Journal of Hydrology: Regional Studies 41 (2022) 101080

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

A hydrological model to estimate pollution from combined sewer overflows at the regional scale: Application to Europe

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ARTICLE INFO

Keywords:
Combined sewer overflow
Water quality
Urban greening
Hydrological reservoir model
EU assessment
Wastewater

ABSTRACT

Study region: Combined Sewer Overflows (CSO) of 671 Functional Urban Areas (FUAs) throughout the European Union + UK (EU28), representing almost half of the EU28 population.
Study focus: CSO loads can be quantified at the local scale through measurements, or with calibrated hydrological models. However, they are difficult to quantify at a large scale (e.g. regional or national), due to a lack of data, and the models used at local scale cannot be applied in the absence of knowledge of the combined sewer (CS) network. This paper presents a 6-parameter lumped hydrological model to simulate a CS network and its overflows, using population and rainfall data of 671 EU28 FUAs.
New hydrological insights for the region: When properly calibrated, the model can predict the CSO hydrographs as well as aggregated CSO descriptors of a catchment with known impervious surface area connected to a CS with a reasonable reliability. When model calibration is not possible, using default values of the parameters enables a first approximation estimate of CSOs, accurate within one order of magnitude, which can be used to support scenario analysis for regional and continental CSO management. At the EU28 scale, the estimated total CSO volume is $5.7 \cdot 10^3$ Mm^3/y, with a dry weather flow content in CSOs of 460 Mm^3/y (assuming a dry weather flow of 200 l/population equivalent (PE)/day including sanitary discharges, industrial discharge and infiltration). A collection of case studies on CSOs is also provided.

1. Introduction

Combined sewers (CS) are a widespread reality in Europe and elsewhere (Zabel et al., 2001; Pistocchi et al., 2019). They are usually designed to collect the dry weather flow (DWF) and stormwater runoff, and convey a certain amount of the combined wastewater flow (DWF+runoff) to a Wastewater Treatment Plant (WWTP). DWF is generally considered the combination of sanitary flow, infiltration water and industrial wastewater discharged to urban sewers. When the flow exceeds the maximum conveyance capacity of the network, the surplus is discharged through Combined Sewer Overflows (CSOs) into the environment. The adverse impact exerted by

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https://doi.org/10.1016/j.ejrh.2022.101080
Received 3 January 2022; Received in revised form 30 March 2022; Accepted 4 April 2022
Available online 22 April 2022
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Nomenclature

CS	combined sewer
CSO	combined sewer overflow
d	CSO duration (h)
$dens$	population density (p/ha)
d_n	network dilution rate (-)
d_t	tank dilution rate (-)
DWF	dry weather flow (mm)
EU28	European Union + UK
FUA	Functional Urban Area
k_0	reservoir constant of the catchment surface (t^{-1})
k_1	reservoir constant of the network (t^{-1})
k_2	reservoir constant of the tank (t^{-1})
MAE	mean absolute error (%)
P	annual rainfall (mm)
P_t	rainfall per time step (mm)
q_{DWF}	dry weather flow per person per day (l/d/p)
t	dimensionless time step (-)
Q_{DWF}	dry weather flow in the sewer network (mm)
RO	stormwater runoff = runoff
V_{CSO}	spilled CSO volume (Mm^3/y)
V_{DWF}	spilled DWF volume (Mm^3/y)
W_0	catchment storage capacity (mm)
W_1	network storage capacity (mm)
W_2	tank storage capacity (mm)
WWTP	wastewater treatment plant
Δt	time step (h)

CSOs on the receiving water bodies can be traced back to DWF, pollutant loads, substances transported by surface runoff and remobilization of in-sewer sediments and sewer biofilm (Gromaire et al., 2001; Müller et al., 2020). The volume, frequency and duration of the overflows depend on the frequency and intensity of rainfalls, on the design of the sewer system (e.g., the amount of internal storage) and on the acceptable flow at the WWTP (Zabel et al., 2001).

Current studies suggest that urban runoff will increase due to urbanization and the intensification of the hydrological cycle due to climate change, potentially increasing wastewater spills through CSOs (Meehl and Tebaldi, 2004; Barceló and Sabater, 2010; Keupers and Willems, 2013; Balistrocchi and Grossi, 2020). Infrastructure aging also enhances anthropogenic pressures and impacts (Dirckx et al., 2011; Rombouts et al., 2013; Bar-Zeev et al., 2021). Therefore, CSOs are one of the main current and future challenges in urban wastewater management, and the understanding of CSO impacts is key to their mitigation (Joshi et al., 2021; Montserrat et al., 2015).

The Urban Waste Water Directive (UWWTD, European Commission, 1991) and the Water Framework Directive (European Commission, 2000) have motivated CSO monitoring campaigns throughout Europe (See et al., 2021). Quantification of CSO impacts and occurrence at the national scale can be found for the Baltic sea (Bollmann et al., 2019), UK (Environmental Agency, 2020), Germany (Nickel and Fuchs, 2019), Austria (Clara et al., 2012), Slovakia (Sztruhár et al., 2002) and The Netherlands (Liefting and de Man, 2017), and most of the other available data are local studies at the city scale (see references in Appendix C). Therefore, scientific knowledge to support large-scale quantitative policy analysis is lacking, and the understanding of the magnitude of the problem at the European scale is still rather limited due to the absence of data. No specific criteria and guidelines exist at the European level (Zabel et al., 2001). Most Member States have regulated CSOs, but requirements are heterogeneous and not always effectively enforced across the Europe (Pistocchi et al., 2019).

In light of this, the aim of this contribution is to present a hydrological model able to provide a preliminary estimation of CSO loads at the catchment scale. The model was applied to perform a screening-level assessment of CSO loads at the European Union (EU), including former Member State UK (hereinafter, EU28) level. This work is organized in four parts:

1) Hydrological model development.
2) Model verification: comparison of the modeled results with literature ones for specific catchments served by a CS. 42 case studies with known CSO volumes were collected, covering UK, Germany, the Netherlands, Spain, Poland, Italy, Austria and France.
3) Sensitivity analysis of the model.
4) Application of the model at the EU28 scale, considering the 671 EU28 Functional Urban Areas (FUAs), that represent the main urban agglomerations (see Pistocchi and Dorati, 2018). A FUA consists of a densely inhabited city and of a surrounding area (commuting zone) whose labor market is highly integrated with the city (Dijkstra et al., 2019).

Based on the results of our estimates, we draw suggestions to improve the management of CSOs in the context of the EU legislation on urban wastewater.

2. Materials and methods

2.1. Hydrological model

We make use of a lumped hydrological model describing a unit (e.g., 1 m^2 or 1 ha) of impervious urban area served by a combined sewer system, building on the simple model presented in Pistocchi and Dorati (2018). The model consists of a cascade of three linear reservoirs (the linear reservoir is a concept widely used in similar studies, e.g. van Daal-Rombouts et al., 2016; Buytaert et al., 2004; Sun and Bertrand-Krajewski, 2013): the catchment surface, the in-sewer storage (the network) and the storage capacity at the head of the wastewater treatment plant (hereinafter the “storage tank” or simply “tank”). In-sewer processes are neglected and we assume complete mixing of DWF and runoff. The network and the tank are characterized by a reservoir constant, k_x (t^{-1}), and maximum storage volume W_x (mm), where $x = 1, 2$ for the network and storage tank, respectively. Before reaching the network, a portion of rainfall is retained in the storage provided by the catchment surface (e.g., ponds, streets), that is the upstream reservoir considered in our study, whose maximum storage capacity is W_0 (mm) and the surface constant is k_0 (the constant k_x is defined in the following paragraphs).

The model considers as input a discrete time series of rainfall P_t representing a sequence of rainfall (mm) at discrete intervals of constant time length Δt. In our case, the available rainfall time series has a time step $\Delta t = 3$ h, but the proposed hydrological model uses the dimensionless time t (ranging from 0 to 1) instead of Δt, thus $t = 1$ when $\Delta t = 3$ h. Rainfall S_t retained on the surface within each time step is modeled as per the conceptual Eq. 1:

$$S_t = \min\left[W_0, \quad \begin{pmatrix} P_t + S_{t-1} & if \quad P_t > 0 \\ S_{t-1}e^{-k_0 t} & if \quad P_t < 0 \end{pmatrix}\right] \tag{1}$$

where W_0 is the maximum storage volume that can be retained on the catchment surface and $t = 1$. The exponential term expresses the exponential decrease in the retained rainfall over the time. The default value of the surface reservoir constant is set to the empirical value $k_0 = 0.3\ t^{-1}$ (a value of $k_0 = 0.1\ t^{-1}$ affects CSO aggregated estimations typically by 1%, with few cases below 10%, i.e. within the accuracy of our estimates, see Results section). We considered that the reservoir fills when $P_t > 0$ without losing water (infiltration and evaporation) and it empties when $P_t = 0$. The emptying process is generally due to infiltration and evaporation. The description of these dynamics in an urban context, using an explicit model, entails additional assumptions and model calibration. In this study we decide to account for both phenomena empirically and implicitly through the reservoir depletion constant k_0.

The rainfall that reaches the network, R_t (mm per time step), can be expressed by P_t minus the rainfall that is retained on the surface Δ:

$$R_t = \max(0, \quad P_t - \Delta) \tag{2}$$

where $\Delta = W_0 - S_{t-1}$ is the available storage capacity. When $\Delta > 0$, a portion of the rainfall can be retained, while when $\Delta = 0$, the storage capacity of the surface is full, and no additional water can be stored (in Eq.1, the maximum value of S_{t-1} is W_0, thus Δ cannot go below 0). S_{t-1} can be calculated as per Eq.1.

When the sewer network does not have a buffering capacity before the overflows, the overflow volume E_t (mm) from the network during one time step may be modeled as (Pistocchi and Dorati, 2018):

$$E_t = \max(0, \quad R_t + Q_{DWF} - k_1 W_1) \tag{3}$$

where Q_{DWF} (flow, mm per time step) is the dry-weather flow in the sewer network, $k_1 W_1$ is the maximum conveyance of the network, whose exceedance triggers the overflow. W_1 includes volumes of storage facilities introduced in the drainage network to decrease CSOs and the storage capacity of pipes. Pistocchi and Dorati (2018) assumed $k_1 W_1 = d_n Q_{DWF}$, d_n being a dimensionless “dilution rate” triggering overflows. Q_{DWF} can be estimated from the population discharging in the sewer network, assuming a representative per capita contribution, q_{DWF}. When the network is modeled by a linear reservoir with constant k_1 and maximum capacity W_1 whose exceedance triggers the overflow, the network flow F_t (mm/t) is:

$$F_t = (R_t + Q_{DWF})\left(1 - e^{-k_1 t}\right) + F_{t-1}e^{-k_1 t} \tag{4}$$

In this case, the overflow volume E'_t (mm/t) from the network during one time step is:

$$E'_t = (R_t + Q_{DWF} - k_1 W_1) \quad \left(a + b\left(1 - \frac{1}{k_1}\left(1 + ln\left(\frac{R_t + Q_{DWF} - F_{t-1}}{R_t + Q_{DWF} - k_1 W_1}\right)\right)\right) + c\left(\frac{1}{k_1}\left(1 + ln\left(\frac{R_t + Q_{DWF} - F_{t-1}}{R_t + Q_{DWF} - k_1 W_1}\right)\right)\right)\right) - \left(\frac{R_t + Q_{DWF} - F_{t-1}}{k_1}\right)\left(a \quad \left(1 - e^{-k_1}\right) - be^{-k_1} + c\right) \tag{5}$$

Where a, b and c are the following Boolean statements:

$$a = (R_t + Q_{DWF} - F_{t-1} \geq 0) \times (R_t + Q_{DWF} - k_1 W_1 \geq R_t + Q_{DWF} - F_{t-1}) + (R_t + Q_{DWF} - F_{t-1} < 0) \times (R_t + Q_{DWF} - k_1 W_1 \geq 0)$$
$$b = (R_t + Q_{DWF} - F_{t-1} \geq 0) \times (R_t + Q_{DWF} - k_1 W_1 < R_t + Q_{DWF} - F_{t-1}) \times \left(R_t + Q_{DWF} - k_1 W_1 \geq (R_t + Q_{DWF} - F_{t-1}) e^{-k_1 t}\right)$$
$$c = (R_t + Q_{DWF} - F_{t-1} < 0) \times (R_t + Q_{DWF} - k_1 W_1 \geq R_t + Q_{DWF} - F_{t-1}) \times \left(R_t + Q_{DWF} - k_1 W_1 < (R_t + Q_{DWF} - F_{t-1}) e^{-k_1 t}\right)$$

A proof of Eq. 5 is given in Appendix A.

The sewer network discharges to a WWTP through an equalization tank modeled as a linear reservoir, with a constant k_2, and constrained by a maximum capacity W_2, whose exceedance triggers another overflow. This overflow is shown to be given by the following equation, that means that, depending on the situation, the overflow volume can be one among $E^a{}_t$, $E^b{}_t$, $E^c{}_t$, $E^d{}_t$ (see Appendix B for details):

$$E'{}_t = aE^a{}_t + bE^b{}_t + cE^c{}_t + (1 - a - b - c)E^d{}_t \tag{6}$$

where $E^a{}_t$, $E^b{}_t$, $E^c{}_t$, $E^d{}_t$ are defined in Appendix B, and a, b, c can be 0 or 1.

This model can be implemented at the time step of the rainfall time series. The combined sewer (CS) model parameters are the rate constant surface storage k_0 (set at 0.3 t^{-1}), the catchment storage W_0 (mm), the network dilution rate d_n (related to the maximum conveyance to the tank), the network storage W_1 (mm), the tank dilution rate d_t (related to the maximum conveyance to the WWTP) and the tank storage W_2 (mm). The reservoir constant k_2 can be calculated as $Q_{DWF}\, d_t / W_2$, as described above, and $k_1 = Q_{DWF}\, d_n / W_1$. The input data are the q_{DWF} and population density (or alternatively, Q_{DWF}).

The linearity of the model makes it applicable to a unit catchment area, and the results can then be proportionally extrapolated to a catchment of a given area by simple multiplication, assuming no scale dependency of the parameters. While the calculation is referred to the model time step, we are interested in aggregated output such as the annual average CSO volume V_{CSO} and the annual duration d of CSOs. Moreover, we are interested in quantifying the pollution conveyed by CSOs. As this is the blend of DWF and runoff, it is important to estimate the relative importance of the two. The content of DWF in CSO can be estimated as (Pistocchi and Dorati, 2018):

$$DWF_{content} = \frac{Q_{DWF}}{Q_{DWF} + R_t} \tag{7}$$

where R_t can be calculated from Eq. 2.

The model described above was benchmarked against the well-known SWMM model (EPA, 2021), by comparing our model with a reference SWMM model simulation. The latter regarded a catchment served by a combined sewer network (Vaihingen, Germany) with a buffer tank, upstream of a WWTP, assumed to represent the entire storage volume of the network. The catchment had an impervious surface of 321.9 ha, with a runoff coefficient of 54%, and the tank volume was set to $W_2 = 1.82$ mm. The DWF of the catchment was 41.25 L/s, and the maximum discharge before an overflow from the tank was 330 L/s. The SWMM model was forced with a time series of precipitation from a real measurement station in Germany (LUBW Baden-Wuerttemberg, 30 minute station data, Station No. 62038, Station Vaihinmgen A.D. Enz). We set $W_0 = 0$ mm in order to neglect the effect of the surface storage, and we considered as input to our model the precipitation (during the year 2017) multiplied by the runoff coefficient. The tank dilution rate was fixed at $d_t = 8$, while $W_1 = 0$ because all the storage is concentrated in the tank. The network dilution ratio (d_n) was calibrated to well reproduce the CSO annual

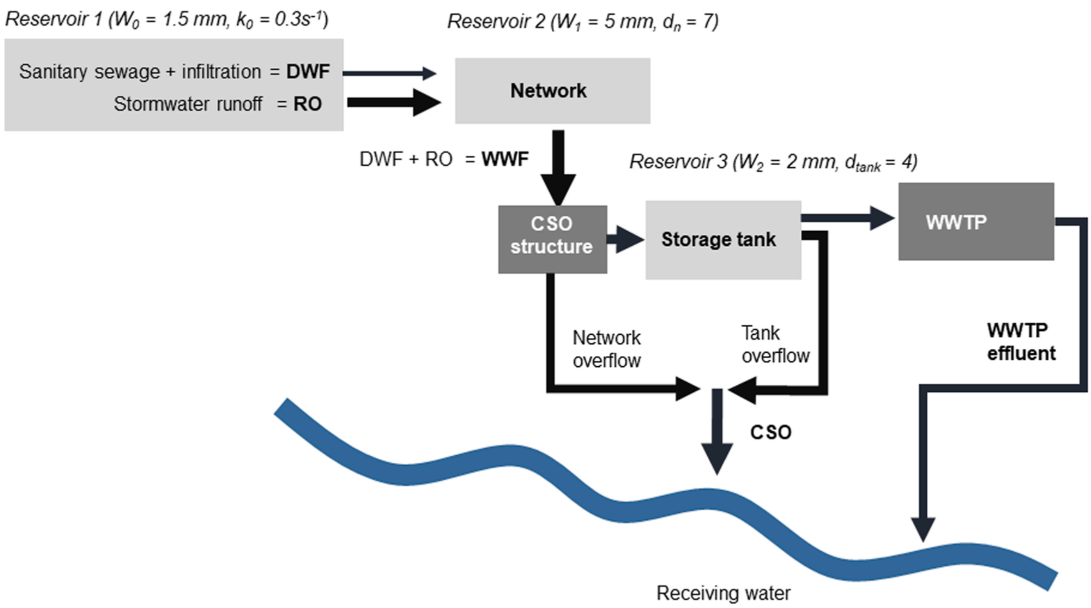

Fig. 1. Scheme of the model (baseline scenario).

volume and the spill duration, as discussed below.

The modeled CSO from the tank is $V_{CSO} = 0.55$ Mm^3 over 1 year, while our model predicted $V_{CSO} = 0.53$ Mm^3 after calibrating d_n to a value of 17, to reproduce the benchmark data well. The overflow duration was 191.5 h in our model and 174.5 h from the known time series. Fig. 2 compares our model and the benchmark in terms of CSO event volumes as well as a few representative hydrographs. It shows how, in spite of an overestimation of peak flows and underestimation of recession duration (suggesting an overall underestimation of the system's flood buffering capacity), the proposed hydrological model can mimic the number and volume of overflow events, once appropriately calibrated. In particular, Fig. 2a shows an acceptable agreement between the spilled volumes per event of the two models, but a clear worsening for small events (when the CSO spilled volume per event is below 4500 m^3); the small events contribute to 10% of the annual spilled CSO volume. The CSO volume of small events significantly depends on local design of the network and hydraulic parameters, which cannot be captured by our simple hydrological model, causing a discrepancy of predictions compared to the benchmark for smaller events. Fig. 2b shows a portion of the hydrographs. The retention effects of the network are actually not considered, thus the resulting peaks and volumes represent a worst case scenario. Overall, the Nash–Sutcliffe model efficiency coefficient is 0.87, slightly improving to 0.89 if the events below 4500 m^3 are excluded.

2.2. Model verification

The model was compared with literature data in order to check its accuracy. We carried out a literature review to collect data of

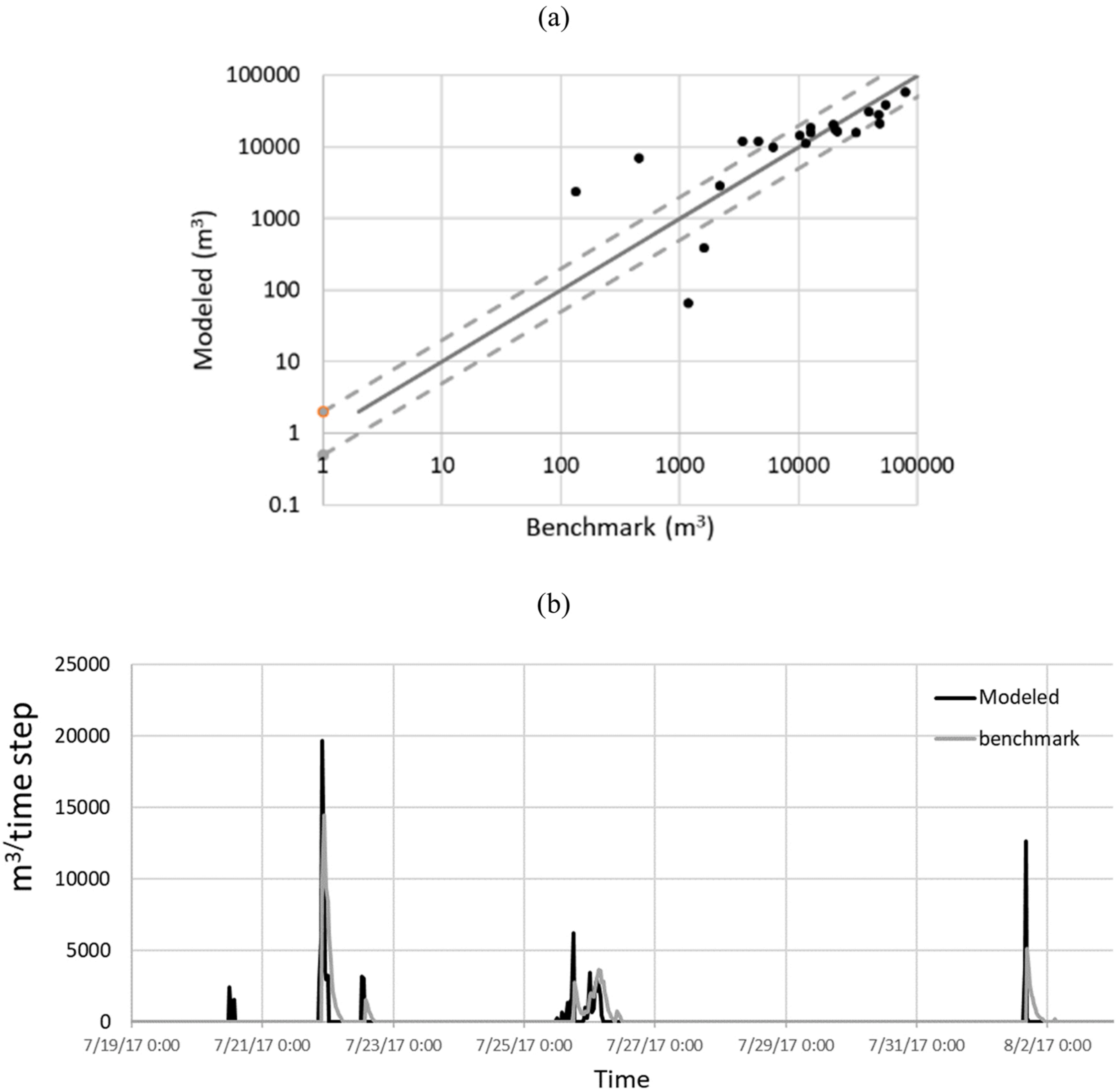

Fig. 2. (a) CSO volume per event, > 1000 m^3/event; (b) hydrograph shape in summer. Lines in Fig. 2a represent a factor of 2 deviation. The event is defined as a rainfall event with CSO, where the rainfall event is a series of time step with $P_t > 0$.

CSO volumes, durations and other useful metrics for representative urban catchments in the EU28. Additional data, not available in the public domain, were collected by the authors from public and environmental national authorities. A total of 42 cases were collected, covering UK, Germany, the Netherlands, Spain, Poland, Italy, Austria and France, distributed as shown in Fig. 3. The CSO volume over a certain period of time (typically, the yearly value) was known in 32 cases, the spill duration in 11 cases and the rainfall volume triggering a CSO (P_{tr}, mm) in 3 cases. The collected case studies were also used as reference material to support the selection of the default values. Appendix 3 contains the collected case studies and the related model parameters.

For each urban area for which we retrieved information on CSOs, we simulated overflows with the model taking into account the rainfall time series for the FUA where the catchment was located. The model parameters were adjusted to reflect the local characteristics as described in the references (DWF, dilution rates and storage capacities). When DWF was not available, it was estimated from total population connected to the CS network divided by the total impervious surfaces connected to the CS network based on the default q_{DWF}= 200 L/day per capita (see Appendix E and Table 1 for further details). When some or all of the other parameters could not be estimated case-specifically, we considered the default values listed in Tab.1.

2.2.1. Sensitivity analysis

A sensitivity analysis was performed testing different values of W_0, W_2 and d_t for six different catchments in order to explore how these hydrological parameters affect the results. The maximum values of W_0, W_2 and d_t were chosen based on the 42 case studies collected in Appendix C. For W_0, we assumed that an upper value could correspond to the surface storage allowed by an extensive

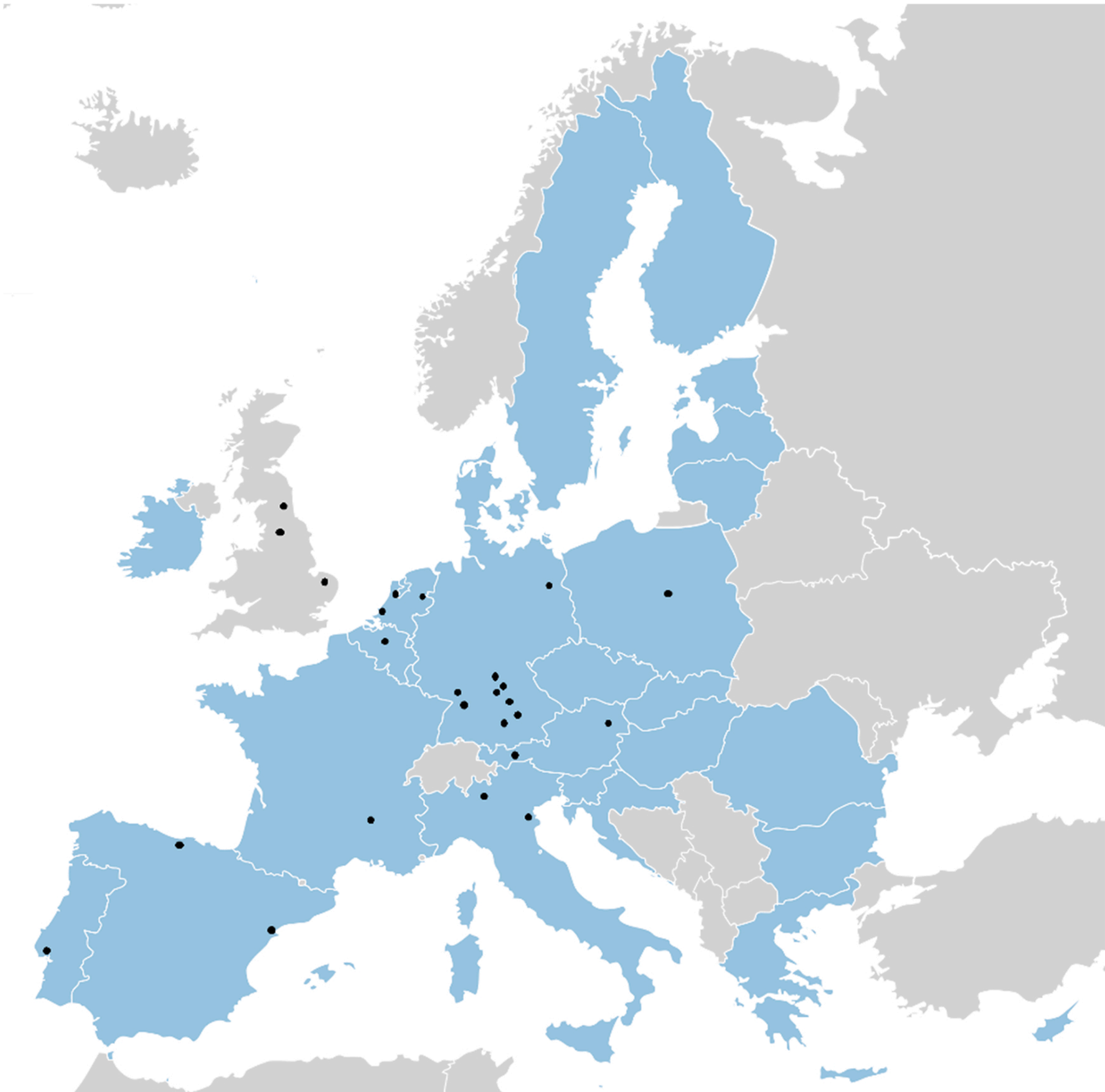

Fig. 3. Distribution of collected literature case studies (some case studies are from the same area and catchments are clustered so that they appear as a single point in the map). European Union Member States are shaded in pale blue.

Table 1
Input parameters and default values.

Parameter	Default Value assumed	Comment
q_{DWF}	200 L/day per person	Dry weather flow (DWF) per inhabitant per day, including sanitary flow, industrial flow and infiltration. This is a common average value adopted in EU28 (e.g., Abdellatif et al., 2015; Barone et al., 2019; David and Matos, 2005; Fu and Butler, 2012; Launay et al., 2016; Mascher et al., 2017; DEFRA, 2018). Effects of population density and DWF values are discussed in Appendix E.
W_0	1.5 mm	Storage capacity of the catchment surface. In line with Nehls et al. (2015), Vanrolleghem et al. (2015).
k_0	0.3 t^{-1}	Reservoir constant of the catchment surface. By using $k_0 = 0.1\ t^{-1}$ results do not appreciably change
d_n	7	Dilution rate of the network pipes, that multiplied by the total DWF gives the maximum conveyance of the network to the tank
W_1	5 mm	Storage capacity of the network
d_t	4	Dilution rate of the tank, expressing he maximum conveyance to the WWTP
W_2	2 mm	Storage capacity of the tank

greening of urban surfaces. In line with Quaranta et al. (2021), we consider greening of 35% of the impervious surface with a 30 cm thick soil of effective porosity equal to 10%. This corresponds to W_0= 0.35 × 300 × 0.1 ~ 10 mm (also in line with Casal-Campos et al., 2015). 30 mm was tested only for the sensitivity analysis. We considered an upper limit of W_2= 10 mm (i.e. $W_1 + W_2$= 15 mm) in line with the highest values found in literature (case study in Utrecht). The maximum d_t value was 23 (Llopart-Mascaró et al., 2015), and it is generally around 4. Based on these considerations, we selected for parameters W_0 and W_2 the values 0.1 mm, 1 mm, 5 mm, 10 mm (for W_0 we also explored the effects of a value up to 30 mm); for d_t the values 2, 4, 10, 15 and 20 were chosen.

2.3. Application to the EU28 context

In order to estimate CSO loads at the EU28 scale, the model was applied to 671 Functional Urban Areas (FUAs) that are the main urban agglomerations in the EU28, home to 320,090,394 inhabitants and covering 4,166,177 ha of impervious surface, as described in Pistocchi and Dorati (2018).

For each FUA, we used the population and impervious surface area (hence population density) and 3-hourly rainfall time series as described in Pistocchi and Dorati (2018). The population density in each FUA was calculated with the HRL-LUISA combination, corresponding to density data calculated with the population estimated from LUISA (Lavalle et al., 2015) and the impervious surface from HRL (Copernicus, 2015). We considered the HRL-LUISA combination because the data for all the 671 FUAs are known. The reliability of satellite data is discussed in Appendix D.

As described above, we refer the calculation to an impervious unit area connected to a combined sewer (CS) within the FUA. The results are scaled to the whole FUA through multiplication by the total impervious surface in the FUA served by the CS. The impervious surface served by a CS is estimated by multiplying the total impervious surface of the FUA by the share of population served by CS (% CS), assuming the values shown in Pistocchi et al. (2019), mostly based on the national average for each FUA country.

In principle, the model parameters can be calibrated for any combined sewer network with available overflow monitoring data, provided that the inputs (impervious area extent, population of the combined sewer catchment and rainfall) are representative. However, overflow data are not accessible for an analysis at the EU28 scale. Therefore, we modeled overflows for all FUAs in the EU28 using default values for the parameters, chosen based on engineering practice and the literature (e.g., Zabel et al., 2001; Sun and Bertrand-Krajewski, 2013; Morgan et al., 2017; Pistocchi et al., 2019; Rizzo et al., 2020) as in Table 1.

By way of exception, for Germany and Austria we assumed $d_n = 30$, based on expert judgment and data collected in Appendix 3. Moreover, in the case of the Netherlands the sewer discharge is typically conveyed from a storage volume to the WWTP by pumping, and the pumping capacity is typically 0.7 mm/h in addition to the DWF, independent of the used storage volume. The storage/settling tank is not in-line between the system and the WWTP. In order to reflect this configuration in the model, both the storage/settling tank and the sewer network storage were combined in W_2, with unrestricted flow from W_1 to W_2. Therefore we used a very high dilution rate of the network ($d_n = 10{,}000$) in order to ensure that no overflow occurs from the network. We then set $W_1 = 1.5$ mm and $W_2 = 8.8$ mm. For all the other countries, the default values of W_1 and W_2 are used.

The model output is a time series of overflow volumes and the respective DWF content with the same time step as the input rainfall. However, for our EU28 application we computed an aggregated model output for each FUA including annual average volume of CSO, its DWF content and annual average duration of the spills.

The first indicator is key to represent the overall discharge of pollutants from combined sewers. The second is required to characterize the pollution and the share of wastewater generated in the FUA that does not undergo treatment before discharge. The duration of spills is an unambiguous metric of the occurrence of short-duration pollution events affecting the receiving water bodies.

3. Results

3.1. Model verification

A comparison of predicted annual CSO volumes with those reported for the case studies listed in Table 1 of Appendix C is shown in Fig. 4. The absolute error is defined as:

$$Error = \frac{|X_p - X_{kn}|}{X_{kn}} \quad (8)$$

Where X_p is the predicted result and X_{kn} the known one for each case study. The mean absolute error (MAE) is then calculated.

The error on the estimated overflow volume V_{CSO} over the study period of each case, typically 1 year ranges between − 79% and 197%, and the MAE is 54%, with no apparent relation between errors and catchment (and CSO output) data. Table 2 shows the minimum and maximum reported and predicted values, thus the extreme cases, to which higher errors are associated.

The rainfall value that triggers the overflow, P_{tr}, is also predicted within a factor 2 (Fig. 4c, d, e): for instance, in the case of Ecully the model usually indicates overflows when a rainfall event exceeds 15 mm, but with few events already at 9 mm, while the trigger rainfall event is reported to be 10 mm (pers. comm. of Jean-Luc Bertrand-Krajewski). The simulated P_{tr} is 3 mm versus the detected one of 7 mm for Torrelavega (Andrés-Doménech et al., 2010) and 4 mm versus 7 mm for Berlin (Matzinger et al., 2009). These estimates are obtained using the default values, and could be improved by locally calibrating CS parameters (which is not an objective of this study).

Our model estimates an average annual V_{CSO} = 73 mm/y for the Dutch FUAs (weighted average with the FUA impervious surface), while government data estimates 46 mm/y (Liefting and de Man, 2017). For the German case, Fuchs (2019) estimates 69.2 Mm^3/y of DWF discharged by CSOs, corresponding to 1.4% of the total produced DWF, referred to 35 million connected inhabitants to the CS (79 million x 45%, where 45% is the CS share). Our model estimates 1.8% of discharged DWF and a CSO annual volume of 37 Mm^3/y referred to 27.6 million of inhabitant (the 94 main German FUAs). By a linear extrapolation, 37 Mm^3/y correspond to 46.9 Mm^3/y for 35 million inhabitant, which differs by − 32% from 69 Mm^3/y. The estimation of the CSO volume does not depend on the volume itself, but rather on the catchment characteristics. The duration is predicted well within the range 50–200 h, and the accuracy of the estimation reduces for more extreme events (larger and smaller durations).

To improve the prediction for each catchment, local design data would be necessary to better calibrate the model, but these data are generally not available at the large scale. Nevertheless, the results shown in Fig. 4 indicate that the predicted overflows can be regarded as a first approximation of the reported overflows. The proposed hydrological model can be therefore used for a screening-level assessment of CSO loads at the EU28 level as it reflects the variability of the response of CSO to the rainfall regime, catchment and network characteristics covered by the representative test cases.

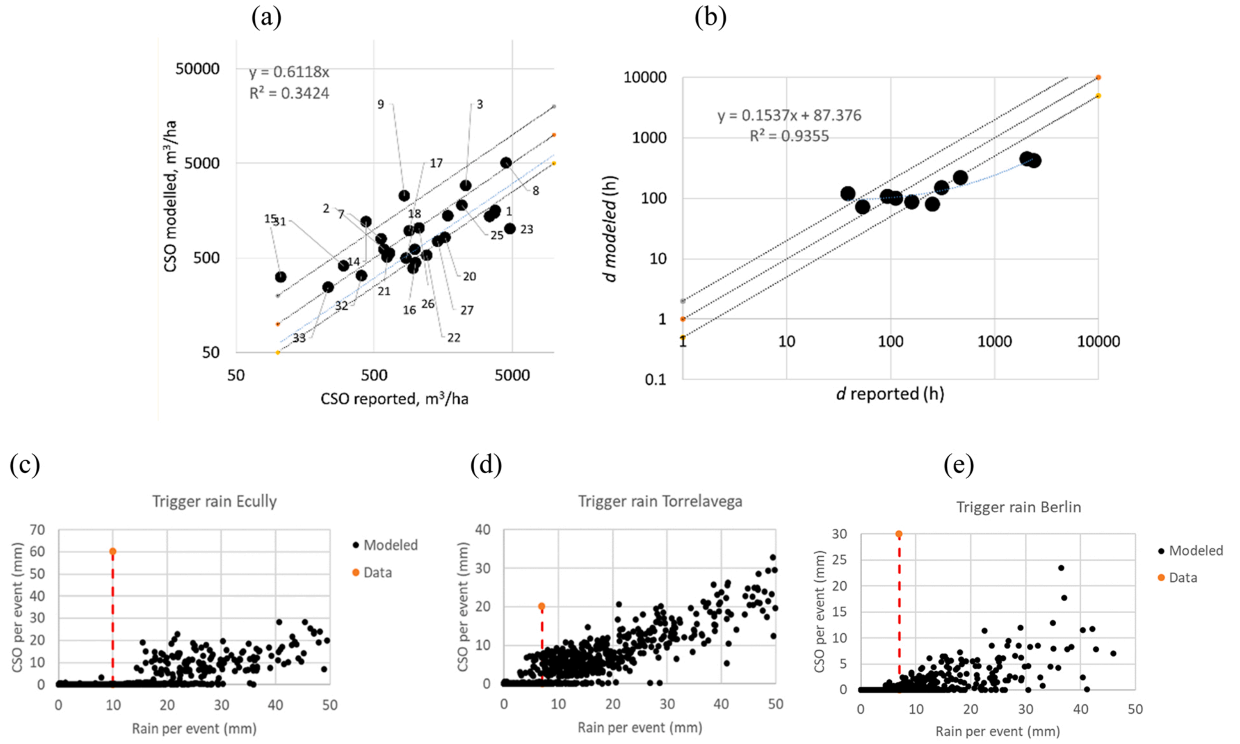

Fig. 4. Modeled data versus literature data for the catchments listed in Appendix C: CSO volumes (a), annual spill duration *d* (b) and trigger rain P_{tr} (c, d, e), where the dotted line represents the reported trigger rainfall. The numbers in figure (a) correspond to the catchment number as in Appendix C.

Table 2
Comparison between predicted (Pred.) and reported (Rep.) CSO volumes and specific catchment volumes per hectare of impervious surface, with minimum and maximum values of the reported data. The catchment number (see Appendix 3) is within parenthesis.

Minimum values V_{CSO}				Maximum values V_{CSO}			
Mm^3/y (34)		m^3/y/ha (15)		Mm^3/y (16)		m^3/y/ha (8)	
Rep.	Pred.	Rep.	Pred.	Rep.	Pred.	Rep.	Pred.
0.02	0.02	106	314	7.0	3.1	4500	5071

3.2. Sensitivity analysis

In order to estimate how the above mentioned outputs are affected by the model parameters, a sensitivity analysis was carried out for the surface storage W_0, tank storage W_2 and tank dilution rate d_t. W_1 was not tested because the hydrological model mostly depends on the value of $W_1 + W_2$, rather than on the specific value of W_1 and W_2. This allowed to change the parameter W_2, and to take in mind that any combination of W_1 and W_2, such that their sum is equal to W_2, does not significantly affect the results. For example, results did not appreciably change when W_2= 10 mm and W_1 = 5 mm, or W_2 = 3 mm and W_1 = 12 mm. For the Innsbruck catchment (the catchment with the highest value of annual rainfall P among the investigated ones, Table 3), the calculated annual CSO volume is 357 mm/y with W_2 = 3 mm and W_1 = 12 mm, and 353 mm/y with W_2 = 10 mm and W_1 = 5 mm. The same for the other FUAs, where the differences are few percentage points. The only cases where the model outputs depend on the specific values of W_1 and W_2 are for very high network dilution rates, i.e. when $d_n > > 30$, thus for the Dutch case (d_n = 10,000 as discussed above). Therefore, local values for W_1 and W_2 were considered for the Netherlands, as discussed above.

We ran the model for six different combinations of rainfall time series and population density, corresponding to catchments among those considered in the validation stage, representative of the different geographic contexts of EU28. For each catchment, we took the population density reported in the literature, and the rainfall time series of the FUA where the catchment is located (Table 3). We kept all parameters to their initial values, and made one at a time among W_0, W_2 and d_t vary over the respective ranges described above. The results of the sensitivity analysis are shown in Fig. 5.

The surface storage capacity W_0 apparently affects the annual CSO volume and spill duration, while W_2 (tank storage capacity) affects it to a lesser extent. The tank dilution rate d_t reduces the annual CSO especially when $d_t < 8$, that means that higher values do not affect appreciably the results and may only implicate higher costs (retrofitting of the network). At W_0 = 30 mm and 10 mm, the dilution rate of the tank does not affect appreciably the results. When considering the DWF content in the CSOs, the tank storage W_2 does not significantly contribute, while the dilution rate of the tank shows the highest benefits at $d_t < 8$.

From the above mentioned results, two key points can be derived:

1) An increase in the surface storage W_0 exhibits more significant effects than a W_2 increase.
2) A tank dilution rate above d_t= 8 yields practically no incremental benefits on CSO reduction. Furthermore, d_t is limited by the fact that it is not possible to flush the WWTP with excessively diluted wastewater, in order not to disrupt the activated sludge process.

The catchment with the highest CSO volume, among the six investigated in this section, is Innsbruck, because the value of annual rainfall is the highest one, while the catchments with the least duration are located in Lodz and in Comacchio, which have the highest population density (i.e. the highest DWF). When the DWF is higher, for a fixed network and tank dilution rate, the conveyance of the network is higher and reduces the overflow frequency.

3.3. Application of the hydrological model to the EU28 scale

With the default parameters discussed in Table 1 we produced an estimate of the annual CSO volume for each of the 671 FUAs for a unit impervious surface catchment connected to a CS. The volume of CSO for the FUA is then obtained multiplying this unit-area CSO volume by the impervious surface area of each FUA and by the share of CS attributed to the FUA (usually extrapolating national average CS shares). The resulting CSO volume is V_{CSO} = 5739 Mm^3/y. The DWF content in CSO is V_{DWF} = 460 Mm^3/y, or 1.97% of the discharged DWF from 320 million people living in the 671 FUAs. The average spill duration per year is 95 h per FUA, with the smallest

Table 3
Combinations considered for the sensitivity analysis: average annual rainfall P calculated over the 16-year time series and population density *dens* per impervious surface.

Number	Catchment location	P (mm/y)	*dens* (p/ha)	Geographic context
1	Bruxelles, Belgium	734	108	North Europe
2	Comacchio, Italy	683	546[a]	South Europe
3	Innsbruck, Austria	1276	180	Alpine city
4	Lisbon, Portugal	692	120	South-West Europe and sea city
5	Lodz, Poland	541	21	Central Europe
6	Stuttgart, Germany	838	91	Central Europe

[a] summer period.

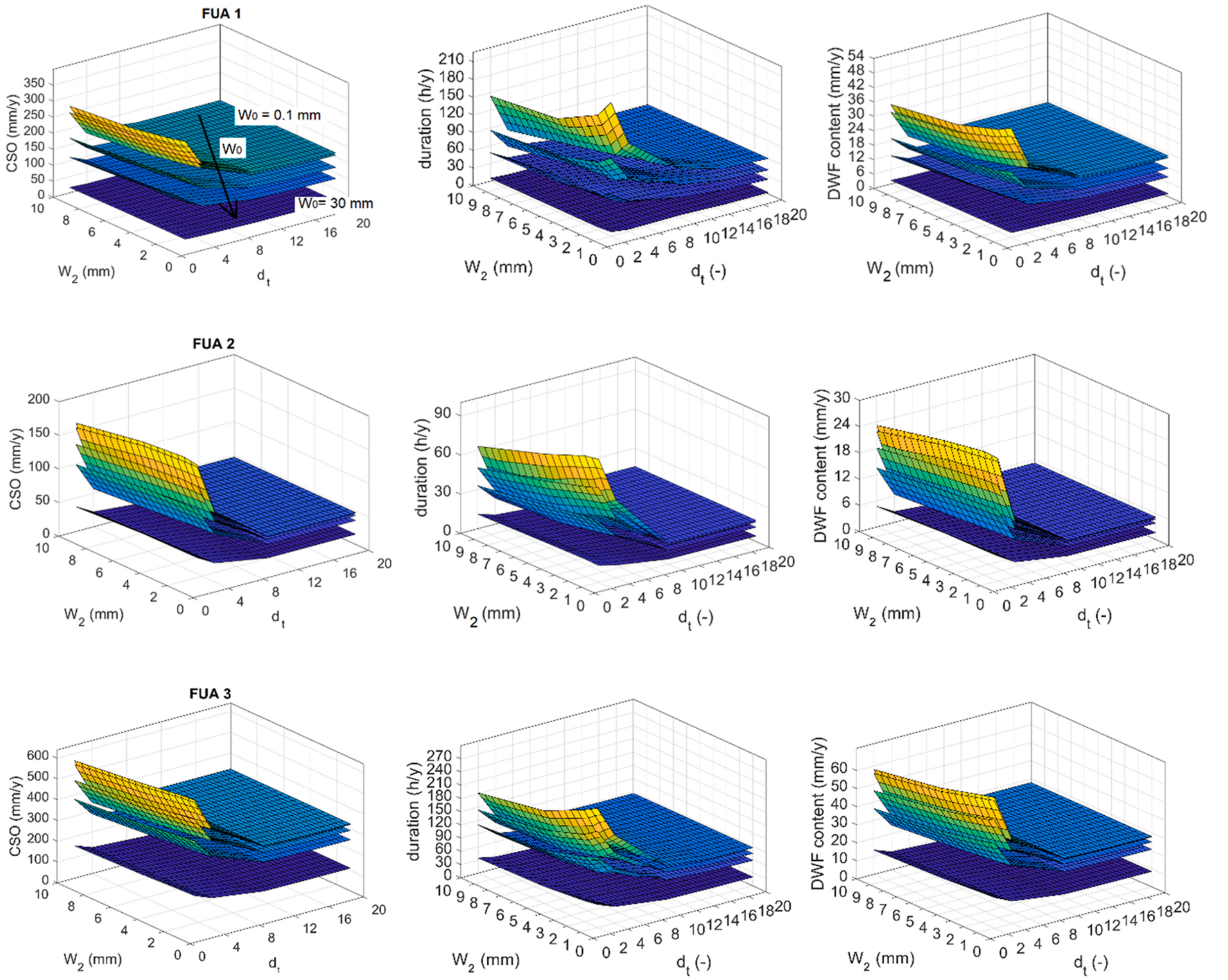

Fig. 5. The figures show the CSO annual volume, spill annual duration per year and DWF content in CSO versus the tank storage W_2 (mm) and the tank dilution rate d_t. In each figure, each surface represents the results for a certain surface storage W_O (W_O = 0.1 mm, 1 mm, 5 mm, 10 mm, 30 mm). The higher W_O, the lower the W_O surface location on the Z-axis.

value 25 h in a Spanish FUAs and the highest ones in Germany, UK and Austria (typically > 100 h, probably associated to the higher d_n used value), with the highest value of 256 h in Germany. Table 4 summarizes the results per EU member state + UK.

4. Discussion

The annual CSO volume, its DWF content and its duration can be predicted as a first approximation with the proposed hydrological model, when the latter is parameterized on the basis of local catchment characteristics. In a screening-level assessment of CSO loads at the EU28 level using default parameters that reflect the available evidence, we estimated an annual CSO volume across 671 FUAs totaling 5739 Mm^3/y, and conveying a content of DWF of 460 Mm^3/y representing 1.97% of the total DWF generated in the FUA.

Our approach suffers from uncertainties that can be only reduced through a more realistic representation of the catchments, which requires data usually not available at the large scale. As a first example, we parameterized the impervious surface based on satellite imagery. As the conveyance of the combined sewer network is a multiple of DWF, by default estimated from total connected population divided by the total impervious surface, our model calculation is likely to overestimate CSO volumes in all cases where the connected impervious surface to the CS is significantly smaller than the total impervious area served by the CS. We also tend to overestimate overflows where significant network storage capacity is available, in excess of the default value we consider (W_1=5 mm). These two aspects can arguably account for the factor 2 errors found when comparing our predictions with documented literature case studies. Another factor affecting the total volume of CSO at the regional scale is the share of combined sewers compared to separate sewers. The uncertainty in the absolute value of CSO volumes and duration is arguably less important when aiming at a comparison of policy scenarios at the EU scale. In this case, the model can be used to quantify the change in volumes and duration of overflows following

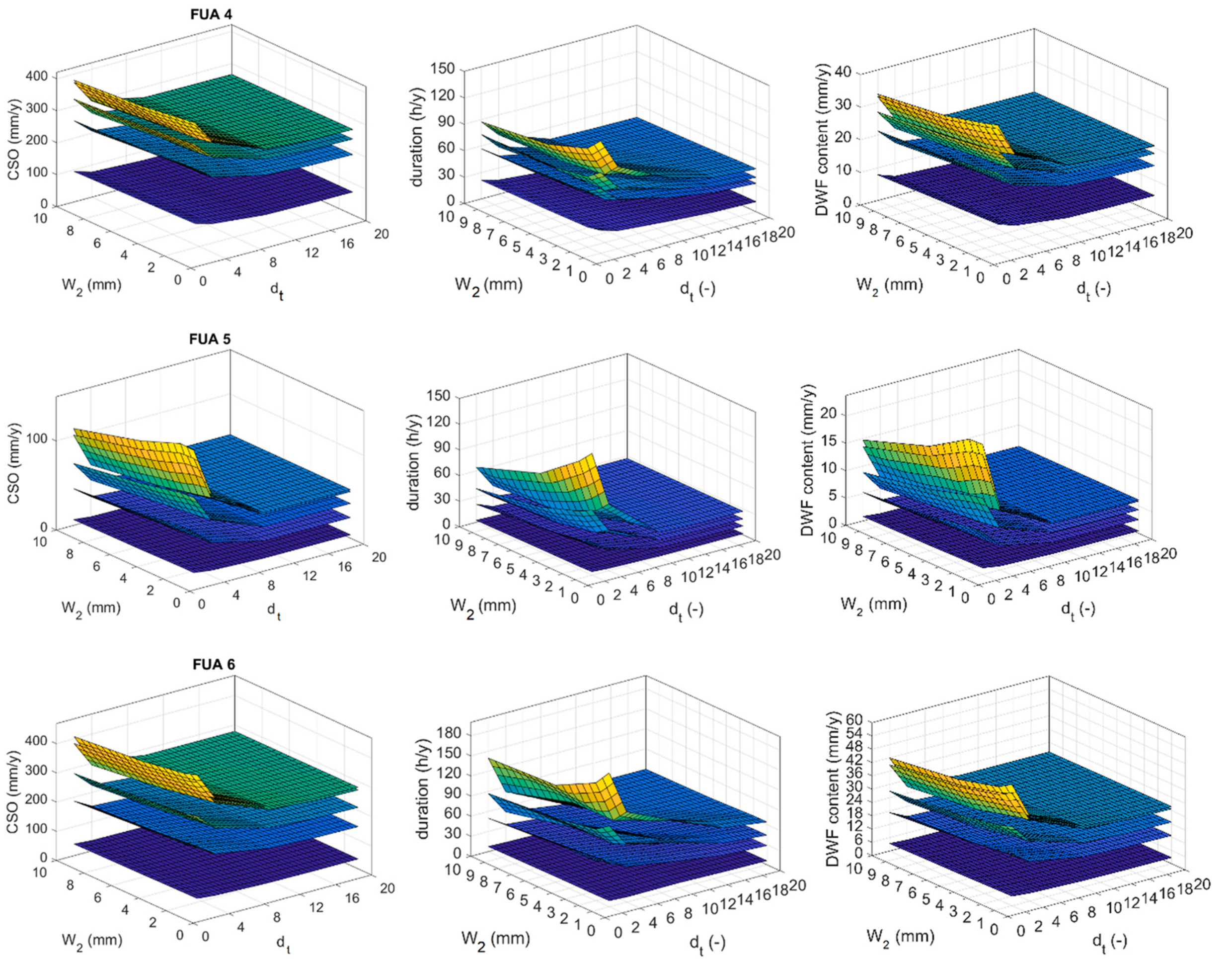

Fig. 5. (*continued*).

from certain policies and measures.

With regard to V_{DWF}, we expect the concentration of pollutants in the overflow to be well approximated by $C = (C_1 \cdot \text{DWF} + C_2 \cdot \text{Runoff})/(\text{DWF} + \text{Runoff})$, with DWF = dry weather flow, C_1= concentration in DWF, C_2= concentration in runoff. For certain contaminants (e.g. pesticides, metals, polycyclic aromatic hydrocarbon), C_1 is considered to be close to 0 and C_2 is dominant. On the contrary, for other contaminants, C_2 is practically 0. If we set C_2= 0, the DWF content in CSO, DWF/(DWF+Runoff), is a proxy for the concentration of such contaminants, a reason why the DWF content in CSO is computed as an indicator. When it comes to contaminants mainly borne by runoff (C_2 dominant on C_1), the "event mean concentration" is usually highly variable, hence runoff volume was used as a proxy for pollution load. Furthermore, we did not consider the release of in-sewer pools of pollutants due to resuspension or erosion of sewer sediments and biofilm (Gasperi et al., 2010). Therefore, it is expected that by applying C1 as a proxy for raw wastewater and C2 as a proxy for runoff entering sewer systems, the total pollution load in CSOs is underestimated. The amount of the underestimation depends on the specific pollutant considered. For dissolved compounds that do not absorb to the sewer sediment or biofilm, like several pharamceuticals and pesticides, the underestimation will be negligible, while for strongly sorbing compounds, such as polycyclic aromatic hydrocarbons (PAHs) or metals, the contribution of in- sewer pools can be much higher (Gasperi et al., 2010). The model also did not consider the state of the receiving water, e.g. the amounts of DWF as percentage of the receiving water flow or volume. We used a default DWF value of 200 l/s per person, in line with the recommendations of the UK Ministry of Housing Local Government's Technical Committee on Storm Overflows and the Disposal of Storm Sewage (1970). By using a larger value of DWF per inhabitant, the total amount of CSO would reduce (since the conveyance capacity of the simulated CS would increase), so that our estimates can be considered precautionary (i.e. they overestimate the CSO volumes). Appendix E (Supplementary material) demonstrates the effect of DWF and population density in more detail.

The sensitivity analysis we have presented shows how, in order to reduce CSOs, an increase in the surface storage W_0 is more effective than an analogous W_2 increase, highlighting the fact that surface management strategies (e.g. disconnection to CS or retention measures by urban greening) are more effective than increasing the storage capacity of the network of the same amount. Surface storage is best implemented through urban greening measures as it can generate additional environmental and social benefits. However, implementing extensive greening in urban areas poses challenges that need to be properly addressed (Quaranta et al., 2022).

Table 4
Result summary per member state. FUA data from Pistocchi and Dorati (2018) and Pistocchi et al. (2019).

Member State	FUA Population	Impervious surface (ha)	CS share	V_{CSO} (Mm^3/y)	V_{DWF} (Mm^3/y)	Duration (h)
AT	4,588,740	74,345.3	0.28	59	2	1085
BE	6,443,432	92,960	0.92	259	27	1252
BG	4,418,480	46,884.1	0	0	0	1140
CY	652,116	10,737.2	1	27	2	115
CZ	6,479,220	105,440.1	0	0	0	1311
DE	59,968,345	1034,050	0.46	773	35	14,355
DK	3,787,829	72,765.5	0.5	104	11	441
EE	84,2163	9522.9	0.5	8	1	252
EL	6,504,849	47,319.4	0.39	63	4	623
ES	29,506,445	265,935.3	0.13	92	8	4584
FI	2,660,816	54,975.9	0.175	27	3	637
FR	44,417,942	660,120.5	0.32	841	68	7491
HR	2,031,614	24,520.9	0.59	86	6	439
HU	5,261,016	62,500.7	0.325	42	4	698
IE	2,902,400	33,383	0.24	34	3	691
IT	32,378,354	348,709.1	0.7	1287	90	5754
LT	2,069,485	18,648.2	0.5	15	2	519
LU	492,047	11,298.7	0.9	42	4	120
LV	1,211,846	8162.7	0.5	6	1	341
MT	376,851	4611.4	1	12	1	51
NL	11,728,632	172,986	0.73	135	6	2084
PL	22,380,223	227,646.2	0.92	414	43	4849
PT	5,707,432	78,153.5	0.34	164	11	840
RO	9,286,236	69,354.6	0	0	0	2551
SE	5,228,647	70,409.5	0.12	22	2	1144
SI	929,883	12,464.6	0.59	57	4	194
SK	1,854,749	24,822.2	0.075	6	1	695
UK	45,980,602	523,448.9	0.7	1207	123	9785

5. Conclusions

The knowledge of CSO volumes and duration suffers from severe gaps at regional and EU scale, and there are limited possibilities for the quantitative analysis of policies at this level. Here we have presented a first attempt at modeling CSOs at the European scale. CSO volumes and DWF contents were quantified by implementing a hydrological model, which has proven to be reasonably realistic against independent evidence (measurements or more detailed studies) when properly parameterized. We used the model with default parameter values for the appraisal of the scale of the problem at the EU28 scale.

A higher accuracy and finer detail can be arguably achieved only through specific studies at the local scale, particularly when it comes to finding optimal trade-off between surface water quality improvement, and costs of measures. Mitigation can entail green solutions, but in many cases also disconnecting impervious surfaces, besides increasing network capacity through infrastructure retrofitting (grey solutions), or better management (e.g. real time control solutions).

Cost-effective management of CSO requires solutions tailored to the specific conditions in each urban area. Case-specific optimal strategies may be better accommodated in appropriately designed management plans at the urban scale, addressing together multiple objectives including urban development, climate change adaptation, biodiversity support and pollution control, and potentially mobilizing investments from a variety of actors. Within this context, measures such as urban greening may bring several additional benefits while helping prevent runoff, and have potentially higher benefits to costs ratio compared to their grey alternatives. Optimization of the existing infrastructure including real time control may also significantly reduce CSOs. The model presented here may be used to support an assessment of CSO mitigation strategies with related benefits and costs at the regional scale, before delving into specific studies to support local design.

Author statement

The research was designed, coordinated and supervised by AP, who formulated and developed the hydrological model used for the assessment. EQ conducted the verification of the model and the simulations at EU scale. H.J.L and SF provided specific input and data as fee-paid experts supporting the European Commission, and together with AS contributed to the elaboration of the paper. EQ and AP wrote the paper with contributions from all other authors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The work has been developed in the context of the Blue2 project of the JRC and DG ENV of the European Commission, and in support to the impact assessment of options for the revision of the European wastewater legislation. The research was designed, coordinated and supervised by AP, who formulated and developed the hydrological model used for the assessment. EQ conducted the verification of the model and the simulations at EU scale. H.J.L and SF provided specific input and data as fee-paid experts supporting the European Commission, and together with AS contributed to the elaboration of the paper. EQ and AP wrote the paper with contributions from all other authors. The Authors would like to thank Jeroen Langeveld of Parter4Urbanwater for his comments and input, and Will Shepherd who helped A.S. out by organizing census and area data for two of the UK case studies.

A MS Excel © implementation of the model used for this assessment and the setup for all 671 FUA are publicly available as supplementary electronic material.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101080.

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