

Comparison of 1D-1D and 1D-2D urban flood models

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Abstract

The present study aims to compare two different modelling approaches in the assessment of urban flooding. A real case study is used, which is a small urban catchment located in the center of Athens, Greece (Ano Patisia, Kypseli). In the first modelling approach (1D-1D), the combined sewer system and the surface system are coupled using the Storm Water Management Model (SWMM), which simulates flow both in the storm sewer system and on the surface (streets). SWMM solves the 1D Shallow Water Equations (1D-SWE) in both sewer and surface systems as a set of links and nodes. In the second modelling approach (1D-2D), the surface and sewer system are coupled using MIKE URBAN and MIKE FLOOD. The coupled model solves the 2D-SWE in the surface system and the 1D-SWE in the sewer system. The results show the importance of considering the interaction of sewer and surface system when modelling urban drainage networks. The 1D-2D coupled models can be a very useful tool in simulating flood extent and flood inundation in urban areas. The comparison provides an insight into the limitations of 1D-1D models in simulating flood extent and flood inundation, problems that can be overcome by using 1D-2D coupled models.

Keywords: Urban flooding, 1D-1D model, 1D-2D model, SWMM, MIKE URBAN-MIKE FLOOD

1. Introduction

In highly populated urban areas, floods are among the most common and catastrophic natural hazards as they affect most parts (economic, social etc.) of human life and infrastructure (Tsakiris 2013; Pistrিকা *et al.* 2014; Bellos and Tsakiris 2015). Nowadays, several pieces of software, both commercial and non-commercial, are available for the hydrologic and hydraulic simulation of the stormwater runoff quantity and quality. Many researchers have reviewed the applicability of various rainfall-runoff models for urban areas (e.g., Zoppou 2001; Elliot and Trowsdale 2007; Neelz and Pender 2009). Two of the most well-known and most used models are SWMM (Rossman 2010) and MOUSE (DHI 2016a). Conventional modelling approaches (1D and 1D-1D) are able to simulate quite accurately the drainage network. However, in cases of major rainfall events, these types of models are not able to simulate inundation depth in built-up areas and to visualize flood extent (Bisht *et al.* 2016). For the representation of

the surface flooding depth and extent, more accurate models than 1D-1D are needed, such as the 1D-2D models, which are based on the 2D-SWE and are solid tools for modelling and simulating flooding in urban areas (Leandro *et al.* 2009). This paper presents and assesses two different modeling approaches for the assessment of urban flooding in a small urban catchment located in the center of Athens, Greece (Ano Patisia, Kypseli). In the first modelling approach (1D-1D), the combined sewer system and the surface system are coupled using the Storm Water Management Model (SWMM), while in the second modelling approach (1D-2D), the surface and sewer system are coupled using MIKE URBAN and MIKE FLOOD. Due to the fact that the site is ungauged and there are no flow measurements in the pipes of the system, the simulations took place using the following Intensity Duration Frequency (IDF) curve of the area (Mimikou *et al.* 2000):

$$i = 15.39T^{(0.276)}d^{(-0.725)} \quad (1)$$

2. Materials and Methods

2.1 Case Study Area

The oldest part of the drainage network of Athens comprises a set of conduits and facilities that collect and drain the combined flow of stormwater and wastewater (combined sewers), which is divided into the following subcatchments: B, C, D, E, F, Z1, Z2, I-H, H1, H2 and Th. It covers a total area of 1310 ha and the wastewater drains in the Central Sewerage Pipeline (CSP) while the stormwater drains in Kifisos River and in the stream of Prophet Daniel. The subcatchment modeled in the present study was D (89 ha) (Fig. 1). The study area is a highly urbanized and impervious area, located in the region of Ano Patisia, Kypseli (Athens, Greece). The combined sewer network consists of 112 nodes and 79 combined sewer pipes, with a total length of about 5 km. The drainage system comprises either circular pipes (newest part of the network) with diameters ranging from 0.3 to 0.6 m, or egg-shaped pipes (oldest part of the network) with depths ranging from 0.9 to 2.4 m. The slopes of the pipes range from 0.6 to 10.8 % (with an average of 3 %). Fig. 1 presents the aerial photo of Zone D of the combined drainage system of Athens (left) and the combined sewer system, the boundary of the study area and the land uses (right) (Corine 2006).

2.2 SWMM Model

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 for the design, analysis and planning of drainage systems, and for the simulation of runoff quality (e.g., Zhu *et al.* 2016; El-Sharif and Hansen 2001; Hsu *et al.* 2000; Tsihrintzis and Hamid 1998). In our study, the Dynamic Wave (DW) model was used for the hydraulic calculations and infiltration was calculated using the Curve

Number (CN) method. The main parameters for a subcatchment in SWMM software are: (i) area (ha); (ii) width (m); (iii) slope (%); (iv) percent impervious; (v) Manning's n for pervious and impervious areas; (vi) depression storage (mm) in pervious and impervious areas. Parameters (i), (iii) and (iv) were determined using the appropriate tools in ArcGIS 10.3.1. The width of the subcatchments (parameter ii) was determined as the area divided by the average maximum length of the subcatchment (Rossman 2010). Finally, for parameters (v) and (vi), typical values from the literature were used (ASCE 1992; Rossman 2010). The model parameters and their variation ranges are shown in Table 1.

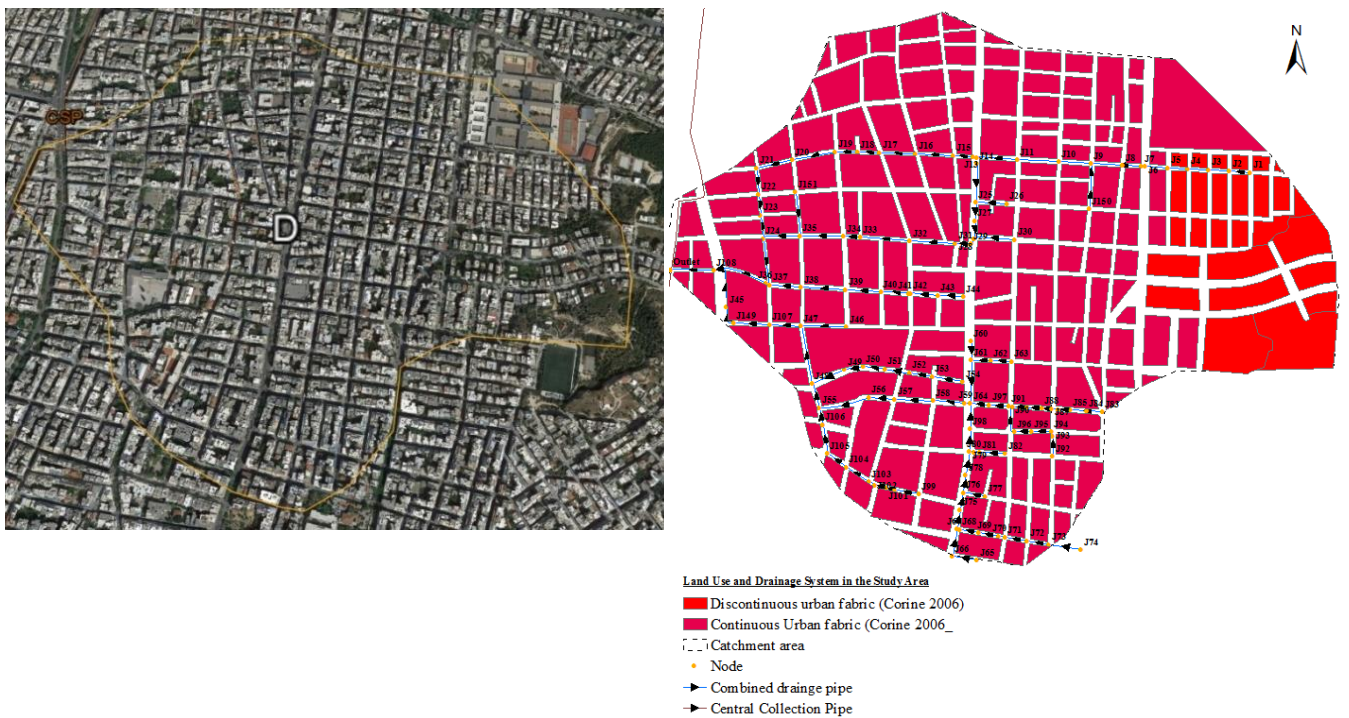


Figure 1: Aerial view of Zone D of the combined drainage network of Athens (left); Representation of the combined drainage system of subcatchment D and land uses (right) (Corine 2006)

Table 1: Key model parameters involved in this study

No.	Parameter	Description	Range	No.	Parameter	Description	Range
1	N-Imperv	Manning's N for impervious area	0.013	6	Con-Manning	Manning's N for the conduits-roads	0.013~0.014
2	N-Perv	Manning's N for pervious area	0.10	7	Slope-sub	Average percentage surface slope (%)	0.082~9.037
3	Dstore-Imperv	Depth of depression storage on impervious area (mm)	2	8	Width-sub	Subcatchments width (m)	7.93~162.77
4	Dstore-Perv	Depth of depression storage on pervious area (mm)	5.51	9	%Imperv-sub	Subcatchments percent of impervious area (%)	45~90
5	CN	Curve Number	77~94				

2.3 MIKE URBAN-MIKE FLOOD Models

MIKE URBAN is a hydraulic pipe flow model based on the MOUSE/MIKE11 engine which solves the full form of the 1D-SWE (DHI 2016a). Moreover, MIKE URBAN incorporates the SWMM engine. The main advantages of MIKE URBAN over SWMM5 are that MIKE URBAN offers GIS integration, and moreover, it offers the capability for 2D simulations for the overland flow paths through the coupling with the MIKE FLOOD software (DHI 2016a; DHI 2016b.) MIKE FLOOD is a hydrodynamic surface flow model based on the MIKE21 engine which solves the 2D-SWE in a structured grid (DHI 2016c). MIKE URBAN and MIKE FLOOD are coupled in order to cope with the interaction between the underground combined drainage system flow and the flow on the surface system spilled by the manholes of the system. The main components for an integrated 1D-2D simulation are: (i) data for the combined drainage network (e.g., subcatchments area, pipes shape, length, Manning coefficient, manhole location and ground and surface elevation etc.); (ii) Digital Elevation Model (DEM); (iii) definition of 2D model area and resolution; (iv) specification of flooding and drying depth; (v) Manning number for overland surface paths; (vi) equation for the flow exchange at the inlet between the 1D and 2D models (orifice equation, weir equation or exponential equation). In our study, for the hydrologic calculations in each subcatchment, the Kinematic Wave method was selected. The main parameters were the area of each subcatchment, the percent of imperviousness of the subcatchment and the subcatchment slope (Table 1). For the loss model, Horton's equation was the only choice and the default parameters were used for simplicity. For the exchange of flow between the 1D and the 2D models, the orifice equation was used. Finally, it should be mentioned that the 2D model is based on a 5x5m grid square-shaped cell, obtained from the same DEM.

3. Results and Discussion

3.1 1D-1D vs 1D-2D Model

Due to the fact that the site is ungauged, simulations in both models (1D-1D and 1D-2D) took place using the IDF curve presented in Eq. (1). The simulations, took place for two synthetic design storms of 1-hour duration and for return periods of 10 (29.06 mm) and 25 years (37.42 mm). The rainfall distributions for the synthetic design storms were developed using the Alternating Block Method (USBR, 1977). The most representative results for both models (1D-1D and 1D-2D) are reported here, which include runoff produced from the subcatchments (hydrologic model), flow in combined sewers, flow in the overland surface system (only for the 1D-1D model) and the extent of flood inundation (only for the 1D-2D model). Fig. 2 shows the runoff produced from one subcatchment of the system (hydrologic model), for return periods of 10 and 25 years and for duration of 1 h, for the 1D-1D and the 1D-2D models. As it can be observed, runoff predicted from the two models (Fig. 2) is in good agreement. The time of peak and the peak runoff are comparable, while the runoff volumes produced from the subcatchment differ

only slightly. The runoff calculated with the 1D-1D was 2.3 m³ and 4.0 m³, while the volume calculated with the 1D-2D model was 3.2 m³ and 4.1 m³, for return periods of 10 and 25 years, respectively, and for storm duration of 1 h. Fig. 3 presents the flow in a combined sewer of the drainage network (1D-1D and 1D-2D model) for return periods of 10 and 25 years and for storm duration of 1 h. The flow in the sewers simulated by the two models show differences. This is probably because the 1D-1D model uses for the hydraulic computations the SWMM engine, whereas the 1D-2D model uses the MIKE11 engine. Moreover, overflow from the manholes of the system is simulated with the orifice equation in the 1D-2D model, whereas in the 1D-1D model any flow in excess of the sewer pipe capacity is automatically diverted to the open surface system (Gironás *et al.* 2009). In Fig. 4, one can see the flow in the overland surface system (roads), simulated with the 1D-1D model, for return period of 10 and 25 years and storm duration of 1 h. The sewer system is surcharged and the water level is high enough to cause water to flow out from the drainage system to the overland surface system (roads). Water flow at the downstream end of the surface system is zero. This is not the case, but an artifact of the way that SWMM5 model draws the water surface profile within an open channel (Gironás *et al.* 2009). Regarding the flood-inundation maps, only those obtained from the 1D-2D model are presented in Fig. 5. It is possible to obtain flood-inundation maps from the 1D-1D model (Zhu *et al.* 2016), but according to Mark *et al.* (2004) and Leandro *et al.* (2009) the above procedure is considered inaccurate. The simulations of the 1D-1D model showed a maximum depth of water in the surface network about 0.10 m and 0.13 m, maximum velocity about 3.1 m/s and 4.1 m/s and a maximum flux of about 1.3 m³/s and 2.7 m³/s, for return periods of 10 and 25 years and for duration of 1 h, respectively. On the other hand, with the 1D-2D model the mean maximum depth of water, in the surface network, was about 0.17 m and 0.19 m, the mean maximum velocity was about 0.43 m/s and 0.60 m/s and the mean maximum flux was about 0.07 m³/s/m and 0.11 m³/s/m, for return periods of 10 and 25 years, respectively, and for duration of 1 h. The maps are obtained from the 1D-2D model and present only water depths in excess of 0.1 m. Differences between the two models are reasonable. Model structure differences include: (i) regarding computer time, on a CPU Intel Core i5-3210M 2.50Ghz and 6 GB RAM, the 1D-2D model takes about 4 h to run, whilst the 1D-1D model only takes about 10 s; (ii) the 1D-1D model and 1D-2D model are using different methods for the calculation of infiltration in each subcatchment; (iii) the overland flow paths in the 1D-1D model are defined by the modeler while in the 1D-2D model the overland flow paths and velocities are simulated based on the inserted DEM. Based on the results, it is shown that the integrated 1D-2D model is able to give a more accurate prediction of overland flow paths and flood extent than the 1D-1D approach. The flows in the sewers of the combined drainage network predicted by the two models are not in good agreement. It can be assumed that, in case where there were flow measurements in the pipes of the system and calibration/validation of both models

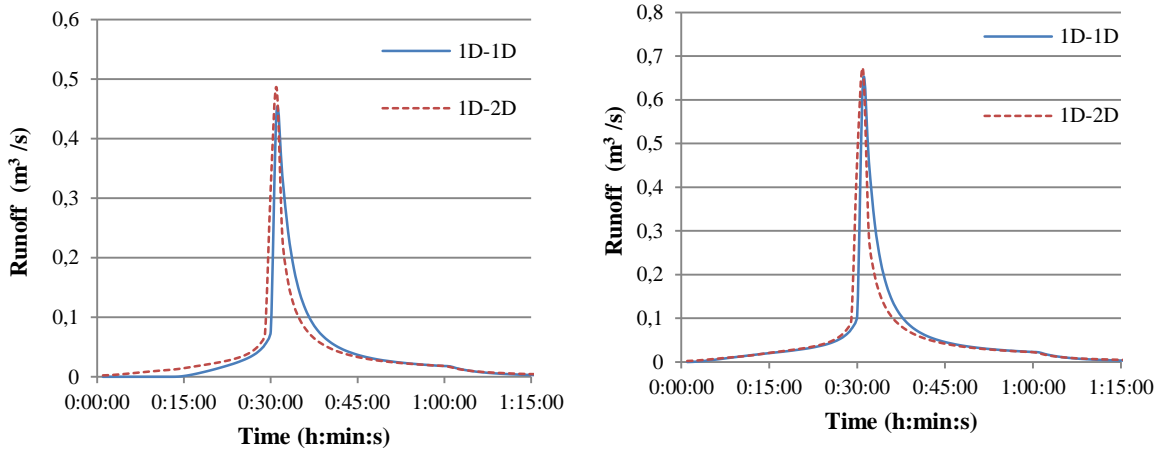


Figure 2: Predicted runoff hydrographs produced from for one subcatchment of the combined drainage network for return periods of 10 years (left) and 25 years (right) and storm duration of 1h

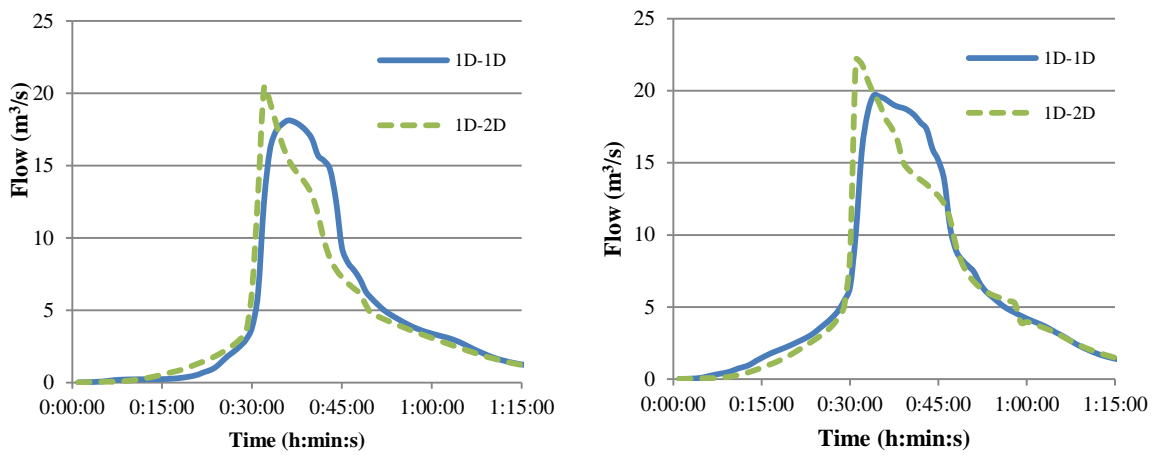
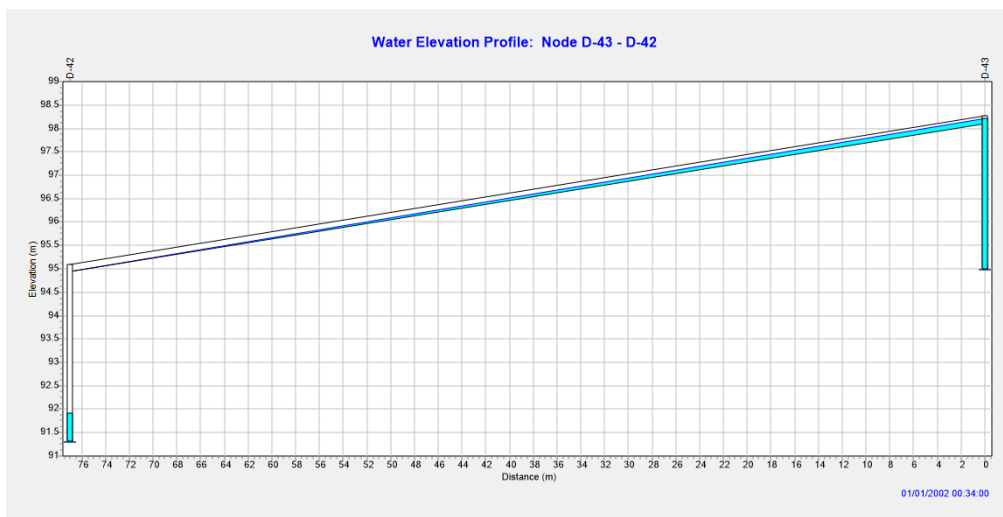


Figure 3: Predicted flow in one sewer of the combined drainage network for return periods of 10 years (left) and 25 years (right) and storm duration of 1h



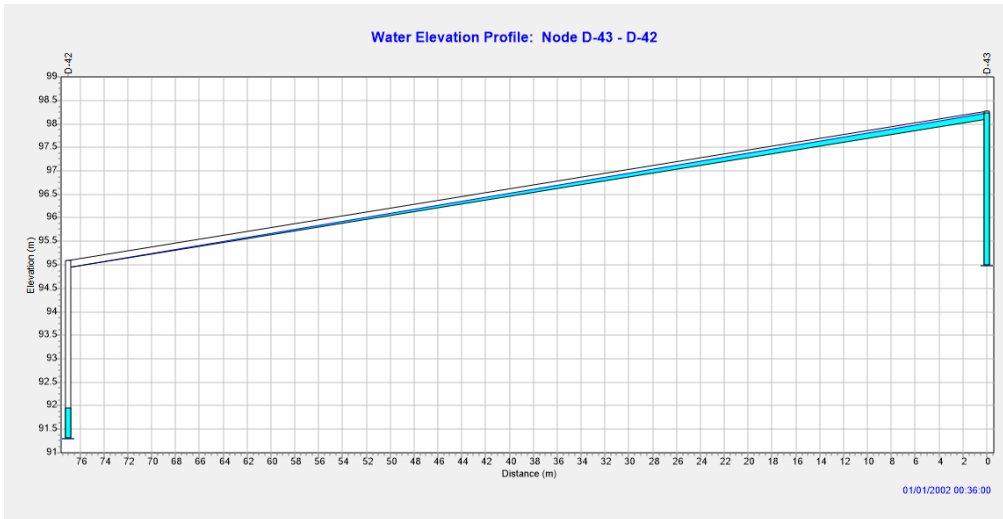


Figure 4: Predicted flow in the overland surface system (roads), simulated with the 1D-1D model, for return period of 10 (top) and 25 (bottom) years and storm duration of 1 hour

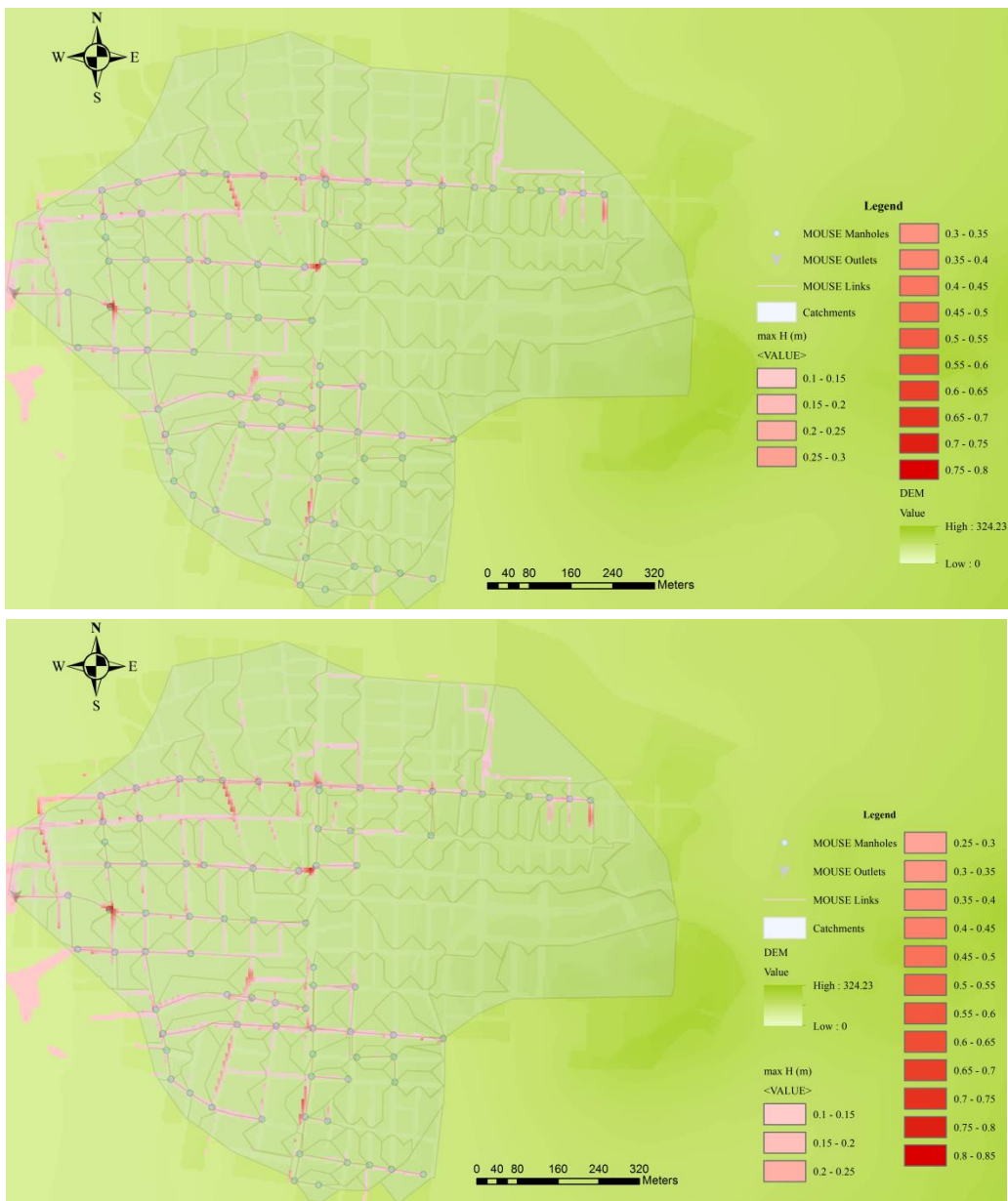


Figure 5: Flood-inundation maps for 10(top) and 25 (bottom) years return period and duration of rainfall of 1 h.

was possible, the differences would not be of that extent. Moreover, it was found that only the 1D-2D model is able to simulate flood extent and flood inundation. In the 1D-2D model, buildings are represented by increasing DEM elevation by 20 m and so the model cannot give results for water depth and flux velocities at those locations. According to Bellos and Tsakiris (2015), this approach can cause numerical errors near the buildings. Moreover, the problem with 1D-1D and 1D-2D model, mainly in urban areas, is the lack of real data, which can be overcome by calibrating a 1D-1D model with the results of a 1D-2D model (Leandro et al. 2009). But this is the case only when a model is needed in short time.

4. Conclusions and Recommendations

This paper presents the comparison of 1D-1D urban flood model (SWMM) with 1D-2D (MIKE URBAN-MIKE FLOOD) in order to demonstrate the model structure importance. The two models were used and compared for the simulation of a small urban catchment (Zone D) in Athens. The simulations took place for return periods of 10 and 25 years and 1 hour rainfall duration. The results showed that the 1D-1D model is faster than the 1D-2D model, but it cannot simulate as accurately the flood extent and flood inundation. Focusing on the 1D-2D model, some ideas can be proposed for further research. The first one is the implementation of rainfall-runoff monitoring in order to be able to calibrate and validate the model. The second one is to carry out a sensitivity analysis for the 1D-2D model. Moreover, it is proposed the experimentation, in the 1D-2D model, with different approaches for the representation of buildings.

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References

Aguado J., Arsuaga J.M., Arencibia A., Lindo M. and ASCE (1992), Design and construction of urban stormwater management systems, New York.

Bellos V. and Tsakiris G., (2015), Comparing various methods of building representation for 2D flood modelling in built-up areas, *Water Resources Management*, 29, 379-397.

Bisht D.S., Chatterjee C., Kalakoti S., Upadhyay P., Sahoo M. and Panda A., (2016), Modeling urban floods and drainage using SWMM and MIKE URBAN: a case study, *Natural Hazards*, 84(2), 749-776.

DHI (2016a), MIKE URBAN CS – MOUSE, User guide, Danish Hydraulic Institute, 430p.

DHI (2016b), MIKE URBAN Model Manager, User Guide, Danish Hydraulic Institute, 414p.

DHI (2016c), MIKE FLOOD 1D-2D Modelling, User Manual, Danish Hydraulic Institute, 150p.

Elliott A. H. and Trowsdale S. A., (2007), A review of models for low impact urban stormwater drainage, *Environmental Modelling and Software*, 22, 394–405.

El-Sharif A. and Hansen D., (2001), Application of SWMM to the flooding problem in Truro, Nova Scotia, *Canadian Water Resources Journal*, 26(4), 439-459.

Gironás J., Roesner L.A., Davis J. and Rossman L.A. (2009), *Storm Water Management Model Applications Manual*. Cincinnati, OH: National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency, 180p.

Hsu M.H., Chen S.H. and Chang T.J., (2000), Inundation simulation for urban drainage basin with storm sewer system, *Journal of Hydrology*, 234(1), 21-37.

Leandro J., Djordjević S., Chen A.S. and Savić D.A., (2009), Comparison of 1D/1D and 1D/2D coupled (sewer/surface) hydraulic models for urban flood simulation, *Journal of Hydraulic Engineering*, 135(6), 495-504.

Mark O., Weesakul S., Apirumanekul C., Aroonnet S. B. and Djordjevic S. (2004), Potential and limitations of 1D modelling of urban flooding. *Journal of Hydrology*, 299(3-4), 284-299.

Mimikou M., Baltas E. and Varanou E., (2000), A study of extreme storm events in the Athens greater area. *The Extreme of Extremes: Extraordinary Floods, Proceedings of a symposium held at Reykjavik, Iceland, July, IAHS Publ. no. 271*.

Neelz S. and Pender G., (2009), Desktop review of 2D hydraulic modelling packages, Environmental Agency, Bristol.

Pistrika A., Tsakiris G. and Nalbantis I., (2014), Flood depth-damage functions for built environment, *Environmental Processes*, 1(4), 553-572.

Rossman L.A., (2010). Storm Water Management Model User's Manual, Version 5.0. Cincinnati, OH: National

Tsakiris G., (2013), Flood risk assessment: concepts, modelling, applications, *Natural Hazards and Earth System Sciences*, 2(1), 261–286.

Tsihrintzis V.A. and Hamid R., (1998), Runoff quality prediction from small urban catchments using SWMM, *Hydrological Processes*, 12(2), 311-329.

USBR (U.S. Bureau of Reclamation), (1977), Design of Arch Dams, U.S. Government Printing Office, Denver.

Zhu Z., Chen Z., Chen X. and He P., (2016), Approach for evaluating inundation risks in urban drainage systems, *Science of the Total Environment*, 553, 1-12.

Zoppou C., (2001), Review of urban storm water models. *Environmental Modelling and Software*, 16, 195–231.