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A simplified methodology for flood simulation in urban catchments

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Abstract: A simplified methodology for urban flooding simulation is proposed, combining the use of detailed, physically-based hydrodynamic models and the Unit Hydrograph theory. The methodology comprises the following steps: a) Unit Hydrograph derivation using a two-dimensional, physically-based detailed model; b) calculation of the losses in order to determine the effective rainfall depth; c) flood event simulation using the principle of the superposition. In this study, the above methodology is implemented in a, small urban catchment located in the city of Athens (Greece). The model used for the first step is FLOW-R2D. For the second step, the well-known SWMM software is used in order to determine losses, which comprise, runoff to the sewers of the system, initial abstraction, surface ponding, and, of less significance, infiltration. In order to derive a magnitude of the uncertainty of the results of the proposed method, an ensemble of 100 Unit Hydrographs is derived. The parameters which were modified in order to produce this ensemble were the Manning coefficients in the two friction zones (residential and urban open space areas). For the sampling, the Latin Hypercube technique was adopted. It is found that although the uncertainties to the derived results has to be taken into account, the proposed methodology can be a fast and efficient way to cope with the dynamic flood simulation in an urban catchment.

Key words: urban flooding, FLOW-R2D model, SWMM software, unit hydrograph

1. INTRODUCTION

The urban hydrology is of great importance (Jha et al., 2012), as the risk for people and properties from flooding is high (Tsakiris, 2013; Pistrika et al., 2014), and is increasing over the last few decades. Although there is a significant progress in the field of rural hydrology, urban hydrology modelling is still characterised by many weaknesses, due to the complexity of the urban environment, the number of the processes involved in the urban water cycle, and because phenomena are highly influenced by the dynamics and the spatial variability of the rainfall event.

The methodology presented herein is based on a previous work by Bellos and Tsakiris (2016), in which a physically-based hydrodynamic model was used coupled with the hydrological Unit Hydrograph theory, in an attempt to simulate the runoff of a real flash flood event in a rural catchment. Although the catchment was located in the north suburbs of Athens and its major part was rural, it still had a significant built-up area. In the present study, this methodology is extended in order to be implemented at the urban scale.

2. MATERIALS AND METHODS

The methodology consists of the following steps: a) Unit Hydrograph derivation using a detailed numerical model based on the full form of the two-dimensional Shallow Water Equations (2D-SWE); b) calculation of the losses in order to define the effective rainfall depth; c) flood simulation using the principle of superposition.

The losses in the rural scale are mainly dominated by infiltration. However, in the urban scale, the losses are mainly due to the runoff diverted in the sewers of the system, and the initial abstraction (interception, ponding and wet surface), and to a lesser degree due to the infiltration phenomenon.

The numerical model used in Unit Hydrograph derivation is the FLOW-R2D model (Tsakiris and Bellos, 2014), whereas for losses SWMM (Rossman, 2010) is used.

2.1 FLOW-R2D model

The FLOW-R2D is an in-house numerical model, which solves the 2D-SWE using the Finite Difference Method through a modification of the McCormack numerical scheme. FLOW-R2D has been applied in the urban environment (Bellos and Tsakiris, 2015a) and in several case studies (Bellos and Tsakiris, 2015b; Papadaki et al., 2016).

2.2 SWMM software

EPASWMM5 is a fully dynamic rainfall-runoff simulation model, employing in hydraulic computations the momentum, mass and energy conservation laws (Rossman, 2010). SWMM was primarily developed for urban areas and can be used in the design, analysis and planning of drainage systems, and in simulation of runoff quality (e.g., Zhu et al., 2016; El-Sharif and Hansen, 2001; Hsu et al., 2000; Tsihrintzis and Hamid, 1998).

2.3 Case Study Description and Application

The case study consists of a small urban catchment located in the centre of Athens (Greece), in a neighbourhood called Kypseli. The area is highly populated and characterised by dense urban development (multi-story buildings and generally limited open space). However, in the specific, drainage area, there exist some open spaces due to the existence of hills at the upper part of the drainage area. Figure 1 presents a satellite view of the urban catchment and the location of the urban open space. It should be mentioned that this is one of the few Greek areas in which a combined sewer system is still in operation.

Figure 1. Catchment boundaries of the case-study and location of the open urban space (National Cadastre & Mapping Agency of Greece, www.ktimatologio.gr).

Based on the combined drainage network characteristics and the hydrologic and hydraulic conditions, the area in SWMM was delineated into 7 subcatchments. The network consists of 26 nodes and 25 combined sewers, with a total length of about 1.1 km. The sewer network comprises both egg-shaped conduits (with characteristic depths ranging from 0.90 m to 1.20 m), or circular pipes with diameter of 0.40 m.

3.RESULTS AND DISCUSSION

3.1 Unit hydrograph derivation using FLOW-R2D

Due to the fact that the computational domain is a built-up area, the dominant element of the simulation is the way in which the buildings are represented. There are several ways for representing the buildings in the relative literature (e.g., Abderrezzak et al., 2008; Bellos, 2012). In the specific study, due to the fact that the Digital Terrain Model (DTM) is relatively coarse, in order to represent the complexity of the city infrastructure, the computational domain was classified in two friction zones: a) the residential area; and b) the urban open space.

In order to have a magnitude of the uncertainties of the proposed method, one hundred (100) Unit Hydrographs were derived using different combinations of Manning coefficients for the two friction zones. The sampling was made using the Latin Hypercube Sampling technique, assuming that the Manning coefficient in the main urban area ranges from 0.02 to 0.05 s/m$^{1/3}$, whereas in the forest area it ranges from 0.03 to 0.08 s/m$^{1/3}$. Regarding the input data, the DTM consisted of a grid with a resolution of 5 x 5 m. 10-min Unit Hydrographs were derived, hence the input rainfall had an intensity of 1.67 mm/h. Regarding the required parameters, based on passed experience (Bellos and Tsakiris, 2016), the time step was determined as Δt=0.001 s, the threshold which distinguishes the wet and dry cells as h_{dry}=0.0001 m and the diffusion factor as ω=0.99.

For mass conservation purposes, each of the derived Unit Hydrographs is multiplied by a correction factor which is determined dividing the volume of the water entered in the computational domain through rainfall by the volume of the water of the Unit Hydrograph (Bellos and Tsakiris, 2016).

It should be mentioned that the derivation of each Unit Hydrograph required about one day of computational budget. The derivation of 100 Unit Hydrographs would be very difficult unless a High Performance Computing (HPC) platform was used. In this work, the HPC platform of the Computational Centre of the National Technical University of Athens was used, which consists of a cluster with 24 cores.

3.2 Effective rainfall calculation using SWMM

The calculation of losses is performed using the SWMM software. The various required parameters of the model are calibrated against observed data recorded in the urban drainage system. The observed data are obtained from a storm event which occurred on the 24th of February, 2006 (Antonaropoulos and Associates, 2006). The following parameters were used in a manual calibration: the width of the subcatchments, the percentage of the impervious area in each subcatchment of the system, the Manning coefficients, the initial abstraction depths of the pervious and impervious areas, and the Manning coefficient on the sewer system. Table 1 presents the calibrated values of these parameters. The range of these parameters refers to the 7 subcatchments, in which the drainage area is divided. In Figure 2, the comparison between the simulation results derived by the SWMM and the measured data is shown. A good comparison is shown in terms of magnitude of peak, and general shape of the predicted hydrograph.

Due to the fact that during this event no flooding is observed on the surface of the catchment, a 6 h-duration synthetic storm was generated in order to test the proposed methodology. The hypothetical storm comprises two parts: a first part in which the rainfall intensity is low, called Event 1, and a second part in which the rainfall intensity is high, called Event 2 (Figure 3). Figure 4 presents the losses due to the runoff diverted into the sewers of the system, the infiltration and the initial abstraction, assuming that the several required parameters of SWMM take the values derived in the calibration phase.

Table 1. Calibrated parameters for the SWMM software

Parameter	Calibration
Width (m)	82 ~ 918
Impervious area (%)	13 ~ 77
Manning coefficient of the impervious area (s/m$^{1/3}$)	0.015
Manning coefficient of the pervious area (s/m$^{1/3}$)	0.2
Initial abstraction of the impervious area (mm)	2.54
Initial abstraction of the pervious area (mm)	6.51
Manning coefficient of the sewer system (s/m$^{1/3}$)	0.013

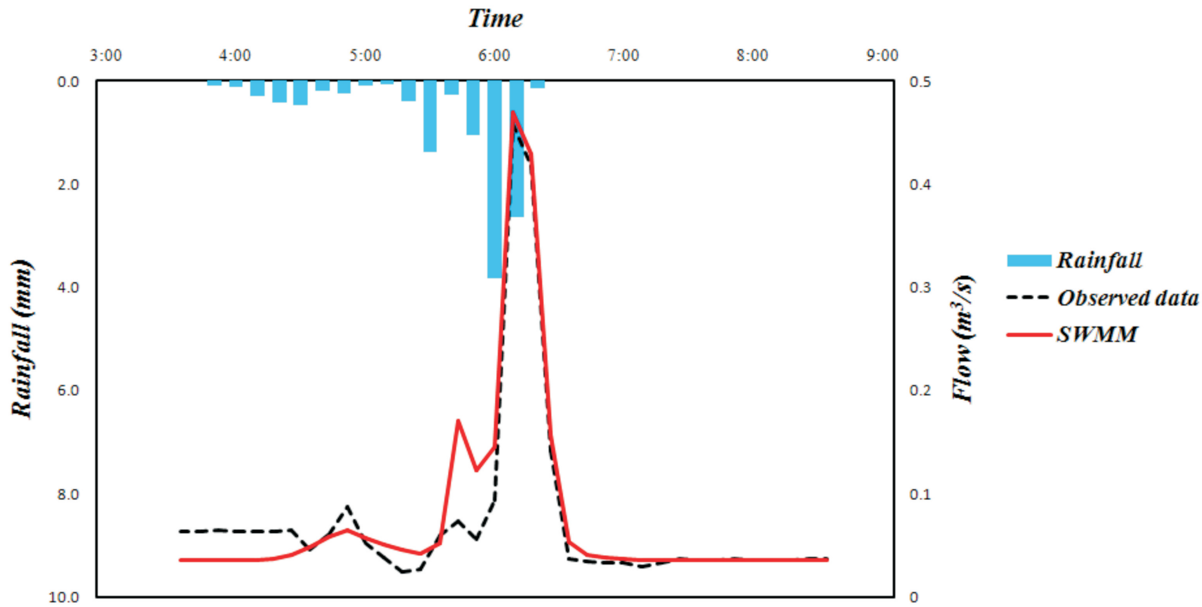

Figure 2. Comparison of measured and predicted by SWMM hydrographs during the calibration phase

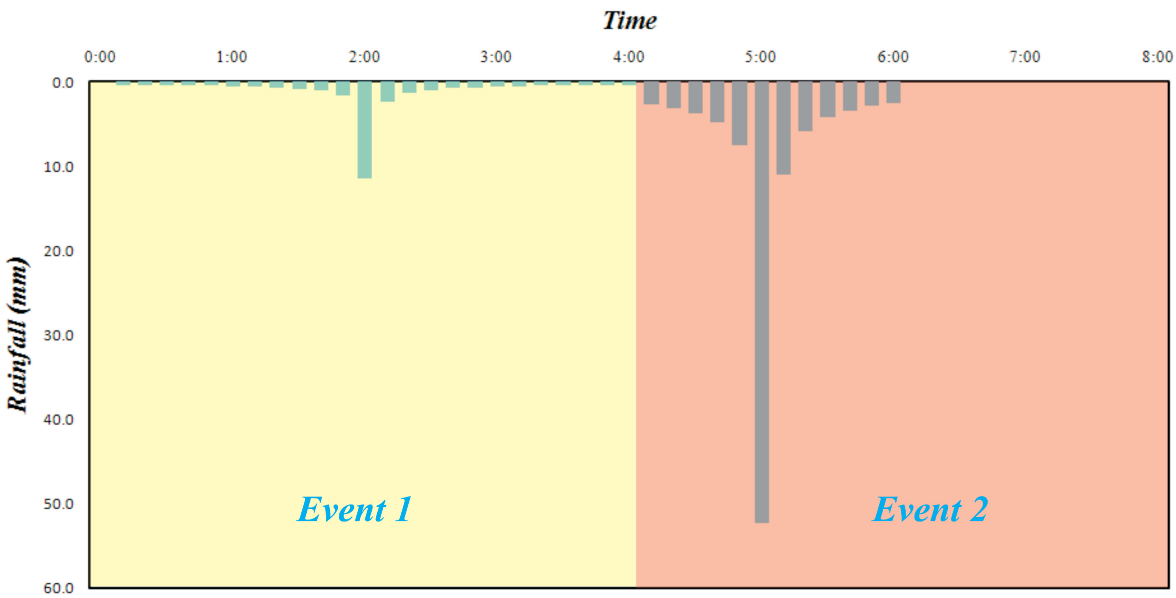

Figure 3. Hypothetical storm with two subsequent events of low and high intensity

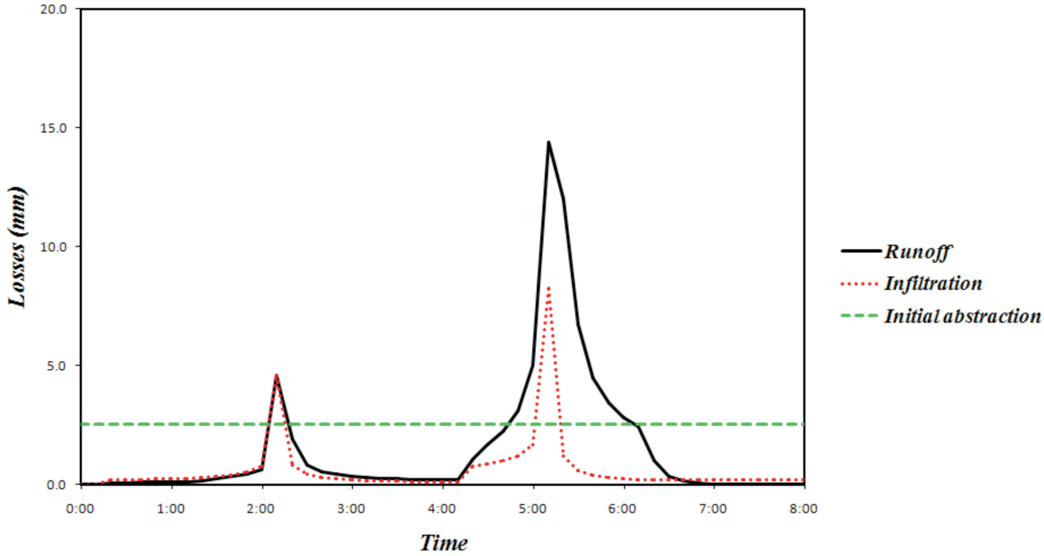

Figure 4. Predicted losses by SWMM

3.3 Flood simulation

Using the principle of superposition, an ensemble of 100 flood simulation events was derived. Figure 5 presents the band of 95% confidence of the solution, whereas Figure 6 presents the box-whisker plots of the two flood peaks of the hypothetical storm, for both Events.

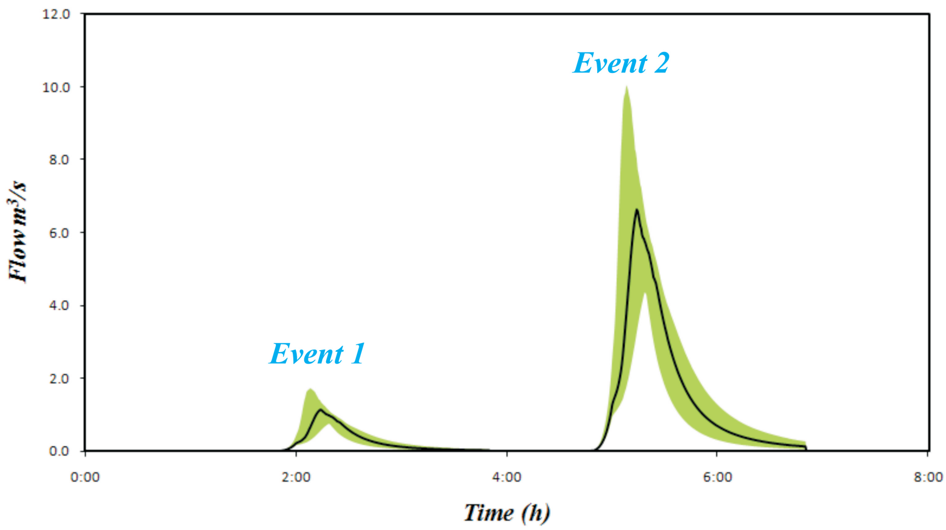

Figure 5. Uncertainty band of the urban flooding using the proposed methodology

It can be noticed (Figure 6) that as far as the peak of the flood events is concerned, significant uncertainties exist, and hence, the range of the Manning coefficients is of high importance. Besides, the uncertainty band is greater for Event 2 than Event 1. Probably this is due to the fact that the second event is characterised by more intense rainfall, and therefore, is more dynamically affected. One disadvantage of the methodology is that with the given computational power, the methodology can be implemented in relatively small catchments. However, the proposed methodology can be a useful, fast tool in the decision making process, flood warning schemes, etc., in comparison with the time consuming physically-based, 2D models, whereas it can cope with the dynamics of the flooding occurring on the catchment surface, in comparison with the typical 1D/1D urban drainage models, which consist of 1D simulation both in surface and drainage flow (Kourtis et al., 2017).

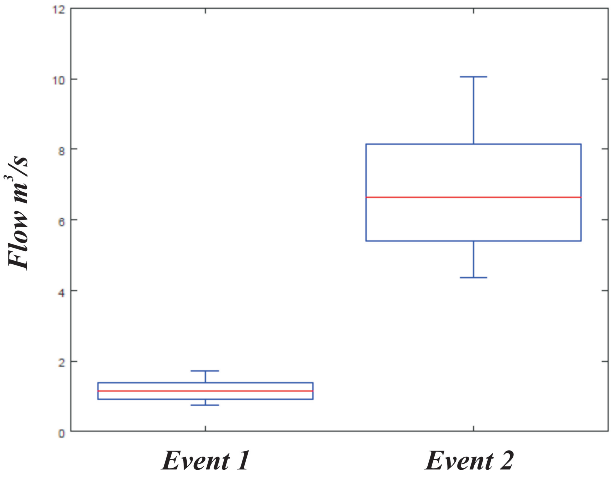

Figure 6. Box-whisker plot of the flood peaks, for the two events of the hypothetical storm

Although there are several values for the Manning coefficients in the relative literature, it is found that most times in the real world applications of these coefficients are significantly higher than those of the literature (Jarrett, 1985; Christelis et al., 2016), due to the fact that they compensate for the various energy losses occurring in real world flood events. Therefore, a careful strategy should be adopted for the selection of these values, coupling the modeller's experience and existing data, in order to either perform a calibration phase, or narrowing the range of values.

4. CONCLUSIONS

A new simplified methodology, combining physically-based hydrodynamic models and the hydrological Unit Hydrograph theory, is presented for urban flooding simulation. Uncertainties are noticed in the derived results due to the Manning coefficients, which probably are increased as the flood is more dynamically affected. Despite this fact, and adopting a more careful strategy for friction modelling, the method can simulate the dynamics of the flood on the catchment surface with a fast and efficient way, and therefore, it can be a useful tool in decision making processes.

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