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Assessing the environmental impact of combined sewer overflows through a parametric study [†]

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Abstract: Design and management of combined sewer overflows (CSO) 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. Namely, overflows are usually designed for activation when $Q > \sim 5Q_{mw}$ (though it may vary, depending on countries 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 of these factors could make the impact on the receiving water body of similarly designed overflows to be quite different. In this study, the behaviour of a CSO placed at the outlet of urban catchments with same size, but different hydrological and urbanistic characteristics, has been simulated with SWMM. The considered hydrological parameters were catchment imperviousness, width and slope, and routing Manning coefficient and depression storage for both pervious and impervious surfaces. Urbanistic characteristics of the catchment affecting the combined sewer hydraulic regime were studied by changing the density of population and the mean per capita wastewater discharge. After defining realistic ranges for each parameter, the time series of discharged overflows have been calculated for all the combinations of the variable catchment parameters, corresponding to 20 years long precipitation series from a single rain gauge. The obtained results 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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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

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 so to convey both wastewater and stormwater during rain events. Especially during these 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 put remedy to this, it is common use placing 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 to have a strong negative impact on the environment [4]. Moreover, also 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:

$$C = \frac{Q}{Q_{mw}} \tag{1}$$

Different values for C can be found in literature, e.g. in UK $C = 6$ had been 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:

$$C = \frac{200\frac{mg}{L}}{40\frac{mg}{L}} = 5 \tag{2}$$

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

Although regulations changed in 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 urbanistic characteristics of urban catchments, also changing in many cases, may have an influence on CSO behaviour, 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 behaviour 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 hydrological and urbanistic characteristics of catchments.

2. Methods

A simplified method to assess CSOs uncertainty has been developed taking advantage of a software framework written for the purpose.

2.1 Hydrological and urbanistic input parameters

An urban catchment with an area $A = 1\ km^2$ was considered. For the sake of focusing on how different hydrological and urban characteristics affect CSOs, the drainage network was here reduced to a single node.

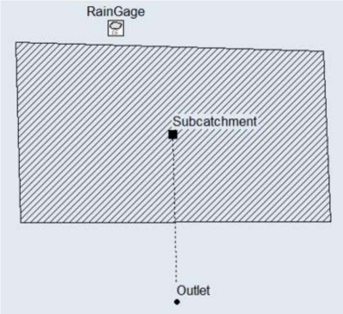

Figure 1. Scheme of the urban catchment simulated in SWMM 5.1.

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 better understanding CSOs events, this work dealt with these two variables, defined as follows:

$$F^y = \sum_{i=1}^{N} f_i^y \tag{3}$$

$$V^y = \sum_{i=1}^{N} D_i^y \Delta t \tag{4}$$

being:

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

V^y the volume of water discharged expressed in $\left[\frac{m^3}{year}\right]$ relevant to the y^{th} year;

and where:

$$f_i^y = \begin{cases} 1, & D_i^y > 0 \wedge D_{i+\frac{t}{\Delta t}}^y = 0 \\ 0, & D_i^y = 0 \end{cases} \tag{5}$$

and:

$$D_i^y = Q_i^y + Q_{mw} - CQ_{mw} \geq 0 \tag{6}$$

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

$\Delta t = 10\ minutes$ 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 $t = 10\ minutes$ 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 the Eq. (2), that is $C = 5$.

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 per Capita (DWC) [18] and the Density of Population (DP) were made available from ISTAT. The percentage of the Impervious surfaces (I) were 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, quite 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].

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

$$Q_{mw} = (\varphi \cdot DP \cdot DWC) \sim I \tag{7}$$

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). Eq. (7) expresses the production of sewage per unit surface. This assumption led to a significant reduction of computational time required to run all the simulations, since the 8 parameters investigated would have resulted in 6^8 scenarios, while aggregating DWC, DP and I, the number of simulations had been reduced to 6^6, with a 36 times reduction.

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

Parameter	Minimum	Maximum	Number of values
Daily Water per Capita $DWC\left[\frac{L}{ab\cdot day}\right]$	100	500	6
Density of Population $DP\left[\frac{ab}{km^2}\right]$	1000	8000	6
Impervious surface $I[\%]$	10	80	6
Width $W[m]$	$\frac{1}{4}\sqrt{A}$	$4\sqrt{A}$	6
Average Slope $S[\%]$	0.1	0.5	6
n Manning of impervious surfaces $n_{imp}\left[\frac{s}{m^{\frac{1}{3}}}\right]$	0.01	0.02	6
n Manning of pervious surfaces $n_p\left[\frac{s}{m^{\frac{1}{3}}}\right]$	0.03	0.08	6
Depression Storage of impervious surfaces $d_s[mm]$	0.5	2	6

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: they had a resolution of 10 minutes and covered the period from 2002 to 2021 (inclusive). A simple pre-processing of the data was carried out to remove outliers.

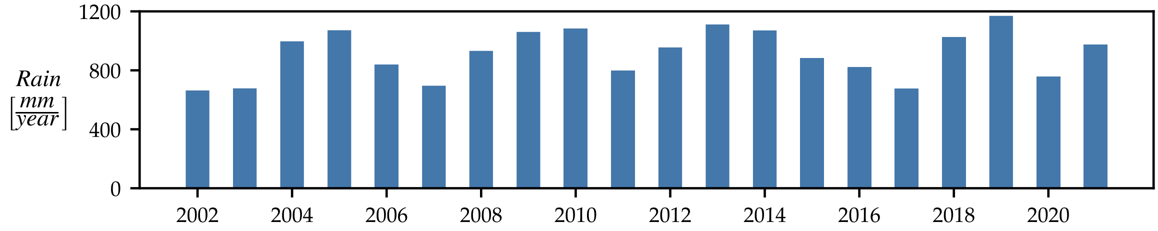

Figure 2. Yearly rain in Ercolano. http://centrofunzionale.regione.campania.it/#/pages/sensori/archivio-pluviometrici

2.2 Software framework

From Eq. (7) 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 has been set up and it consisted of:

1. SWMM 5.1. [24] as the core simulation software for each single run that covered 20 years of rainfall events;
2. 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 to run multiple models simultaneously, the Python program embedded two packages:

a. "pyswmm 1.1.1" [25]: it has been employed to run the engine of SWMM;

b. "swmm-api 0.2.0.16" [26]: it has been employed to generate the 6^6 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 were respectively $20 \cdot 6^6$, corresponding to the case of $C = 5$. Histograms plots (Figure 3) highlight the high variability of the variables with respect of all the investigated scenarios.

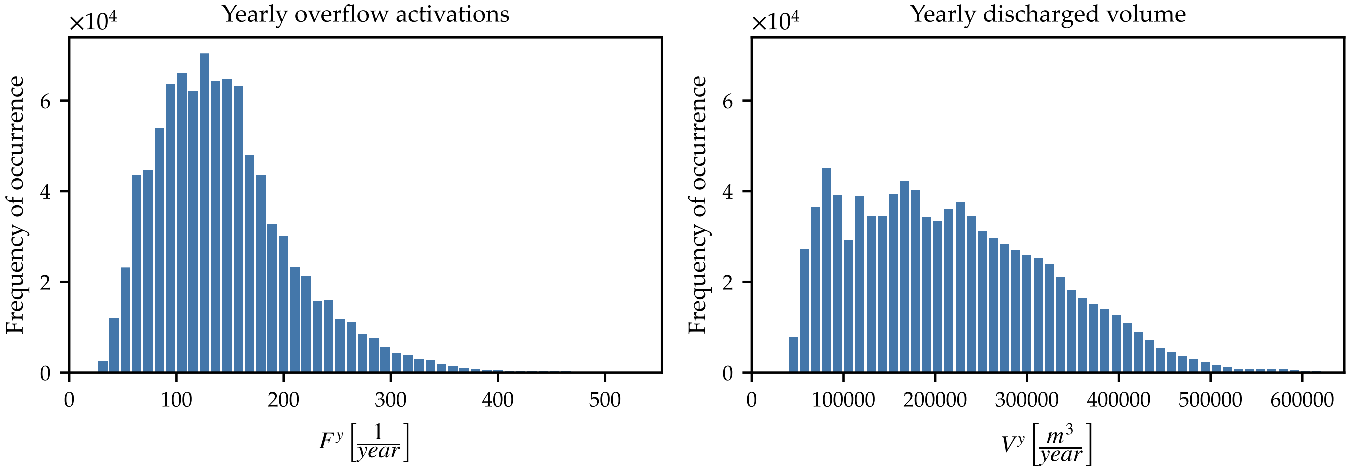

Figure 3. Histogram plots for F^y and V^y: each variable respectively covers $20 \cdot 6^6$ values from the output results while 50 bins are showed.

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 $38980\,\frac{m^3}{year}$ and $645751\,\frac{m^3}{year}$ 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**
$F^y\ [year^{-1}]$	145	64	[98; 178]
$V^y\ \left[\frac{m^3}{year}\right]$	215802	108453	[126854; 290509]

F^yTo 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.

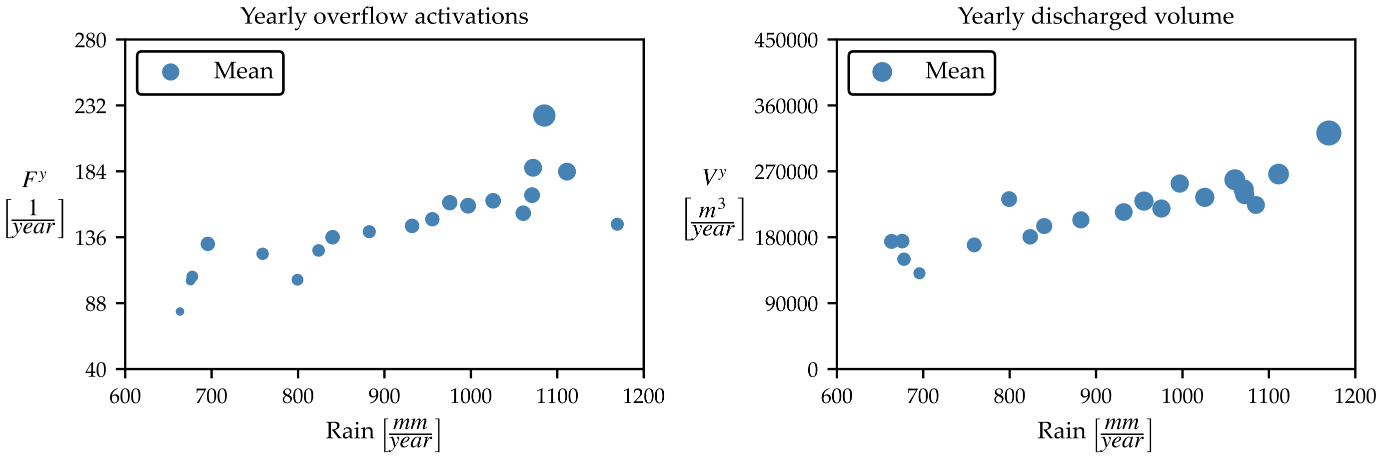

Figure 4. Relationship of annual rainfall with F^y (left panel) and V^y (right panel).

Correlations between the output data from the 6^6 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:

$$F = \sum_{y=2002}^{2021} F^y/20 \quad ; \qquad V = \sum_{y=2002}^{2021} V^y/20 \tag{8}$$

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

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

	$\boldsymbol{F\ [year^{-1}]}$	$\boldsymbol{V\ \left[\frac{m^3}{year}\right]}$
Increase	$\boldsymbol{W}$: [−45% ÷ +28%]	$\boldsymbol{Q_{mw}\sim I}$: [−63% ÷ +57%]
Decrease	$\boldsymbol{Q_{mw}\sim I}$: [+47% ÷ −25%]	$\boldsymbol{n_{imp}}$: [+5% ÷ −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 sewage production is in turn due to DWC and DP as expressed by Eq. (7).

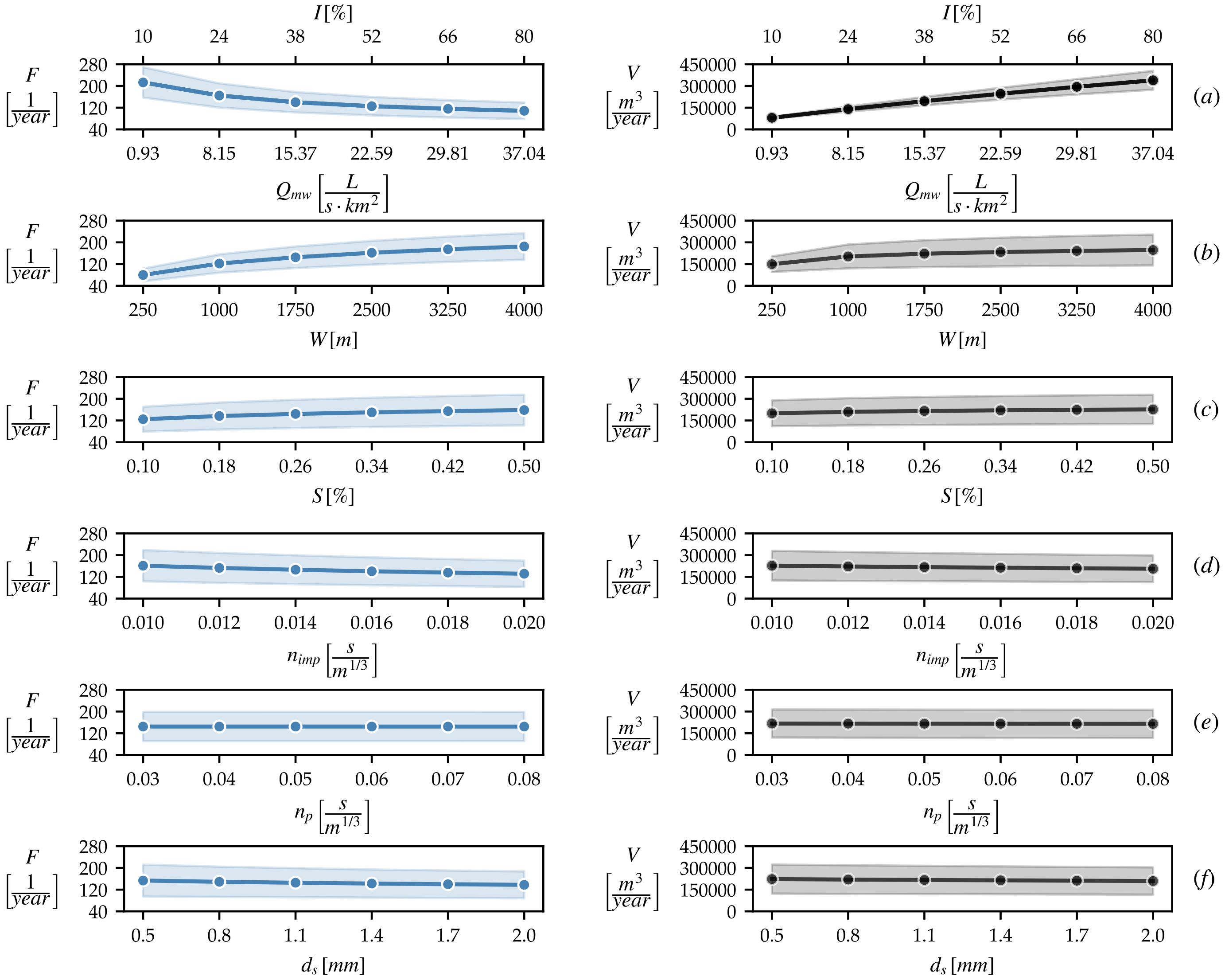

Figure 5. Influence of investigated parameters on frequency F and volume V. From (a) to (f): mean wastewater discharge and imperviousness, width, slope, impervious Manning, pervious Manning, depression storages. Markers stand for the average of F and V relevant to each parameter value; bands stand for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

5. Conclusions

The results 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 urbanistic 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 behaviour of CSOs to simply predictable ranges of frequency and discharged volumes, 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 overflows variability with more accuracy thus to design site-specific CSOs structures with more detail Future studies will delve more deeply into the parameter sensitivity analyses and will involve the use of different rainfall regimes, along with different dilution coefficients.

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Data Availability Statement: Rainfall sub-daily data of the Ercolano rain gauge (sensor n. 21760) were downloaded from http://centrofunzionale.regione.campania.it/#/pages/sensori/sensor-utility for the period 2002 – 2021. Temperature daily data of Ercolano were downloaded from http://centrofunzionale.regione.campania.it/#/pages/sensori/archivio-pluviometrici for the period 2002 – 2021. Population data can be found at http://dati.istat.it/Index.aspx .

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

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