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A simplified approach for the hydrological simulation of urban drainage systems with SWMM

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ABSTRACT

The management of an Urban Drainage System (UDS) is a complex task, as it requires extensive knowledge about precipitation regime, hydrological features of the catchment, hydraulic characteristics of the drainage network, and information about the water use by the served inhabitants. Complex semi-distributed hydrological and physically based hydraulic models are nowadays available to summarise such information and run simulations. However, in many cases, the uncertainty of the available hydrological information hampers the use of complex models. Hence, simple models with few parameters and small computational effort may be preferable, especially for UDS management problems requiring the execution of many simulations. This paper proposes a convenient approach to define effective lumped Simplified Models (SMs) of UDSs, the parameters of which can be estimated directly from cartographic information. For several case studies of UDS with different morphological and topological characteristics, SMs were built, capable of reproducing the hydrographs provided by available semi-distributed Detailed Models (DMs), assumed as benchmark in absence of measured hydrographs. To this aim, the SWMM simulation software was used, and the SM lumped parameters were calibrated by maximising the goodness of fit between the hydrograph of the DM and of the SM. The results show that SMs satisfactorily predict the hydrographs for all the case studies, and that robust relationships between the calibrated parameters and morphological and topological characteristics of the UDS can be established. This suggests that SMs can be used by decision makers for preliminary design, planning studies and management problems of UDSs, as their parameters can be soundly estimated from cartographic information. An example of application of SMs to Combined Sewer Overflow prediction is also presented.

1. Introduction

Urban Drainage Systems (UDSs) are complex due to the spatial extension of the infrastructures, the interaction with other systems (Chocat et al., 2001), the variability of the operation conditions over time, and the numerosity of interconnected or interwoven parts (Sivakumar and Singh, 2012). Thus, it is very important to have one or more models of the UDS to predict the behaviour of the system under different conditions (Butler et al., 2018), and at different locations, as it is difficult to fully understand the governing physics of the problem, and to correctly interpret and implement them in an integrated model (Mitchell et al., 2007; Rauch et al., 2002).

Generally, UDSs design and management problems cover three main aspects: hydrology, hydraulics, and water quality. When modelling, these aspects are synthesised with different modules, as follows:

- A hydrological module is responsible for modelling the rainfall-runoff processes, accounting for precipitation and temperature regimes, hydrological characteristics of the catchment, losses due to infiltration, evaporation, and other processes.
- A hydraulic module is responsible for routing the flows through the wastewater and/or stormwater convey system (conduits and pipes, manholes, overflows, outlets), the storage facilities (first flush detention basins, online or offline storages to manage flood events), and the pumping stations.
- A water quality module is responsible for modelling the dynamics of pollutants through the system.

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Nomenclature

List of Acronyms and Symbols

α	Base of the power-law function
A	Area
β	Exponent of the power-law function
A_x	Cross area
C	Dilution Coefficient
CSO	Combined Sewer Overflow
ds_i	Depression storage of impervious surfaces, from literature
$ds_{i,SM}$	Depression storage of impervious surfaces, calibrated
ds_p	Depression storage of pervious surfaces, from literature
$ds_{p,SM}$	Depression storage of pervious surfaces, calibrated
D	Drainage density
DM	Detailed Model
DWF	Dry Weather Flow
E	Error
E_{rel}	Relative Error
f^W	Calibration coefficient for the width
f^I	Calibration coefficient for the imperviousness
f^{ds_i}	Calibration coefficient for the depression storage of impervious surfaces
f^{ds_p}	Calibration coefficient for the depression storage of pervious surfaces
f^{n_p}	Calibration coefficient for the Strickler coefficient of the pervious surfaces
f^p	Calibration coefficient for a generic parameter
GIS	Geographic Information System
I	Percentage of imperviousness, evaluated on UDS information
I_{SM}	Percentage of imperviousness, calibrated
IQR	Inter-quartile range
κ	Slope of the linear function
λ	Intercept of the linear function
L	Length of conduit
n	Manning roughness coefficient
n_i	Manning coefficient of impervious surfaces, from literature
n_p	Manning coefficient of pervious surfaces, from literature
$n_{p,SM}$	Manning coefficient of pervious surfaces, calibrated
N	Number of simulations
NSE	Nash-Sutcliffe Efficiency
O	Horton-Strahler order
OF	Objective Function
p	Generic model parameter
Q	Hydrograph
Q_{DM}	Hydrograph of the detailed original model
Q_{SM}	Hydrograph of the simplified model
RTC	Real Time Control
S	Slope
SM	Simplified Model
$SWMM$	Storm Water Management Model
UDS	Urban Drainage System
W	Width, evaluated from UDS information
W_{SM}	Width, calibrated
X	Generic characteristic of the UDS

Regarding the hydrological module, rainfall-runoff models are the standard tool (Devia et al., 2015; Granata et al., 2016). One can choose among several solutions, well presented by Salvadore et al., 2015: lumped conceptual models provide high versatility while sacrificing spatial details and physical description, while semi-distributed physically based models are very detailed and are supposed to be more precise, but they are not as easy to handle as lumped models. Regarding the hydraulic module, many software tools rely on the numerical solution of the Saint-Venant equations (Chow, 1959) for the gradually varied unsteady flow conditions. As per the water quality aspects, a recent review (Jia et al., 2021) presents the most widely used modelling approaches.

Generally, both design and management of the infrastructures within an UDS require an extensive knowledge about the characteristics of the urban catchment. However, UDS preliminary design, planning studies and many management activities do not require the knowledge of the flow characteristics in every conduit, but rather a reliable estimation of the discharge at specific locations. For example, when studying Combined Sewer Overflows (CSOs), it is important to estimate the discharge of wastewater and stormwater in the upstream conduit, but it is not strictly necessary to calculate the flow in all the other conduits of the catchment upstream of the CSO; a similar argument may be done for storages, pumping stations, and other flow regulation devices.

European and national regulations are increasingly stringent on environmental issues regarding the UDSs. As a result, the water utilities are prompted to be engaged and act on the theme, and CSOs are seen as a main source of pollution, especially because it is very difficult to predict discharged volumes of polluted water and mass of pollutants, and their behaviour shows great variability with respect to the hydrological characteristics of served urban catchments (Farina et al., 2022). In this sense, CSO mitigation is often an issue addressed by modellers. However, the dependence of the CSO behaviour from different hydrological parameters is still largely uninvestigated, and one of the difficulties of conducting a CSO parametric analyses lies in the over parametrization of DMs. Using SMs for CSO studies could free researchers or modellers from this problem, helping to advance the scientific knowledge on CSO behaviour.

Complex Detailed Models (DMs) usually present both hydraulic and hydrologic modules: the former involves the simulation of the flow characteristics (i.e., flow depth and velocity) in the sewer channels of the UDS, which requires complete information on the hydraulic and geometric characteristics, and on the topographic layout of the conduits. When this information is lacking, expensive field surveys are needed. Furthermore, the calibration of the large number of parameters may lack in uniqueness of the set of parameters that produce a good fit with observed flow (Okiria et al., 2022; Spear, 1997), meaning that different sets of parameters can lead to similar "optimal" solutions (equifinality thesis, Beven, 2006).

Indeed, in preliminary design or in management problems, a lumped Simplified Model (SM) of the entire UDS, or of a part of it, may be of help to ease the work. A SM is here intended as a hierarchical surrogate model (Mahmoodian et al., 2018), with minimal complexity, where elements of the UDS are deliberately neglected or heavily approximated for simplicity of use, extended areas of the urban catchment are treated as single units (Beven, 2012), and the hydraulics of the drainage network is not computed. SMs can be robust since they have few describing parameters. In other words, the benefit of using SMs lies in the simplification of the numerical modelling together with the significant reduction in the number of parameters to be assigned.

In the literature, the problem of whether using distributed models or lumped models has been tackled, for large scale catchments, by different authors: some papers showed that lumped models offer equivalent results to distributed models (e.g., Yao et al., 1998, Vilaseca et al., 2022, dos Santos et al., 2018), while others found the opposite (e.g., Paudel et al., 2011, Kaleris and Langousis, 2017). Thus, the choice of a highly detailed semi-distributed model over a simple lumped model is not trivial, and it needs to be justified (Okiria et al., 2022), especially for

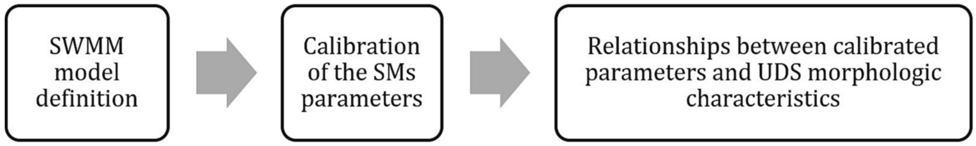

Fig. 1. Study workflow.

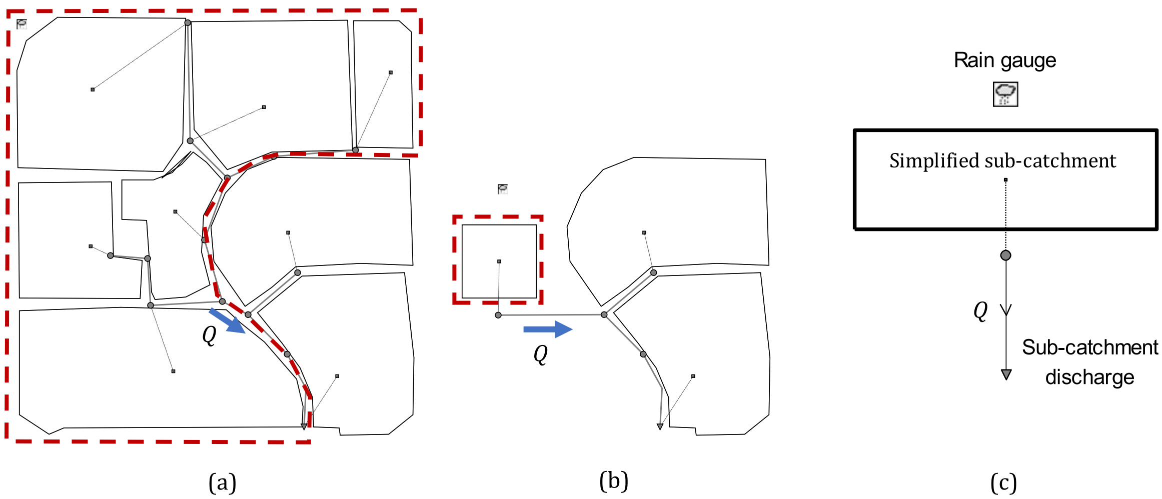

Fig. 2. In this example, the subpart of the original UDS, enclosed in the red dashed line in panel (a) (file "Example1.inp" from example files from U.S. Environmental Protection Agency (USEPA), (2015), is replaced by a simplified model (SM) in panel (b). The conceptual scheme of the SM is sketched in panel (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

smaller scale problems, like UDSs. Also, some studies attempted to use surrogate modelling of UDS to reduce the computational cost of simulations or for optimization purposes (Kwon et al., 2020; Langeveld et al., 2013; Ledergerber et al., 2019; Seyedashraf et al., 2021; Thrysøe et al., 2019; van Daal-Rombouts et al., 2016). However, surrogate models, usually mathematical black-boxes, are inherently case-specific, and cannot be easily generalised.

The objective of this paper is therefore to investigate the capability of SMs, the parameters of which could be easily assigned from cartographic information based on literature indications, to reliably model the hydrograph from relevant portions of the UDS, clustered as one or few catchments characterized by few lumped parameters. Different UDSs case studies from the technical literature, for which a detailed hydrologic-hydraulic model (DM) was also available, were simulated with the freeware and open-source software SWMM. The parameters of the SMs were initially calibrated as those allowing the best fit between the SM-simulated flood hydrograph and the one provided by the DM, assumed as benchmark in absence of measured hydrographs. The calibrated parameters, which in all cases allowed the SM to closely reproduce the hydrographs of the DM, exhibited robust relationships with some morphologic and topological characteristics, extracted from maps or Geographic Information System (GIS) of the studied UDSs. The obtained relationships linking lumped SM parameters with topographic information about the UDS can be of use to modellers, in all cases where few information are available about the UDS, because a reliable SM can be built directly from the cartography and the indications of technical literature.

Among the various possible applications of the SMs, especially convenient in scenario analyses or extended period simulations, an example of the proposed methodology is applied to CSO prediction. The CSO volumes from the SMs and the DMs have been compared, both at yearly scale and at event scale, showing that SMs succeed in correctly predicting CSOs.

2. Materials and methods

The methodology described in this section aims at showing how a simplified model (SM) of the UDS, the parameters of which can be directly assigned from cartographic information, and which neglects the hydraulic simulation of the flow through the network conduits, provides reliable estimates of the runoff for several real UDSs available in the literature.

First, the Storm Water Management Model (SWMM), with which all the simulations are carried out, is briefly introduced.

Second, the development of the SM of a UDS, and how to assign plausible ranges for its parameters are described. For several case studies of UDSs from the literature, for which detailed models (DMs) had been developed, the parameters of the SMs are calibrated within the assigned ranges, by minimising the deviation of the hydrographs, from those obtained with existing DMs, corresponding to the same rain events, assumed as benchmark in absence of direct discharge measurements.

Finally, the existence of relationships linking the calibrated SM parameters with morphologic and topologic characteristics of the UDSs is investigated, showing that the SM parameters could be closely estimated directly from cartographic information. The steps of the study are summarised in Fig. 1.

2.1. Simplified modelling approach with SWMM

The Storm Water Management Model (SWMM) was chosen for the simulations, as it is the most widely used software for hydrological and hydraulic modelling for urban catchments (Owolabi et al., 2022; Yuan et al., 2022). SWMM is flexible, as it allows describing a catchment with different degrees of detail, depending on the number of sub-catchments used for its representation. This software uses a nonlinear reservoir conceptual model (Chen and Shubinski, 1971) to estimate runoff from an idealised rectangular sub-catchment. This latter is divided in three sub-areas: an impervious area with no depression storages, an

Table 1
Ranges of values adopted for the coefficients f^p introduced for the definition of the intervals of variation of the parameters of the simplified models (SM). Ten values were assigned to each range, linearly sampling them between the minimum and the maximum value.

Coefficient	$f^W[-]$	$f^I[-]$	$f^{ds_i}[-]$	$f^{ds_p}[-]$	$1/f^{n_p}[-]$
Range	$[0.25; 3]$	$[0.7; 1.3]$	$[0.1; 3]$	$[0.1; 3]$	$[0.1; 3]$

impervious area with depression storages, and a pervious area with depression storages.

Owing to the short duration of the simulated rain events, the modules describing evaporation, infiltration, and groundwater, as well as the relevant model parameters, were not considered in this study. Basically, the computational scheme for the calculation of the surface runoff from each of the three areas consists in the iterative resolution of a mass balance equation coupled with the Manning equation. In the Manning equation, the surface runoff is idealised as the flow through a wide rectangular channel of cross area A_x, width W, slope S, Manning coefficient n, and height $d - d_s$, where d is the height of the water, and d_s is the height of the depression storages, with $W \gg d$. Then, the flow rate Q is calculated as qA where q is the flow per unit surface (Eq. (1), and A is the size of each of the relevant sub-areas. The mass balance equation and the Manning equation are applied separately for the three kinds of surfaces that compose the schematisation of the sub-catchment. Then, the resulting runoff is the sum of the three contributes.

$$q = \frac{W\sqrt{S}}{An}(d - d_s)^{5/3} \tag{1}$$

A simplified modelling approach, consisting in representing a part of a real UDS, placed upstream of a section of interest (e.g., where specific hydraulic devices are installed, such as CSOs, tanks, pumping stations), through one or few lumped sub-catchments, is presented (Fig. 2).

Since UDSs may include many hydraulic structures like storages, sewer overflows and pumping stations, the whole UDS may be represented by more than a single SM, each placed upstream of those infrastructures, and consisting of:

1. One or more lumped sub-catchments depending on the number of rainfall inputs: each lumped sub-catchment will be attributed a rain input from one rain gauge.
2. A dummy conduit conveying the modelled discharge Q_{SM}: the conduit has fictitious characteristics, in a way that it has a negligible influence on the hydrograph Q_{SM}, thus, only the hydrologic module of SWMM is used.

Since the target of the SMs is the estimation of the runoff of urban catchments, only the hydrologic module of SWMM is used to model the discharge by means of a dummy conduit.

Regarding the first point, since the rain is the major driver of urban runoff processes, it would be preferable to retain the information about the spatial distribution of the precipitation, when available. This can be more important for large catchments in which the spatial variability of the rain could have a big influence on the discharge.

The description of the UDS with a small number of lumped sub-catchments, together with the neglection of the hydraulic simulation of the flows through the single channels, entails a substantial reduction of the number of parameters of the proposed SM. Hence, the runoff can be modelled without the recourse to time consuming and expensive survey campaigns.

The SM of an UDS needs to be represented in SWMM with appropriate values of the hydrological parameters of Eq. (1), so to closely reproduce the behaviour of the UDS. Regarding A and S, the SM retains respectively the area and the mean slope of the relevant sub-part of the UDS, both easily retrieved from topographic maps, through any Geographic Information System (GIS). The other parameters may result extremely variable for different UDSs. Hence, their ranges of variation were defined around plausible values extracted either from maps and satellite images of the UDS, or from the technical literature (e.g., Rossman and Huber, 2016, Yen, 2001). Specifically, the values for the UDS were assumed as follows:

- The width W was assumed as the ratio between the area and the length of the main drainage channel of the UDS (Rossman and Huber, 2016).
- The percentage of the impervious surface I was evaluated from satellite images, as the ratio between the covered surfaces and the area of the UDS.
- The typical values of the depression storage for the impervious surfaces and for the pervious surfaces were assumed equal to $ds_i = 1mm$, and $ds_p = 1mm$, respectively.
- The typical values of the Manning coefficient for the impervious surfaces and for the pervious surfaces were assumed equal to $n_i = \frac{1}{60}\frac{s}{m^{1/3}}$, and $n_p = \frac{1}{7}\frac{s}{m^{1/3}}$, respectively.

For the parameter n_i, large variations were not expected, thus it was kept fixed to the typical value. This simplification was also made possible by the fact that, in Eq. (1), the effects on the runoff of W and n balance out. The possible ranges of variation of the other parameters were defined by multiplying the typical value of each parameter p by the coefficient f^p, so that the SM parameters would be $W_{SM} = f^W W$; $I_{SM} = f^I I$; $ds_{i,SM} = f^{ds_i} ds_i$; $ds_{p,SM} = f^{ds_p} ds_p$; $n_{p,SM} = f^{n_p} n_p$. In this way, the value of the coefficient f^p directly indicates how much the parameter p of the SM deviates from the value extracted from the UDS maps. Table 1 reports the ranges of the coefficients considered for the definition of the ranges of variations of the parameters (for the parameter n_p, the inverse of the coefficient, $1/f^{n_p}$, was considered). The coefficient ranges investigated for model calibration were conveniently limited, so to obtain plausible values of the parameters, avoiding those without physical relevance. Then, ten values were assigned to each calibration coefficient f^p (and therefore to each calibration parameter), linearly sampling them inside the relevant ranges listed in Table 1. Therefore, the investigated solution space consisted of the cartesian product of the ranges of values of the calibration parameters, with cardinality $N = 10^5$.

2.2. Calibration of the SM

As it will be described in Section 2.4, the proposed methodology was applied to several case studies of UDSs retrieved from the literature, for which a DM had been developed with SWMM. As in most cases the measured hydrographs used to develop the DM of the UDS were not available, the hydrograph Q_{DM}, provided by the DM, was assumed as benchmark. A calibration process was then conducted, to identify the parameters W_{SM}, I_{SM}, $ds_{i,SM}$, $ds_{p,SM}$, and $n_{p,SM}$, that allowed minimising the deviation of the hydrograph Q_{SM}, estimated by the simplified model, from Q_{DM}. For each case study, a different rainfall event was selected for the calibration, and an additional event was also used for the validation.

Different Objective Functions can be adopted to quantify the difference between the flow Q_{DM}, calculated with the DM, and the flow Q_{SM}, calculated with the SM. In this paper, the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970), (Eq. (2), to be maximized, is showed, since it is one of the most used metrics in hydrological applications (Biondi et al., 2012; Perin et al., 2020).

$$NSE = 1 - \frac{\sum_{i=1}^{N_t} \left(Q_{DM}^i - Q_{SM}^i\right)^2}{\sum_{i=1}^{N_t} \left(Q_{DM}^i - \overline{Q_{DM}}\right)^2} \tag{2}$$

In Eq. (2), Q_{DM}^i and Q_{SM}^i are respectively the flow values of the DM hydrograph and of the SM hydrograph, at the time $i\Delta t$, where Δt is the simulation time step; the number of time steps is $N_t = T/\Delta t$, where T is the simulation duration; $\overline{Q_{DM}}$ is the mean value of the DM hydrograph.

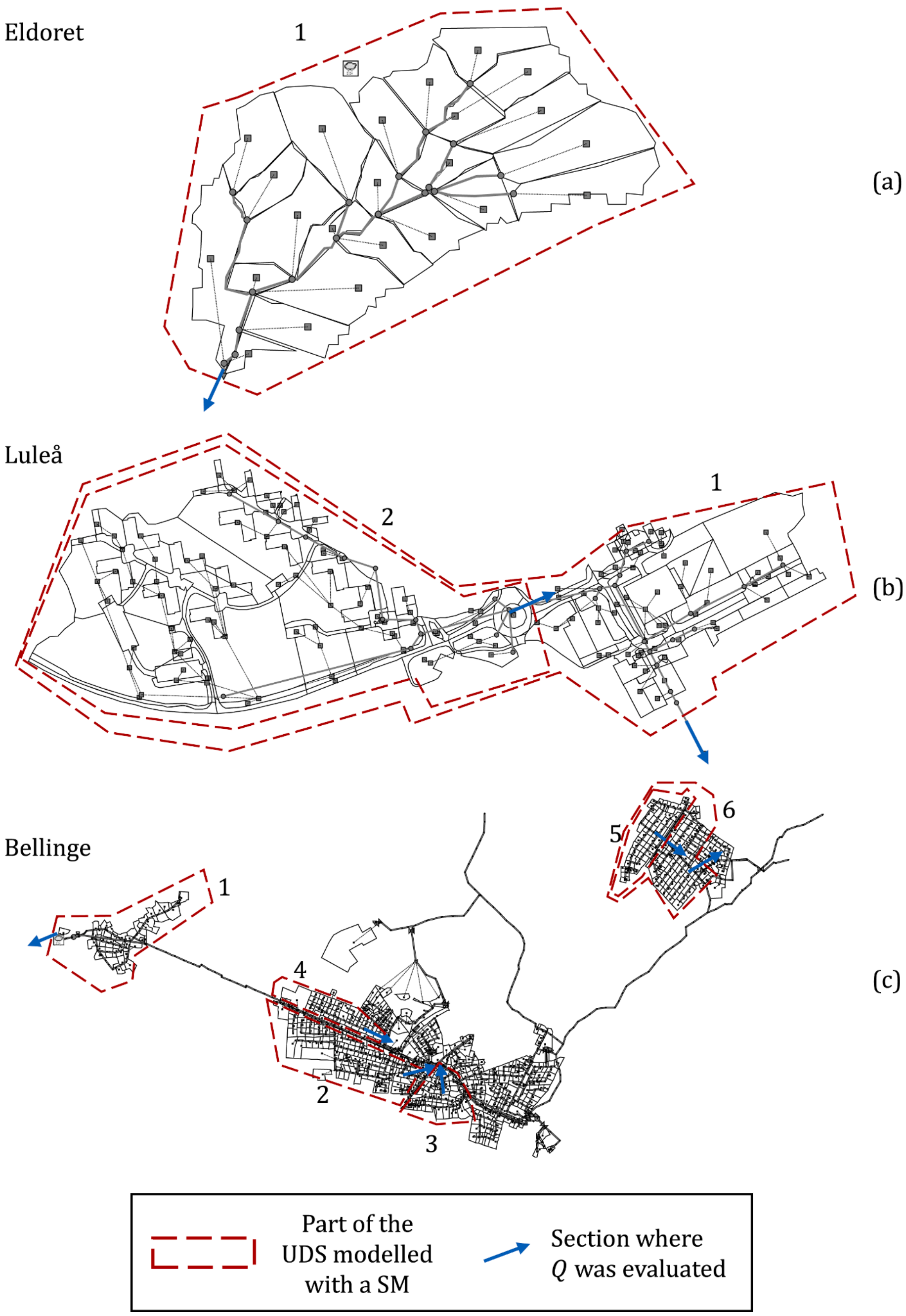

Fig. 3. The parts of the UDS (of the case studies summarized in Table 2) that were modelled with a SM, are delimited in red. The blue arrows represent the sections where the discharge Q was evaluated. Eldoret, Kenya (a) (Abraham Metto et al., 2021). Luleå, Sweden (b) (Broekhuizen et al., 2020, 2021). Bellinge (Odense), Denmark (c) (Pedersen et al., 2021a, 2021b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

N simulations were carried out in SWMM for each case study. Given the number of the simulations to be run, it was chosen to implement a framework in the Python programming language using *"swmm-api"* (Pichler, 2022) (version 0.4.21) to automate several tasks. Specifically, this Python package allows to read and manipulate SWMM input files, run SWMM simulations, and read the binary output files generated. In this study, the original EPA-SWMM (version 5.2.3) was used as the core engine of the computations. Details about the computer configuration used, can be found in Additional Data. After running all the simulations, each runoff time series Q_{SM}^{j} from the j^{th} simulation, being $j = 1..N$, was compared with the runoff time series Q_{DM}, and the OF was evaluated.

2.3. Estimating SM parameters from UDS maps

To assess the feasibility of developing the SM without a benchmark hydrograph available for model calibration, the existence of relationships linking the parameters, obtained through calibration, with the major characteristics of the UDS was investigated. In most situations of practical interest, only cartographic and topologic information, and satellite images of the UDS are available. Hence, the following set of UDS characteristics, easily readable from maps and satellite images, were considered: area, A; average slope, S; width, W; percentage of impervious area, I; Horton-Strahler order (Horton, 1945; Strahler, 1952, 1957) of the drainage network, O; drainage density, $D = \sum_i L_i / \sqrt{A}$ (the summation is extended to the lengths L_i of all the conduits of the UDS). The determination coefficient R^2 of either linear ($p = \kappa X + \lambda$) and power-law ($p = \alpha X^{\beta}$) functional formats equations was evaluated, for any calibrated SM parameter p and UDS characteristic X, with reference to a set of UDS with various characteristics. Whereas the relationship exhibits a high value of R^2, this indicates that the SM parameter could be directly estimated from the available characteristics of the UDS.

Table 2
Summary of the major characteristics of the UDS case studies: Eldoret, Kenya (a) (Abraham Metto et al., 2021); Luleå, Sweden (b) (Broekhuizen et al., 2020, 2021); Bellinge (Odense), Denmark (c) (Pedersen et al., 2021a, 2021b).

Case study	Area $A[ha]$	Slope $S[\%]$	Width $W[m]$	Impervious area $I[\%]$	$\frac{W\sqrt{S}}{n_i}\left[m^{\frac{4}{3}}/s\right]$	Horton-Strahler order O [-]	Drainage density $D = \frac{\sum L_i}{\sqrt{A}}[-]$	Sub-catchments in the DM	Rain event duration $[hr]$	Average rain intensity $\left[\frac{mm}{hr}\right]$
Eldoret 1	696.5	1.50	697	25.0	5118	2	3.0	23	3	10.8
Luleå 1	10.2	1.15	139	65.0	897	3	24.8	146	22	0.39
Luleå 2	6.9	1.45	158	60.0	1140	2	30.0	85	22	0.39
Bellinge 1	21.2	1.1	227	25.0	1432	3	17.2	39	3.5	5.65
Bellinge 2	43.5	1.15	484	30.0	3113	4	12.0	158	3.5	5.65
Bellinge 3	13.3	3.00	195	27.5	2025	3	21.7	39	3.5	5.65
Bellinge 4	13.1	1.37	184	32.5	1295	2	21.9	33	3.5	5.65
Bellinge 5	17.3	0.40	702	32.5	2664	3	19.0	36	3.5	5.54
Bellinge 6	50.0	0.60	689	40.0	3203	4	11.2	112	3.5	5.54

2.4. Case studies

The presented approach was tested on case studies retrieved from the scientific literature, for which UDS characteristics and a validated DM were available, having different catchment size, characteristics of the sub-catchments, and rain input.

The sketches of the UDS of the case studies are represented in Fig. 3. The main features of the DMs of the case studies, together with the duration and mean intensity of the rainfall event used for the calibration, are summarized in Table 2.

Eldoret is a city in Kenya, with catchment area $A = 696.5ha$, average elevation 2200 m, and a subtropical highland climate (Koppen, 1936): the UDS DM was obtained from Abraham Metto et al., 2021. Luleå is a coastal city of northern Sweden, with average elevation 6 m and a subarctic climate (Koppen, 1936): two case studies were obtained from the UDS DM (Broekhuizen et al., 2020, 2021) of a small catchment with area $A = 10.2ha$. Bellinge is a village in Odense, Denmark, with average elevation 13 m and a temperate oceanic climate (Koppen, 1936): six case studies were obtained from the UDS DM (Pedersen et al., 2021a, 2021b) of Bellinge, this latter having a total area $A = 274ha$.

According to the defined ranges of the calibration coefficients f^p, the corresponding ranges of the parameters considered for the SM calibration are reported in Table 3.

3. Results and discussion

3.1. Performance of the simplified models

Overall, the performance of the simplified approach gave satisfactory results in terms of goodness of fit between the hydrographs Q_{SM} from the calibrated SMs and the hydrographs Q_{DM}, for the considered hyetographs. The histogram of Fig. 4 shows the obtained optimal values of NSE (Eq. (2) for each case study, and the average value of NSE (0.87), with the minimum 0.77 for the case study *Bellinge 6* and the maximum 0.95 for the case study *Bellinge 3*.

It is worth reiterating that the maximisation of the NSE allowed to identify the set of parameters that reduced the deviation of the hydrographs of the proposed simplified approach from those of the DM, taken as a benchmark. In fact, the hydrographs Q_{SM} for all the case studies resulted close to the hydrographs Q_{DM}, both for the peak discharge and the peak timing. For example, for *Bellinge 5* (Fig. 5), with $NSE = 0.89$, the discharges of the first and the second peaks are underestimated by only 8.9%, and 11.8%, respectively, while the first peak time is anticipated by only 1 min, and the second peak time is perfectly predicted. The hydrographs of all the other case studies are given in the Appendix.

The good performance of the calibrated SMs is confirmed also for rain events other than those used for calibration. For example, the calibrated SM of *Bellinge 5* was used to simulate the hydrograph of a different rain event and compared with the hydrograph predicted by the DM (Fig. 6): the NSE was 0.87 with a reduction of only −0.02 with respect to the rain event used for calibration.

Although the main advantage of using SMs instead of DMs lies in the significantly reduced number of parameters to be assigned, it also results in great computational advantages, in terms of required simulation time. Larger or more complex UDSs would benefit the most of these advantages. For example, the simulation of the Bellinge case studies, for a period of one month, with the SM would require 5 s, while with the DM it would take 4200 s. More details about the computational gain are given in Table 4. The computational advantage of running SMs is particularly useful in scenario analyses and long simulations, like those for climate change effect assessment.

3.2. Parameters of the calibrated simplified models

For each case study, the best sets of calibration coefficients f^p, and the corresponding parameter values, i.e., those maximizing the NSE

Table 3
Ranges of values adopted for the calibration of the hydrological parameters, for each case study. For each parameter, the range was obtained multiplying a calibration coefficient f^p (Table 1) by a typical value obtained from maps or from the literature.

	$W_{SM}[m]$	$I_{SM}[\%]$	$ds_{i,SM}[mm]$	$ds_{p,SM}[mm]$	$n_{p,SM}\left[s/m^{1/3}\right]$
Eldoret 1	[174; 2090]	[17.5; 32.5]	[0.1; 3]	[0.1; 3]	[0.0476; 1.43]
Luleå 1	[35; 418]	[45.5; 84.5]	[0.1; 3]	[0.1; 3]	[0.0476; 1.43]
Luleå 2	[39; 473]	[42.0; 78.0]	[0.1; 3]	[0.1; 3]	[0.0476; 1.43]
Bellinge 1	[57; 682]	[17.5; 32.5]	[0.1; 3]	[0.1; 3]	[0.0476; 1.43]
Bellinge 2	[121; 1451]	[21.0; 39.0]	[0.1; 3]	[0.1; 3]	[0.0476; 1.43]
Bellinge 3	[49; 585]	[19.3; 35.8]	[0.1; 3]	[0.1; 3]	[0.0476; 1.43]
Bellinge 4	[46; 553]	[22.8; 42.3]	[0.1; 3]	[0.1; 3]	[0.0476; 1.43]
Bellinge 5	[175; 2106]	[22.8; 42.3]	[0.1; 3]	[0.1; 3]	[0.0476; 1.43]
Bellinge 6	[172; 2068]	[28.0; 52.0]	[0.1; 3]	[0.1; 3]	[0.0476; 1.43]

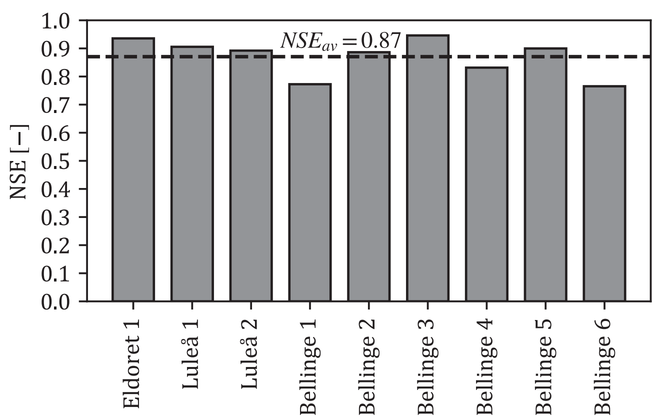

Fig. 4. NSE values of the best solutions found for each case study. The NSE measures the closeness of the SM hydrograph Q_{SM} to the DM hydrograph Q_{DM}.

between the hydrographs Q_{DM} and Q_{SM}, are listed respectively in Table 5 and Table 6. Also, the group of parameters $\frac{W\sqrt{S}}{n_i}$, appearing in the Manning equation (Eq. (1)) was calculated. It is worth noting that the optimal values of NSE were very close to 1, where $f^p = 1$ represents the condition for which the parameters of the SM are deduced by the cartographic analysis, while the NSE value drops as soon as f^p deviates from the optimal value.

To analyse the sensitivity of the SM performance to the different calibrated parameters, for all N simulations of each case study, the scatter plots of each of the coefficients f^p against the NSE were represented. In this way, it was possible to highlight the parameters with the highest importance in the calibration process. For instance, in Fig. 7, referring to *Bellinge 5*, the NSE varies between −0.14 and 0.90 throughout the entire analysed solution space, with the OF being most sensitive to W_{SM} (through f^W), and so being the most important parameter to be calibrated for that case study: indeed, both the maximum (red line) and the average (blue line) NSE values of the space of solutions, for each W_{SM} value, show the highest variability compared to the other parameters, with a clear maximum of $NSE = 0.90$ for $f^W = 0.86$, corresponding to $W_{SM} = 604m$. Furthermore, the spreading of the points over a column, referred to a specific value of a single parameter, and thus depending on the variations of the others, is smaller for the f^W than for the other parameters. This indicates that the solution is more sensitive to changes in W_{SM} than to any other parameter. I_{SM} (through f^I) results the second most important parameter for the SM of *Bellinge 5*, with the maximum NSE for $f^I = 1.23$, thus $I_{SM} = 1.23 I_{DM}$. However, it is noteworthy that even if a percentage of imperviousness $I_{SM} \equiv I_{DM}$ (i.e., $f^I = 1.0$) were assigned, the NSE value would only decrease by a little. Thus, a reliable hydrograph would be still achievable. The latter consideration holds also for all the other case studies.

The same scatter plots of Fig. 7, for all the other case studies, are given in the Appendix. For all the case studies referred to Bellinge and Luleå, $ds_{p,SM}$ and $n_{p,SM}$ seem to have no influence on the output of the simulations, while their influence is very small for *Eldoret 1* case study. The width and the imperviousness were the most important parameters for calibration for all the case studies.

3.3. Relationships between calibrated SM parameters and UDS characteristics

An important aspect of the proposed approach to develop a reliable SM of the UDS is the estimation of the few required parameters. In this respect, the achievement, through calibration, of a set of parameters close to those directly deducible from the cartographies, and capable of providing hydrographs very close to those obtained with the DMs, would confirm the validity and the robustness of the proposed SMs.

In most cases, only geometric and topologic information about the UDS is available, hence it is not possible to rely on benchmark hydrographs to calibrate the model of the UDS. In this usual situation, the identification of general relationships, linking the parameters of the calibrated SM with easily obtainable morphologic characteristics of the UDS, would make possible to develop a reliable SM also in absence of measurements of rainfall and runoff. To this aim, the existence of linear or power-law relationships between the UDS characteristics described in Section 2.4 (summarized in Table 2 for the case studies) and the calibrated SM parameters (Table 6) was investigated. The following relationships, characterised by high values of the determination coefficient R^2, were found:

- The calibrated percentage of imperviousness, I_{SM}, is highly correlated with the percentage of imperviousness of the UDS, I, retrieved from satellite images, with $R^2 = 0.96$ (Fig. 8a).
- The calibrated width W_{SM} is correlated with the width W of the UDS, evaluated from a map, with $R^2 = 0.79$ (Fig. 8b).
- The calibrated group of parameters, $\frac{W_{SM}\sqrt{S}}{n_i}$, is correlated with the width W of the UDS, evaluated from a map, with $R^2 = 0.75$ (Fig. 8c).
- The calibrated group of parameters, $\frac{W_{SM}\sqrt{S}}{n_i}$, is also inversely correlated with the drainage density $\frac{\sum_i L_i}{\sqrt{A}}$, with $R^2 = 0.81$ (Fig. 8d).

The observed decreasing dependence of the group $\frac{W_{SM}\sqrt{S}}{n_i}$ on the drainage density $\frac{\sum_i L_i}{\sqrt{A}}$ (Fig. 8d) can be interpreted as follows. According to Eq. (1), to produce a given specific discharge q with a smaller value of $\frac{W\sqrt{S}}{n_i}$, a higher water height d is needed. This implies that UDSs with higher total length of conduits per unit area tend to accumulate more water, which indeed can be stored in the denser upstream network.

$$I_{SM} = 0.51 I^{1.2} \tag{3}$$

$$W_{SM} = 0.87W \tag{4}$$

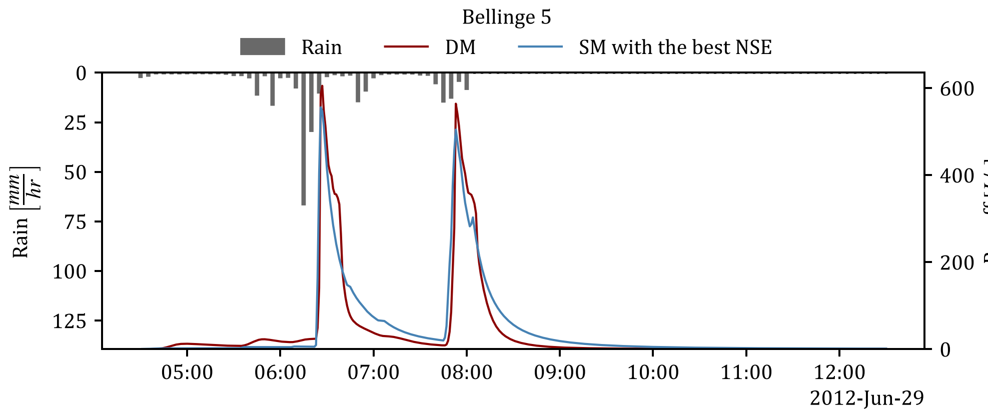

Fig. 5. Best hydrograph obtained for the SM of *Bellinge 5*. The hyetograph (reversed bar plot) has a resolution of 5 min.

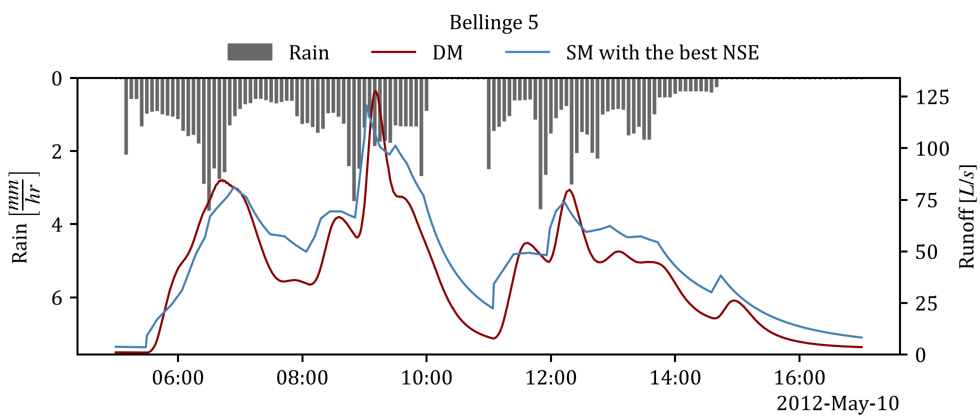

Fig. 6. Validation of the SM of *Bellinge 5*. The SM with the calibrated parameters was simulated with a different rain event and had $NSE = 0.87$.

Table 4
Simulation times for DMs and SMs for a one-month period of simulation, and NSE.

Case study	DM simulation time	SM simulation time	Simulation time reduction $\left(1 - \frac{SMtime}{DMtime}\right)$	*NSE*
Eldoret	34*s*	5*s*	85.3%	0.94
Luleå[1]	28*s*	2*s*	92.9%	0.90
Bellinge[1]	4200*s*	5*s*	99.9%	0.85

[1] *The reported DM simulation time refers to the run of the DM of the whole UDS.*

Table 5
Results from the OF evaluation for all the case studies and optimal sets of calibration coefficients f^p. When a parameter had no significant influence on the OF, it was marked as "*ineffective*".

Case Study	$NSE[-]$	$f^W[-]$	$f^I[-]$	$f^{ds_i}[-]$	$f^{ds_p}[-]$	$1/f^{n_p}[-]$
Eldoret 1	0.94	0.86	0.70	*ineffective*	*ineffective*	1.39
Luleå 1	0.91	1.17	1.30	0.10	*ineffective*	*ineffective*
Luleå 2	0.89	0.86	1.17	0.10	*ineffective*	*ineffective*
Bellinge 1	0.77	1.17	1.17	0.10	*ineffective*	*ineffective*
Bellinge 2	0.89	0.86	1.17	0.10	*ineffective*	*ineffective*
Bellinge 3	0.95	0.86	0.90	0.10	*ineffective*	*ineffective*
Bellinge 4	0.83	1.47	1.17	0.42	*ineffective*	*ineffective*
Bellinge 5	0.90	0.86	1.23	3.00	*ineffective*	*ineffective*
Bellinge 6	0.77	1.47	1.1	2.68	*ineffective*	*ineffective*

$$\frac{W_{SM}\sqrt{S}}{n_i} = 24.28W^{0.8} \tag{5}$$

$$\frac{W_{SM}\sqrt{S}}{n_i} = -679\frac{\sum_i L_i}{\sqrt{A}} + 5044 \tag{6}$$

Eqs. (3), (4), (5) and (6), corresponding to the curves of Fig. 8, could be used to assign the parameters of the SM. Regarding the width, it appears that, in addition to being well correlated with the width read on a map, it is also inversely correlated with the topology of the sewer channels. Given the high R^2 values of those relationships, and given the diversity of the nine case studies, it could be said that their use could be extended also to other case studies, when little information about the response of the UDS to precipitation is available, although their validation would require the analysis of additional case studies.

4. Example of practical application

The availability of a reliable SM can be useful for many practical applications in the management of UDSs. In fact, to study the behaviour of several hydraulic regulation devices (e.g., tanks, pumping stations, combined sewer overflows), the incoming hydrograph in different operating conditions or scenarios is the most important information. Other fields of application of the SMs could be multi-scenario analyses for climate change effect assessment, flood risk assessment, and RTC of UDSs (Arnbjerg-Nielsen et al., 2013; Kirshen et al., 2014; Xiong et al., 2019).

As an example, for the six case studies of Bellinge, for which a one-year long rainfall record and information about the dry weather flow (DWF) were available, the SM was used to estimate the volume dis-

Table 6

Optimal sets of parameters found for the SMs for each case study, and group of parameters $\frac{W_{SM}\sqrt{S}}{n_i}$. When a parameter had no significant influence on the OF, it was marked as "*ineffective*".

Case Study	$W_{SM}[m]$	$I_{SM}[\%]$	$ds_{i,SM}[mm]$	$ds_{p,SM}[mm]$	$n_{p,SM}\left[s/m^{1/3}\right]$	$\frac{W_{SM}\sqrt{S}}{n_i}\left[m^{\frac{4}{3}}/s\right]$
Eldoret 1	600	17.5	*ineffective*	*ineffective*	0.103	4407
Luleå 1	163	84.5	0.10	*ineffective*	*ineffective*	1047
Luleå 2	136	70.0	0.10	*ineffective*	*ineffective*	981
Bellinge 1	265	29.2	0.10	*ineffective*	*ineffective*	1670
Bellinge 2	417	35.0	0.10	*ineffective*	*ineffective*	2680
Bellinge 3	168	24.8	0.10	*ineffective*	*ineffective*	1744
Bellinge 4	272	37.9	0.42	*ineffective*	*ineffective*	1907
Bellinge 5	604	40.1	3.00	*ineffective*	*ineffective*	2294
Bellinge 6	1015	44.0	2.68	*ineffective*	*ineffective*	4716

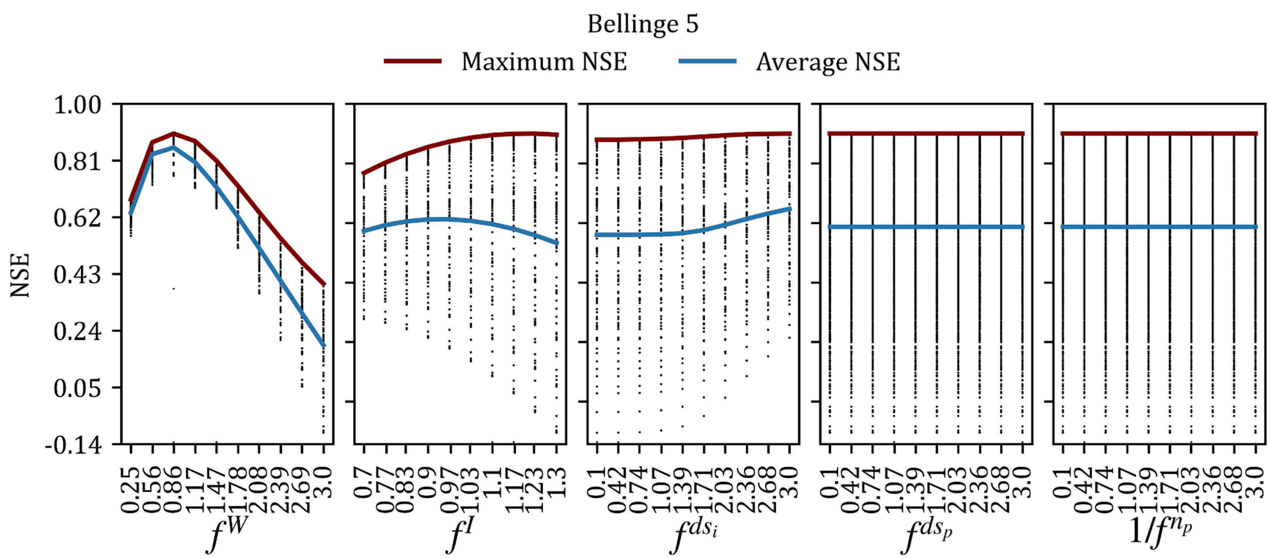

Fig. 7. Analysis of the NSE sensitivity to the different calibration parameters. For *Bellinge 5*, the f^W, hence the width W_{SM}, was the most important parameter to calibrate, as it had the greatest impact on the NSE value.

charged from a hypothetical CSO placed at the outlet of the UDS. The estimated volumes were then compared with those estimated with the available DM of the same UDS, both at yearly scale and at event scale. Typically, CSOs are designed to activate when a desired dilution coefficient C of the DWF is attained during rain events. In this example, the CSO acts as an ideal cut-off of the incoming flow with a threshold value $CSO_{threshold}$, depending on the choice of the dilution coefficient C:

$$C = \frac{CSO_{threshold}}{DWF} \tag{7}$$

This latter depends on the enforcing regulations, the type of water body in which the overflow occurs, and the standards of water quality that the water utility wants to achieve, so an extensive range of dilution coefficients, $C = [3;15]$, was investigated. The CSO volume errors E,E_{rel}, were defined as follows:

$$E = CSO_{SM} - CSO_{DM} \tag{8}$$

$$E_{rel} = \frac{CSO_{SM} - CSO_{DM}}{CSO_{DM}} \tag{9}$$

Starting from the values of Table 2, Eqs. (3) and (4) were used to estimate the parameters I_{SM} and W_{SM} of the SMs. Differently, the parameters $ds_{i,SM}$, $ds_{p,SM}$ and $n_{p,SM}$, showing little influence on the hydrographs for all the case studies, were left equal to the values of Table 2.

For these case studies, the SMs predicted the CSO volumes of one year, namely from April 1st, 2012, to April 1st, 2013 (Fig. 9), with an average $E_{rel} = -6.14\%$, ranging from -21.79% to 18.34%, as reported in Fig. 10. Therefore, the yearly CSO volumes estimated with the SMs result acceptable, compared to the great uncertainty always affecting runoff estimated by whatever model (Deletic et al., 2012). At the event scale, the inter-quartile ranges (IQRs) of E, of all the case studies, fall between -0.17 mm and 0.06 mm, while in the 82% of all the CSO events, E falls between -0.43 mm and 0.49 mm: specifically, -0.43 mm is the 9% percentile of *Bellinge 5*, and 0.49 mm is the 91% percentile of *Bellinge 6* (see boxplots in Fig. 11). Hence, also at event scale, the results of the SM are acceptable.

Hence, SMs can be used to carry out extensive studies on CSOs with the aim of mitigating their impact on the receiving water bodies, like sensitivity analyses to hydrological characteristics of urban catchments or RTC strategies. SMs could also be paired with models of pollution from CSOs, which is, at day, a crucial research field in environmental engineering. Such studies would be more difficult to do with DMs, owing to the uncertain estimation of their high number of parameters in absence of calibration and, as well, for the computational burden, which would not be suitable for long simulations.

5. Conclusions

This paper explored the definition and the applicability of a simplified hydrological modelling (SM) approach for urban drainage systems (UDSs). This approach allows synthesising parts of an UDS placed upstream of specific sections of interest, to assign reliable lumped model

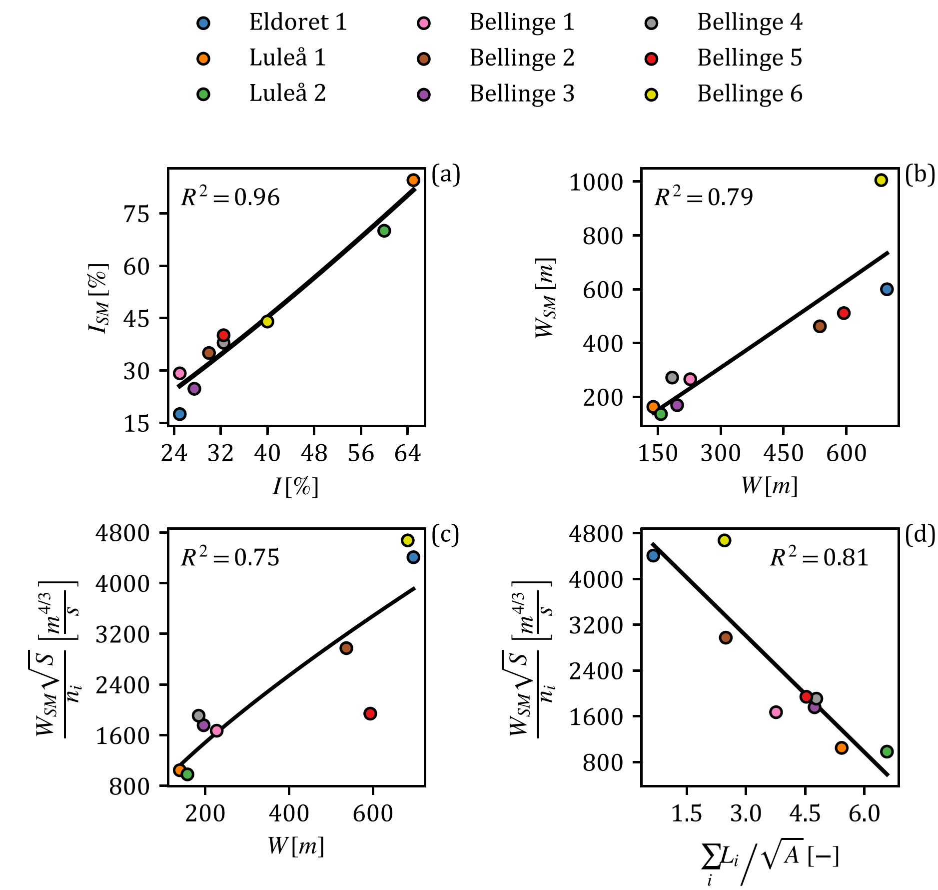

Fig. 8. Panels (a) and (b): relationships linking the values of I, W, read on the maps of the UDSs (Table 2), and the corresponding calibrated SM parameters (Table 6). The relationships between the width W and the drainage density $\frac{\sum_i L_i}{\sqrt{A}}$ and the calibrated group of parameters $\frac{W_{SM}\sqrt{S}}{n_i}$ are also showed in panels (c) and (d).

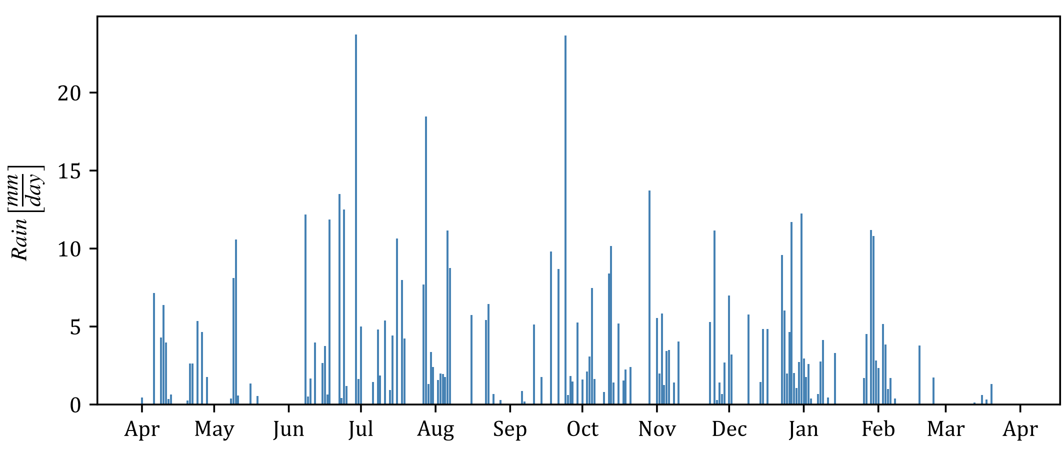

Fig. 9. Daily rainfall record used for calculating the CSO error between the DMs and the SMs for the Bellinge case studies 1–6 (the rainfall record used for the simulations has a resolution of 1 min).

parameters, when little information is available.

The proposed SM approach involves a considerable reduction of the required input data thanks to: (1) spatial clustering of the morphometric characteristics of the urban catchment; (2) waiver of hydraulic modelling of the sewer network. Therefore, the proposed approach is extremely useful where rapid estimates of runoff are required in specific sections of UDSs.

The effectiveness of the proposed SM has been demonstrated by applying the hydrological module of the well-known software SWMM, for which it was sufficient to estimate only five parameters for large urban basins. The approach was tested on nine real UDSs found in literature, for which complex detailed models (DMs) were available: in absence of the measured discharge, the hydrographs Q_{DM} from the DMs were assumed as benchmark for the hydrographs Q_{SM}, calculated with the SMs. Then, a calibration workflow was developed, considering the SM parameters as unknown, identifying the values that minimised the deviation of Q_{SM}, from Q_{DM}, through the evaluation of the maximum Nash-Sutcliffe Efficiency (NSE). The performance of the SMs was satisfactorily good, as witnessed by high values of the NSE obtained for all the case studies.

Robust relationships linking the calibrated SM parameters with the major morphometric characteristics of the UDSs were found, indicating

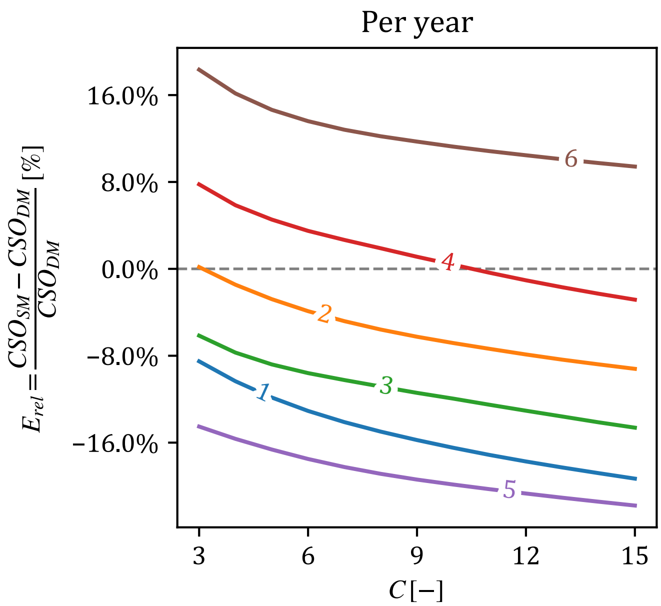

Fig. 10. Yearly CSO volume relative errors E_{rel} between the SMs and the DMs, for the case studies Bellinge 1–6. I_{SM} and W_{SM} of the SMs were estimated with Eqs. (3) and (4).

that the parameters of the SM models can be directly deduced from thematic maps, and based on indications of the technical literature. However, the general applicability of the obtained relationships should be tested on more case studies.

The SMs also showed a remarkable reduction of computational burden, which is particularly useful when Extended Period Simulations are carried out. In this regard, an example of practical application was also presented: the discharged volumes, from a hypothetical Combined Sewer Overflow (CSO), at yearly and daily scale, calculated with the SMs and the DMs, were compared for various UDSs, considering an extensive range of CSO activation threshold values, defined through the dilution coefficient C. In all cases, the difference of discharged volumes, estimated with the SMs and the DMs, resulted quite small.

Additional data

All data and files used in the study are available at the relevant given references or upon reasonable request.

Computer configuration used for this study: Windows 11, CPU AMD Ryzen 4500U, RAM 24 GB, Python 3.11.3, EPA-SWMM 5.2.3, swmm-api 0.4.21.

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CRediT authorship contribution statement

Alessandro Farina: Methodology, Software, Data curation, Investigation, Validation, Writing – original draft, Writing – review & editing. **Armando Di Nardo:** Supervision. **Rudy Gargano:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Job Augustijn van der Werf:** Data curation. **Roberto Greco:** Conceptualization, Methodology, Supervision, Funding acquisition, Validation, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Appendix

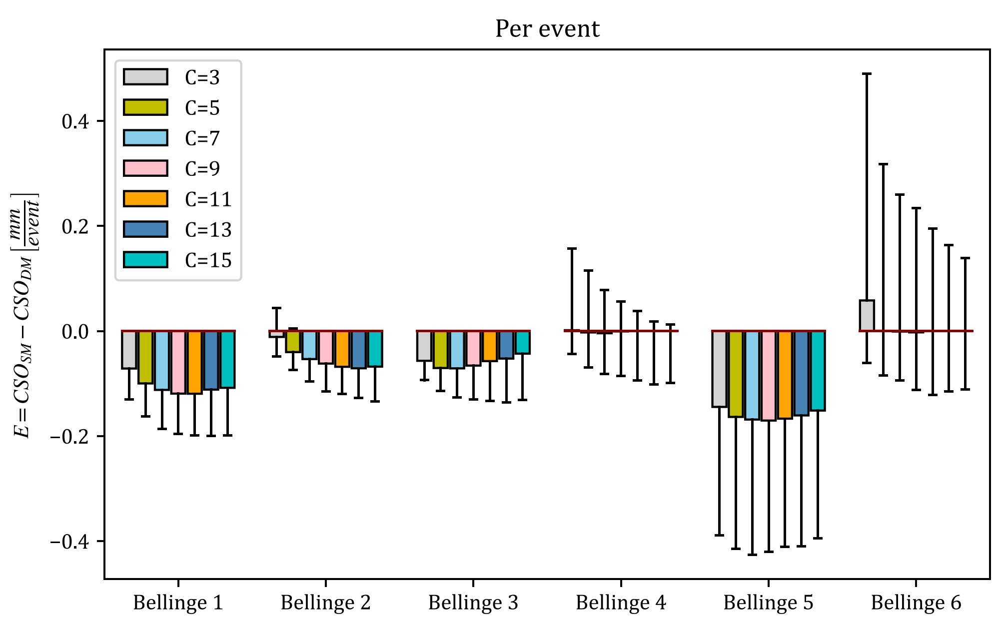

Fig. 11. CSO volume errors E, at event scale, between the SMs and the DMs, for the case studies Bellinge 1–6. I_{SM} and W_{SM} of the SMs were calculated with Eqs. (3) and (4). The boxes show the inter-quartile ranges, while the whiskers show the 9% and the 91% percentiles.

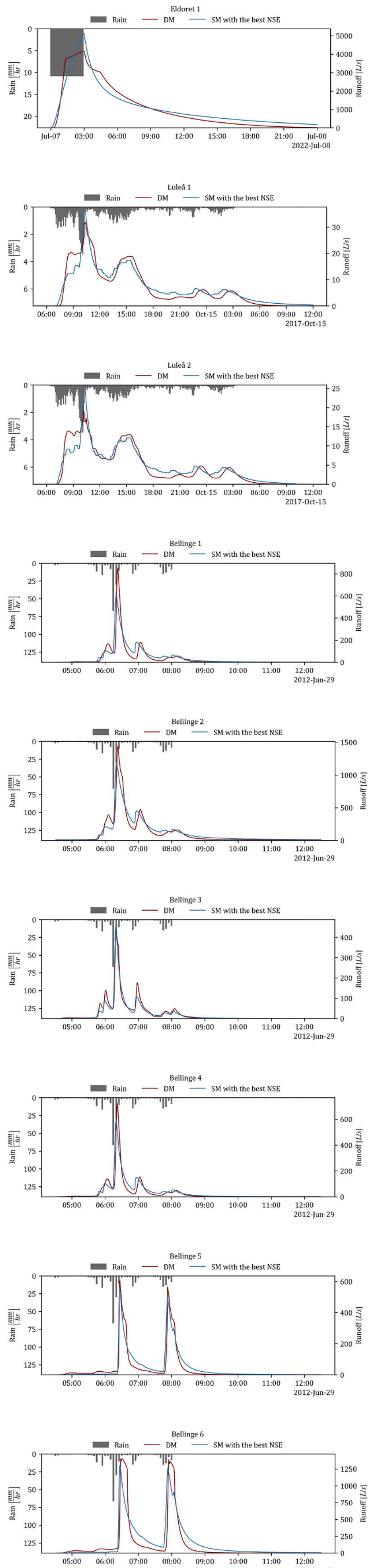

Fig. A1. Best hydrographs obtained for the SMs of all the case studies. The reversed bar plot represents the hyetograph.

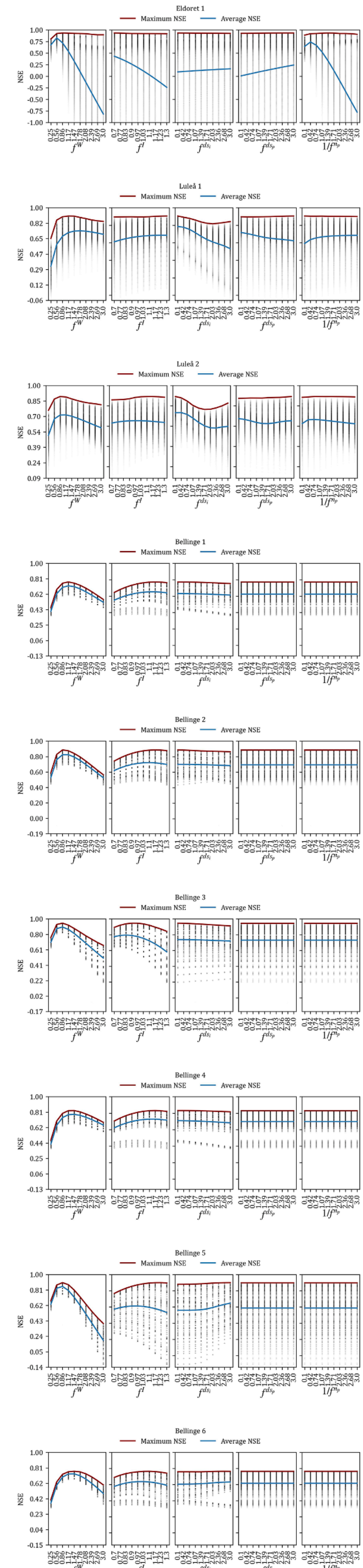

Fig. A2. Analysis of the NSE sensitivity to different calibration parameters. For all the case studies, the f^W, hence the width W_{SM}, and the f^I, hence the imperviousness I_{SM}, were the most important parameter to calibrate, as they had the greatest impact on the NSE value.

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