Comparative Analysis of Uncertainties in Urban Surface Runoff Modelling

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Analyse comparative des incertitudes sur la modélisation du ruissellement urbain

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RESUME

En français

ABSTRACT

In the present paper a comparison between three different surface runoff models, in the numerical urban drainage tool MOUSE, is conducted. Analysing parameter uncertainty, it is shown that the models are very sensitive with regards to the choice of hydrological parameters, when combined overflow volumes are compared - especially when the models are uncalibrated. The occurrences of flooding and surcharge are highly dependent on both hydrological and hydrodynamic parameters. Thus, the conclusion of the paper is that if the use of model simulations is to be a reliable tool for drainage system analysis, further research in improved parameter assessment for surface runoff models is needed.

KEYWORDS

Calibration, Sensitivity analysis, Surface runoff, Uncertainties, Urban drainage modelling

1 INTRODUCTION

In analysis and design of urban storm water drainage systems, an important tool for the consulting engineer is commercial urban drainage models such as MOUSE, InfoWorks, SWMM, etc. However, if results from these models are used in decision-making, it is all-important that the results are valid and correspond to reality. Wrong decisions, based on defective and uncalibrated model predictions, can at worst cause unrealistic estimates of flooding or combined sewer overflow frequencies, or on the other hand result in over-dimensioned - and more expensive – drainage systems with poor self-cleansing. Therefore, it is crucial to clarify where the main uncertainties in urban drainage models are located in order to either reduce the uncertainties or to take precautions in the decisions based on models results.

An urban drainage storm water model can be divided into four individual parts: the precipitation input, the hydrological surface processes, the hydrodynamics of the surface flow, and finally the hydrodynamics of the pipe flow. The object of this paper is to investigate two of the four parts, namely the hydrological surface processes and the hydrodynamics of the surface runoff, as it is the author's conviction that these part of an urban drainage model is encumbered with many and relatively serious errors. This is also described by e.g. Lei (1996), Artina et al. (2005) and Willems and Berlamont (1999).

The object of the paper is to investigate different complexities and types of both hydrological and hydrodynamic processes by comparing three different surface runoff submodels (SRM). These are compared with regards to complexity and calibration. The comparison is implemented using long term simulations and comparing results of combined sewer overflow volumes and occurrence of surcharge or flooding in the catchment. The analysis is based on setup and simulation with the MOUSE model from DHI Water & Environment, but similar models such as SWMM or InfoWorks could most certainly have been applied with the same results.

This study is carried out on the basis of the Danish Frejlev catchment where several investigations have already been completed, e.g. Schaarup-Jensen et al. (1998), Schaarup-Jensen et al. (2005), Schaarup-Jensen & Rasmussen (2004), Thorndahl et al. (2006) and Thorndahl and Willems (2006). Frejlev is a small town of approx. 2000 inhabitants, 7 km southwest of Aalborg, Denmark. The partly combined and partly separated drainage system, is equipped with two high resolution electromagnetic flow-meters (Schaarup-Jensen et al. 1998), which constantly measure the runoff from the catchment of approx. 80 hectares. Within a range of 5 km three automatic tipping-bucket rain gauges are located in and close to the town.

2 METHODS

For clarity reasons, it is preferable to divide the surface runoff into hydrological surface processes and hydrodynamic surface flow (or routing) processes, since the former causes zero-order errors (i.e. volume errors), and the latter causes first- and second-order errors (i.e. errors in the temporal flow variations). In addition, it is important when calibrating a model, initially to calibrate in order to minimize zero-order errors, and secondly, if possible, to calibrate to minimize first- and second-order errors.

The runoff volume from an urban catchment is calculated applying the total precipitation minus the hydrological losses such as evaporation, wetting, filling of terrain depressions and infiltration to soil. In MOUSE this calculation can be implemented using two different methods (complexities):

1. The runoff volume is calculated using a constant reduction of the precipitation on the impervious and semipervious surfaces deducted the initial loss (wetting loss and filling of terrain depressions).
2. The runoff volume is determined by calculation of the individual losses on the impervious, semipervious, and pervious surfaces, specifying wetting loss, filling of terrain depressions and infiltration rates (the latter on the semi pervious and pervious surfaces only)

The temporal flow variation on the surface is based on a calculation of the time from the precipitation hits the surface till it reaches the main drainage pipe. In MOUSE this is implemented by three different approaches (complexities):

a. A time-area method, in which a constant concentration time on the surface is applied
b. A kinematic wave approach, in which the velocity on the surface is calculated, depending on the water depth, by a non-linear reservoir model
c. A linear reservoir model, in which the velocity on the surface is calculated, depending on the water depth, using a linear approach.

It is not possible, in MOUSE, to join the hydrological and hydrodynamic processes arbitrarily; therefore the hydrological approach no. 1 must be combined with the hydrodynamic approach a and c, in the following labelled the time-area model (SRM A) and the linear reservoir model (SRM C) respectively. The hydrological approach no. 2 must be combined with the hydrodynamic approach b, in the following labelled the kinematic wave model (SRM B). An example of the three different hydrographs is shown in Figure 1.

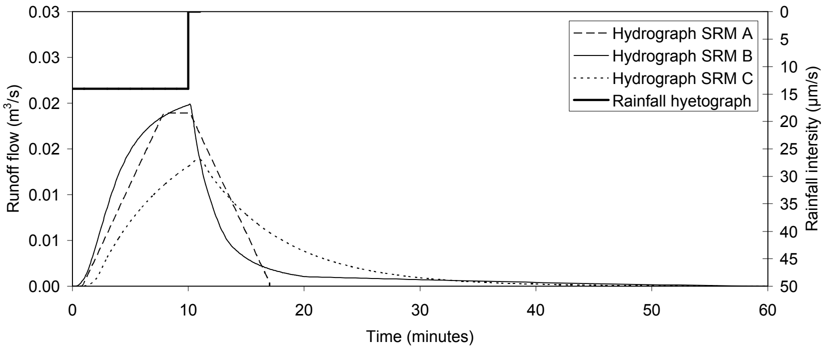

Figure 1 Hyetograph for a 10 min. uniform rainfall event with a constant intensity of 14 µm/s and examples of hydrographs for the three different surface runoff models with default parameters.

2.1 Time-Area model (A)

The time-area SRM is based on the well-known time-area method which includes only the impervious and semipervious parts of the catchment in the calculation. The hydrological part of the model is controlled by two parameters; the hydrological reduction factor which defines the percentage of the impervious and semipervious area contributing to the surface flow as a result of infiltration and evaporation losses, and the initial loss (mm), which is defined as the rainfall depth loss due to wetting and filling of terrain depressions. The technical literature recommends a hydrological reduction factor of 0.7-0.9, and an initial loss of 0.5-1.0 mm. However, recent measurements from various small urban catchments in Denmark show remarkable smaller reduction factors of 0.4-0.6. (Thorndahl et al. 2006)

In the hydrodynamic SRM, a constant concentration time is assessed to every sub catchment, in order to calculate the runoff hydrograph. Assuming a rectangular sub catchment the runoff is computed proportional to the contributing area. Most often the concentration time is assessed globally, i.e. the same value for every sub catchment is used independent of the size of the sub catchment. It is difficult to specify a standard value of the concentration time as the parameter indeed depend on local conditions; however Winther et al. (2006) and DHI (2004) specify the concentration time to 5-7 minutes for small Danish urban catchments.

2.2 Kinematic wave model (B)

In the kinematic wave model, the catchment is divided into five different surface types - two impervious surfaces, a semipervious surface and two pervious surfaces - each defined as a percentage of the total sub catchment area. The two impervious surfaces correspond to (1) roof areas (steep areas), with no depression storage and (2) road, pavement, etc. areas (flat areas) with depression storage. From these surfaces no reduction of the rainfall volume occur (except for wetting loss and depression storage), on the contrary to the semipervious and pervious surfaces, in which the runoff volume is controlled by the infiltration to the soil. The semipervious areas cover surfaces like pavements, paved driveways, terraces, etc. and the pervious surfaces covers areas with medium and large infiltration, e.g. sandy and clayey soils. The infiltration is calculated by Hortons infiltration (Chow 1964):

$$f_{cap,i}(t) = f_{end,i} + \left(f_{start,i} - f_{end,i}\right) \cdot exp\left(-a_i \cdot t\right) \qquad (1)$$

$f_{cap,i}$ is the infiltration capacity (m/s) for one of the area types, $f_{start,i}$ and $f_{end,i}$ are start and end infiltrations (m/s) respectively, a_i is the Horton exponent and t is the time. This approach diverge from SRM A, by including a rainfall intensity dependency, i.e. when the rainfall intensity is larger than the infiltration capacity the runoff from the semipervious and pervious surfaces will contribute to the runoff. Kinematic wave models are often referred to as non linear reservoir in which the routing is calculated by a continuity equation: (2) and a momentum equation – in this case reduced to the Manning formulae (3) – (DHI 2004):

$$i_{eff,i} \cdot F_i - Q_i = F_i \cdot \frac{dy}{dt} \qquad (2) \qquad\qquad Q_i = C_{b,i} \cdot y^{\frac{5}{3}} \qquad (3)$$

$i_{eff,i}$ is the effective rainfall intensity (the total precipitation deducted the hydrological losses), F_i is the catchment area, Q_i is the discharge from the catchment and $F_i \cdot \frac{dy}{dt}$ is a storage term. $C_{b,i} = M_i \cdot b_i \sqrt{S_t}$ and $b_i = \frac{F_i}{L}$. $C_{b,i}$ is a constant, M_i is the Manning number, b_i is the catchment width, S_t is the terrain slope, and L is the catchment length. The indices *i* indicate one of the five area fractions. In Table 1 an example of default values used in SRM B is shown.

	Impervious		Semipervious	Pervious	
Parameter	Steep area	Flat area	Small inf.	Medium inf.	Large inf.
Wetting (m)	$5.0 \cdot 10^{-5}$	$5.0 \cdot 10^{-5}$	$5.0 \cdot 10^{-5}$	$5.0 \cdot 10^{-5}$	$5.0 \cdot 10^{-5}$
Storage (m)	-	$6.0 \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
Start.inf. $f_{start,i}$ (m/s)	-	-	$1.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-5}$	$1.0 \cdot 10^{-5}$
End.inf. $f_{end,i}$ (m/s)	-	-	$5.0 \cdot 10^{-7}$	$1.0 \cdot 10^{-6}$	$5.0 \cdot 10^{-6}$
Exponent a_i (s^{-1})	-	-	$1.5 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
Manning M_i ($m^{1/3}$/s)	80	70	30	30	12

Table 1 Default values in the kinematic wave model (DHI 2004)

2.3 Linear reservoir model (C)

The hydrological part of the linear reservoir model is the same as described under the time-area model (section 2.1) using the hydrological reduction factor and initial loss.

With regards to the routing, the same continuity equation (2) as in the kinematic wave approach is used. The momentum equation is linear and defined as (DHI 2004):

$$Q = C_c \cdot y \quad (4)$$

$C_c = F/T_L$. The default value of T_L is 5 minutes (DHI 2004).

3 HYDROLOGICAL CALIBRATION

3.1 Time area model (A) and linear reservoir model (C)

The time-area model is calibrated regarding runoff volumes using corresponding measurements of rainfall and runoff from the monitoring station in Frejlev, as referred in section 1. In Figure 2 a calibration based on 8 years of corresponding rain and runoff is presented. Using a linear relationship between the rain depth and the runoff depth the two parameters in hydrological model A can be derived, when assuming a spatially uniform distribution of the rain. The hydrological reduction factor corresponds to the slope of the regression line and the initial loss to the intersection with the abscissa.

This calibration is based on a definition of the contributing area as all hard surfaces, i.e. roof and road areas, as well as pavements, paved driveways, terraces etc., corresponding to impervious and semipervious areas of 40 % of the total catchment area in Frejlev. The derived hydrological reduction factor corresponds to a runoff from these surfaces of 48 %, i.e. 19 % of the total catchment area contributes to the runoff.

3.2 Kinematic wave model (B)

Due to the large number of parameters in the kinematic wave model it is almost impossible to calibrate this model using measurements of rainfall and the corresponding runoff only. On the other hand it is possible to calibrate SRM B based on a calibration of SRM A. However, applying the calibration directly will lead to an overestimation of the runoff volumes as this model does not take a hydrological reduction of the impervious area, except wetting and depression storage losses into account. Thus, it is necessary to reduce the impervious areas corresponding to the hydrological reduction factor in order to get realistic runoff volumes. The most important calibration parameters are the infiltration rates on the semipervious areas, since wetting and depression losses are of minor importance and the pervious areas rarely ever contribute to the runoff except for very high intensity rainfall events. Analysing the rain-runoff data, it was expected that a rainfall intensity dependency of the runoff could be proven, and this could defend SRM B in comparison with SRM A. However, analysing 353 rainfall events a significant dependency could not be proven. Hence it is not possible derive a threshold intensity corresponding to the infiltration capacity, in order to identify events in which the semipervious surfaces contribute to the runoff. Therefore, SRM B is calibrated against the SRM A calibration, by manually adjusting the infiltration rates on the semipervious surfaces. The calibration result regarding simulated runoff volumes in the two SRM's is shown in Figure 3. If the semipervious did not contribute to runoff, the points in Figure 3 would fit the bisector perfectly, but since some events actually contribute, as a result of the specified infiltration capacities, there is a small positive scatter.

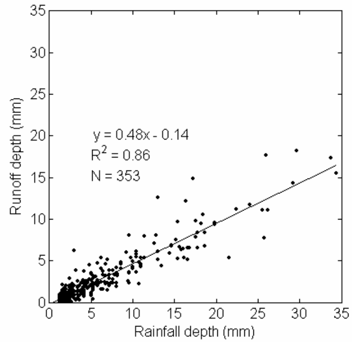

Figure 2 Calibration of the time-area model (Frejlev catchment). Hydrological reduction factor: 0.48 and initial loss: 0.3 mm.

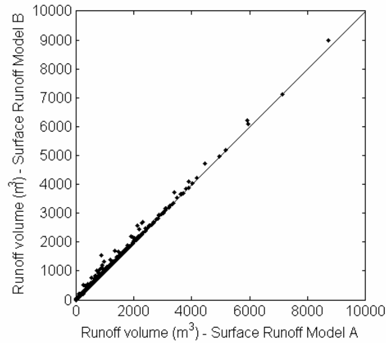

Figure 3 Results of the hydrological calibration of SRM B based on SRM A (Frejlev catchment).

4 SENSITIVITY ANALYSIS OF HYDRODYNAMIC PARAMETERS

Preferably a hydrodynamic calibration would be conducted as well as the hydrological calibration, but as the flow measurements available embrace the runoff from the whole catchment, the surface runoff parameters can not be isolated due to influence of hydrodynamic pipe flow parameters, e.g. friction and head loss. With regards to the missing hydrodynamic calibration, it is selected to carry out a sensitivity analysis of the hydrodynamic parameters in order to estimate in what way the parameter assessment influence the long term statistics of an urban drainage system. Seven long term simulations are completed for each of the three SRM's, using an 18.8 year rain series from the Svenstrup rain gauge, approx. 3 km from Frejlev. The results are compared with regards to overflow volumes, surcharge (i.e. full-running pipes), and flooding of the ground level. In SRM A, a concentration time (t_c) varying from 3 to 21 minutes is selected. In SRM B the catchment length (L) is varied from 10 to 100 m and other values are kept fixed, corresponding to the C_b-values as shown in Table 2, for a subcatchment area of 2500 m^2. The sensitivity analysis of SRM C is based on a variation of the lag time (t_L) from 1 to 18 min. corresponding to the C_c-constants shown i Table 2.

model / sim. no.	A		B		C	
	t_c (min)	T_{sur} (years)	C_b (m$^{4/3}$/s)	T_{sur} (years)	C_c (m^2/min)	T_{sur} (years)
1	3	1.8	2000	2.3	2500	4.7
2	6	3.1	1000	2.3	833	18.8
3	9	6.3	667	2.3	417	18.8
4	12	6.3	500	2.3	278	>18.8
5	15	18.8	400	2.6	208	>18.8
6	18	18.8	267	3.7	167	>18.8
7	21	18.8	200	4.7	139	>18.8

Table 2 Example of the parameters used in the sensitivity analysis and modelled return periods of surcharge in the most critical manhole (distance: 1250 m cf. Figure 5)

Results of overflow simulations are shown in Figure 4 which illustrates that varying the hydrodynamic parameters in a realistic interval have little effect on the overflow volumes. For a return period of two years the mean of each of the three SRM's yields 1468, 1491, and 1474 m^3 respectively. The difference between the smallest and the largest volumes, for the return period of two years, is calculated to 4.1, 4.8, and 9.8 % respectively. In Figure 4 the results of one simulation in which SRM A is hydrologically uncalibrated (corresponding to a standard value of the hydrological reduction factor of 0.9 and concentration time of 7 min) is also shown for comparison with the varied hydrodynamical parameters. It is obvious, regarding overflow volumes, that hydrological parameters are far more decisive than hydrodynamic parameters.

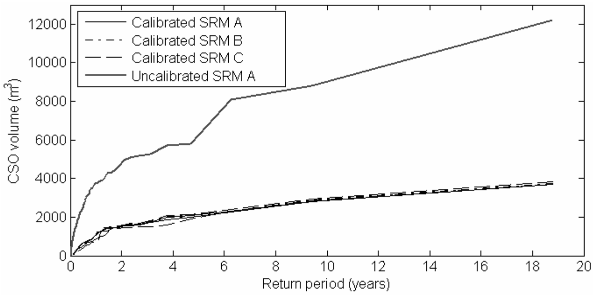

Figure 4 Long term simulations of overflow volumes from the Frejlev sewer system. For sake of clarity only the results corresponding to simulation no. 1 and 7 are shown. The gray line corresponds to the simulation with a hydrologically uncalibrated model.

It is not possible to determine any dependency between any of the SRM's and frequencies of flooding of ground level, as no flooding occurs during the 18.8 simulated years. However, the surcharge is very sensitive to variation in the hydrodynamic parameters for all three models, as illustrated on the longitudinal profile, Figure 5, and in Table 2. The return period of surcharge range from 1.8 years to 18.8 years for the most critical manhole, using model A with a concentration time of 3 and 21 minutes respectively. The same result is also verified in Thorndahl & Willems (2006).

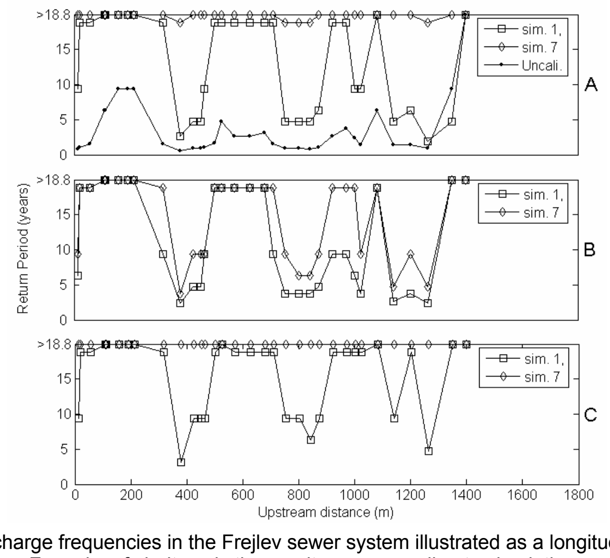

Figure 5 Surcharge frequencies in the Frejlev sewer system illustrated as a longitudinal profile of the main pipe. For sake of clarity only the results corresponding to simulation no. 1 and 7 are shown for each SRM. In addition the hydrologically uncalibrated SRM A is shown in the top plot.

5 DISCUSSION

In the present paper three different surface runoff models were compared. It was shown that simple hydrological SRM's (A and C) could be calibrated with regards to zero-order errors, using two parameters: the hydrological reduction factor and initial loss. The more complex SRM B containing eighteen parameters could be hydrologically calibrated based on the calibration of SRM A and C. Contrary to SRM A and C, SRM B includes rainfall intensity dependency in the simulation of the runoff volume, but unfortunately no intensity dependency could be detected in the corresponding rain-runoff measurements, and therefore the advantages of SRM B could not be emphasized in the hydrological calibration. In addition to this it is shown that the hydrological calibration is crucial in order to get realistic and reliable overflow volumes. With regards to the hydrodynamic routing on the surface, it is shown that each of the three SRM's can be simplified containing only one parameter each. However, since no local runoff measurements have been conducted it is not possible to assess the hydrodynamic parameters based on measurements. Thus, a sensitivity analysis of the hydrodynamic parameters is conducted in order to investigate in what way occurrence of overflow, surcharge and flooding depend on the assessment of the hydrodynamic parameters. It is shown that the overflow volumes are practically independent on both choice of surface runoff model and parameter values. However the conclusion is opposite when surcharge and flooding are investigated. A remarkable change in surcharge frequencies with regards to choice of hydrodynamic parameters is shown, and the same is expected with regards to occurrences of flooding. Unfortunately no flooding occurs within the relatively short simulated period. As the SRM's are hydrodynamically uncalibrated it is not possible to determine if one model simulate the runoff hydrograph from the individual subcatchments more accurately, than the other. With regards to all three SRM's it is obvious that the shorter the transport time on the surface, the larger the peak flow in the drainage system and thus the smaller the return period of surcharge (-or flooding). With the aim of applying more accurate model simulations, the recommendation is to calibrate both runoff volumes as well as the temporal variations in the runoff flow. With regards to the latter, there is a need for further research in the runoff from local sub catchments and in the estimation of the local hydrodynamic parameters.

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