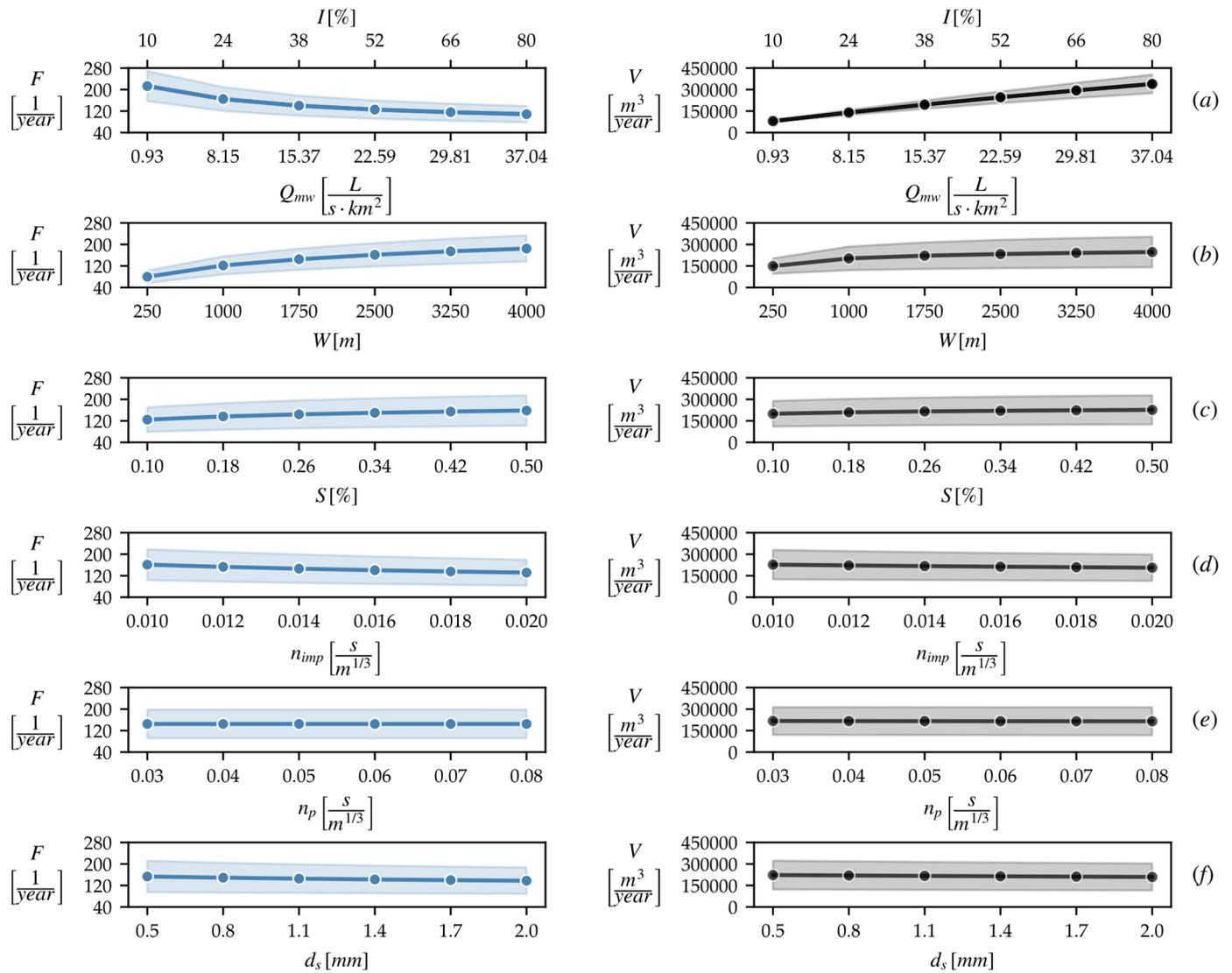


Figure 5. Influence of investigated parameters on frequency F and volume V . (a) mean wastewater discharge and imperviousness; (b) width; (c) slope; (d) impervious Manning; (e) pervious Manning; (f) depression storage. Markers stand for the average of F and V relevant to each parameter’s value; bands stand for the standard deviation relevant to the remaining 6^5 scenarios.

4. Conclusions

The results, although preliminary, show that the average frequency of activation of CSOs and the average discharged volume of polluted water into receiving water bodies depend on hydrological and population characteristics of urban catchments, as well as on the rainfall regime. The parameters mostly affecting the two variables seem to be the average wastewater discharge per unit area; imperviousness and shape of catchments (through the width parameter); rainfall regime. The results also suggest that a deterministic statement of the dilution coefficient does not bind the behavior of CSOs to simply predictable ranges of the frequency of activation and the discharged volume and, indeed, it may not be sufficient to assess the environmental impact of CSOs nor to assure an acceptable level of protection of receiving water bodies from pollution. Instead, multi-scenario simulations could serve as an important tool to assess overflow variability with more accuracy, thus, to design site-specific CSO structures with more detail. Future studies will delve more deeply into the parameter sensitivity analysis and will involve the use of different rainfall regimes, along with different dilution coefficients.

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

List of Acronyms

BOD ₅	Biochemical oxygen demand after 5 days
CSO	Combined sewer overflow
CSS	Combined sewer system
ISTAT	Istituto Nazionale di Statistica
SWMM	Storm water management model
WDN	Water distribution network
WTP	Wastewater treatment plant

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