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Modelling of a combined sewer system and evaluation of mitigation measures using SWMM

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Abstract: Pluvial flooding is often unavoidable and unexpected and can only be mitigated with the design and implementation of appropriate measures. This study presents the analysis, the modelling, the identification of deficiencies in terms of capacity, the location of areas where flooding may occur, and the design of mitigation measures of a part of the combined sewer system of Athens (Zone D, Ano Patisia, Kypseli). The developed hydrologic and hydraulic model was based on the EPA Storm Water Management Model (SWMM5) software. The alternating block method was used to develop storm hyetographs. Floods of various return periods, i.e., 2, 5, 10, 25, 50 and 100 years, were tested. The mitigation measures examined, included, the enlargement of sewer sizes and the sizing of detention ponds parallel to the network. The results indicated that in case of sewer enlargement, the drainage capacity of the combined sewer system increases by 61%, while in the case of installation of detention ponds, the peak discharge at the exit of the system reduces by 29%. Overall, it was found that SWMM is a useful and easy to apply tool in testing the adequacy of existing drainage systems and the design of mitigation measures. SWMM can be used effectively for the simulation of urban drainage systems, and by comparing existing and proposed solutions, it can be a very useful tool for testing mitigation measures even for areas where there is no flow monitoring.

Key words: combined sewer system; urban drainage; SWMM; flooding mitigation; detention ponds

1. INTRODUCTION

Urbanization is one of the main factors of flooding. Extreme flooding events occur in cities with an increasing frequency mainly due to urbanization. During the last century, the city of Athens has experienced a significant number of inundation incidents (Pistrika et al., 2014; Bathrellos et al., 2016).

In this paper, the analysis, the modelling and the identification of deficiencies in terms of capacity of the combined sewer system in Zone D (Ano Patisia, Kypseli) of Athens are presented. The Storm Water Management Model (SWMM) was implemented (Rossman, 2010). The modelling aimed to assess the capacity of this combined drainage system, to locate nodes/areas with flooding problems, and to propose measures of solving the problems. Mitigation measures modeled with SWMM included enlargement of sewer sizes and sizing of detention ponds.

2. MATERIALS AND METHODS

2.1 Case study area

The combined sewer system of Athens comprises a set of conduits and facilities that collect and drain the combined flow of stormwater and wastewater. It is divided into subcatchments, namely B, C, D, E, F, Z1, Z2, I-H, H1, H2 and Th as shown in Fig. 1. The wastewater drains in the Central

Sewerage Pipeline (CSP), while the stormwater drains in Kifisos River and in the stream of Prophet Daniel.

Figure 1. Subcatchments of the combined sewer system of Athens

The subcatchment examined was D (89 ha), which is located in the region of Ano Patisia, Kypseli (Athens, Greece). The combined sewer system is located in a highly urbanized area. The network consists of 112 nodes and 79 combined sewer pipes with a total length of 5 km. The drainage system comprises either egg-shaped pipes with depths ranging from 0.9 m to 2.4 m, or circular pipes with diameters ranging from 0.3 m to 0.6 m. In Figure 2, one can see the land use, the sewer network and the boundary of the study area.

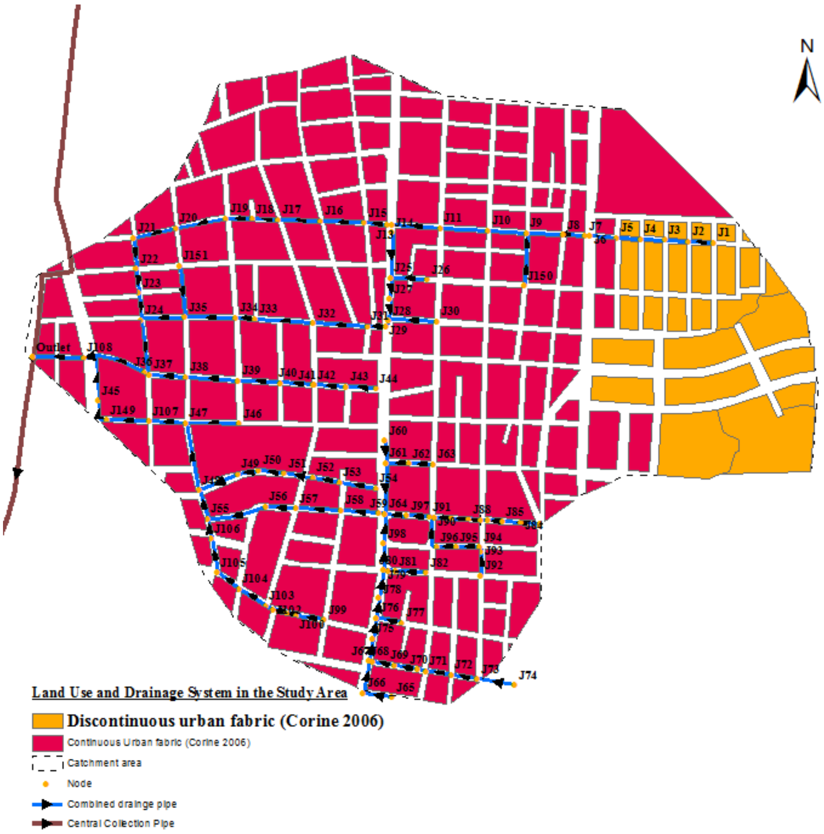

Figure 2. Land use and drainage system in the study area

2.2 SWMM model

SWMM is a fully dynamic rainfall-runoff simulation model employing in hydraulic computations the momentum, mass and energy conservation laws (Rossman, 2010). SWMM can be used in the design, analysis and planning of drainage systems, in estimating the effects of urbanization and in continuous hydrologic simulation in urban areas (e.g., Zhu et al., 2016; Salvadore et al., 2015; El-Sharif and Hansen, 2001; Park et al., 2008; Smith et al., 2005; Hsu et al., 2000; Selvalingam et al., 1987; Jang et al., 2007). Moreover, SWMM can also be used for the simulation of runoff quality in urban areas (e.g., Rossman, 2010; Tsihrintzis and Hamid, 1998; Tsihrintzis et al., 1995; Ouyang et al., 2012; Lee et al., 2010).

2.3 Mitigation measures

Conventional stormwater measures rely on construction interventions in order to collect, as quickly as possible, and transport the runoff to the receiving water bodies. Conventional measures are used mainly for controlling flood runoff events (Damodaram et al., 2010). In our study, a set of scenarios was modeled, using SWMM, to test the effectiveness of conventional measures in reducing flooding compared to the existing conditions. Scenarios included the enlargement of sewer sizes and the design of detention ponds along the sewer system.

Enlargement of sewers: The first mitigation measure examined and modeled with SWMM, was the enlargement of the sewer sizes of the system, in order to increase drainage capacity. The enlargement of the sewers size was examined in the entire drainage network to increase the capacity in order for the system to be able to carry the runoff of rainfalls with return periods up to ten years. The sizing and the simulation of the combined drainage network was carried out using SWMM software for different rainfall durations (1, 2, 3, 6, 12 and 24 h) for the 10-year return period.

Detention ponds: The next measure examined was the construction of detention ponds, at available empty parcels of lands closely located to the drainage network. Detention ponds are excavated reservoirs, which are dry during low flow periods. They provide temporary storage of stormwater runoff for peak attenuation and also, if specially designed, may offer water quality enhancement.

3. RESULTS AND DISCUSSION

Mitigation measure scenarios were simulated and compared with the existing conditions of the study area. As the site is ungauged, the existing condition scenario and the mitigation scenarios were simulated using the following IDF curve (Mimikou et al., 2000):

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

The simulation took place for six synthetic design storms of 10-year return period and durations: 1-hour (24.06 mm), 2-hours (35.16 mm), 3-hours (39.80 mm), 6-hours (47.56 mm), 12-hours (57.55 mm) and 24-hours (69.63 mm). The rainfall distributions for the synthetic design storms were developed using the Alternating Block Method (USBR, 1977).

3.1 Existing condition

The simulation of the existing condition for the six storms revealed that in two nodes the water surpassed the height of the curb and 48 pipes had a filling ratio greater than 0.8. Fig. 3 presents the rainfall and the produced hydrograph at the exit of the combined drainage system for return period of 10 years and for duration of 1 h. The peak discharge was estimated at about 18.3 m^3/s and the time of peak at 36 min. The total volume of water that the dual drainage system (sewers and roads) was not able to drain was 261 m^3. In total, 61 % of the pipes of the combined drainage system had a filling ratio greater than 0.8. However, none of those pipes belonged to the central collector pipe of the combined drainage system, so the Greek Technical Specifications (Presidential Degree 696/74) were not violated.

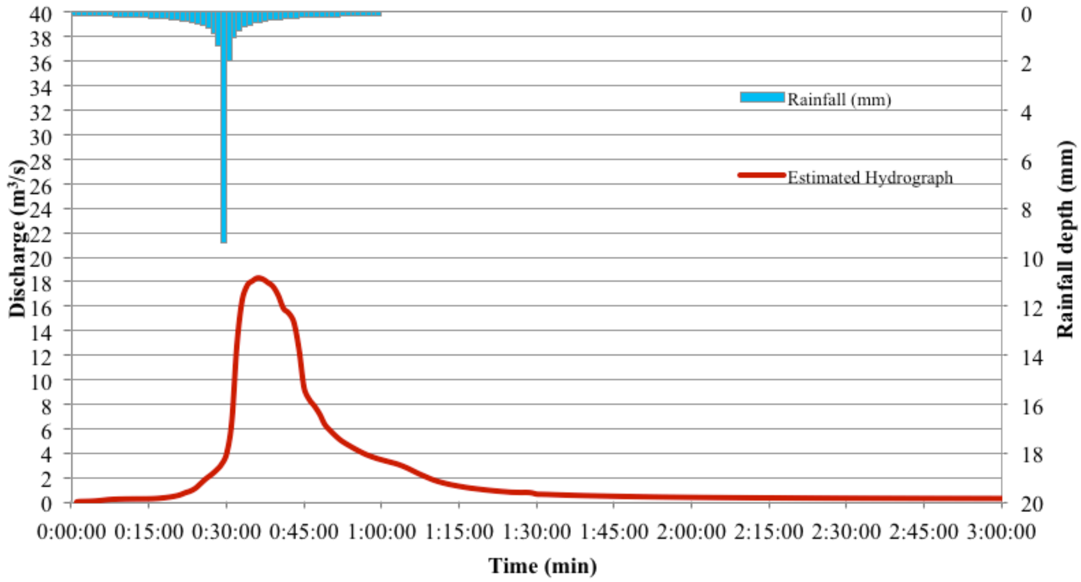

Figure 3. The 10-year, 1-hour rainfall, and the derived hydrograph at the exit of the combined sewer system under existing conditions

3.2 Scenario 1: Sewer enlargement

Under this scenario, in total, 60 of the 79 pipes of the modeled drainage system were selected for enlargement. After the enlargement, the diameter of the circular pipes ranged from 0.4 m to 1.2 m, while the height of the rectangular pipes ranged from 1.05 to 2.4 m and their width ranged from 1.2 m to 3.0 m. The sewer enlargement took place using the trial-and-error method in SWMM model. After the changes, the system was simulated and none of the pipes had a filling ratio greater than 0.8. Moreover, the major system (surface roads) did not operate. Fig. 4 presents the discharge (m^3/s) at the exit of the combined drainage system of Zone D of Athens before and after the sewer enlargement for the 10-year return period and duration of 1 h storm. It can be observed that the peak discharge increased from about 18.3 m^3/s to 29.4 m^3/s, and this is because, after the enlargement of the sewers, the combined drainage system was able to drain all the runoff produced. On the other hand, the peak time essentialy remained the same, 00:34:00 and 00:36:00, respectively. It should be noted that the peak at the exit increases; so, on one hand local flooding is resolved but, on the other hand, the impact on the downstream receiving CSP and Kifisos River should also be examined.

3.3 Scenario 2: Detention ponds

In total, 29 detention ponds were designed with depths ranging from 0.5 m to 3.0 m and volume capacities ranging from 10 m^3 to 1042 m^3. According to the results, the detention ponds reduce the peak discharge at the outlet of the combined drainage system by 29%, from about 18.3 m^3/s to 13.0 m^3/s. As a result, no node is flooding, the filling ratio of the pipes is less than 0.8 and no surface flow occurs on the major roads for return periods up to 10-years and any storm duration. Fig. 5 shows the discharge at the exit of the system for the 10-year return period and duration of 1 h storm, before and after the installation of the detention ponds. The volume of flooding was computed by SWMM at 261 m^3, for the whole study area, before the installation of the detention ponds while after the installation there was no flooding.

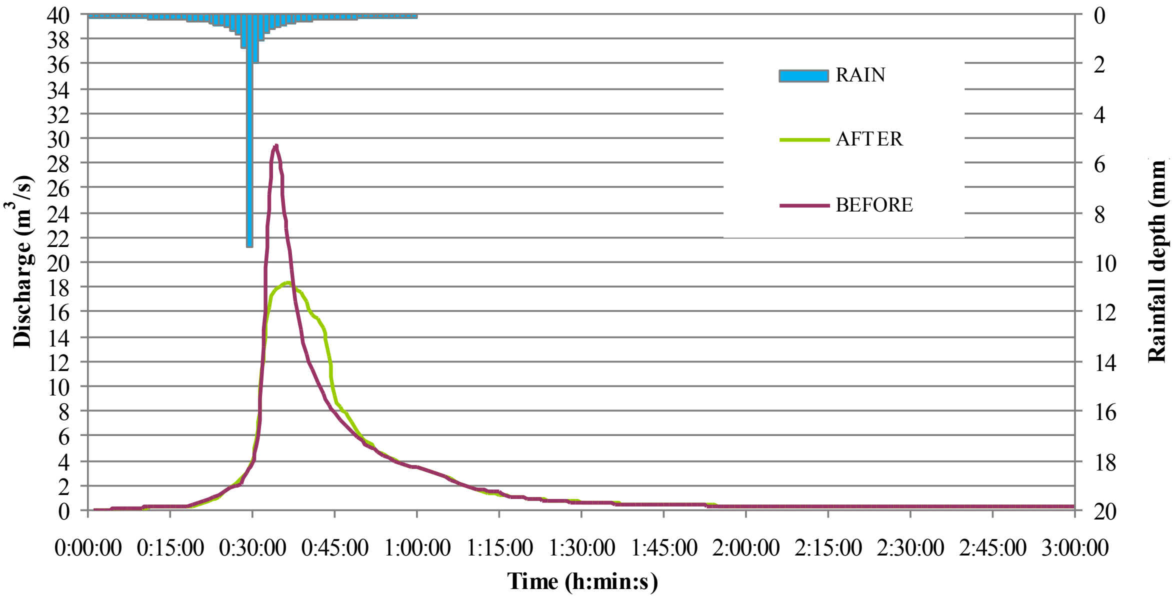

Figure 4. Detail of the hydrograph of the 10-year, 1-hour storm at the exit of the combined sewer system before and after the sewer enlargement (Scenario 1)

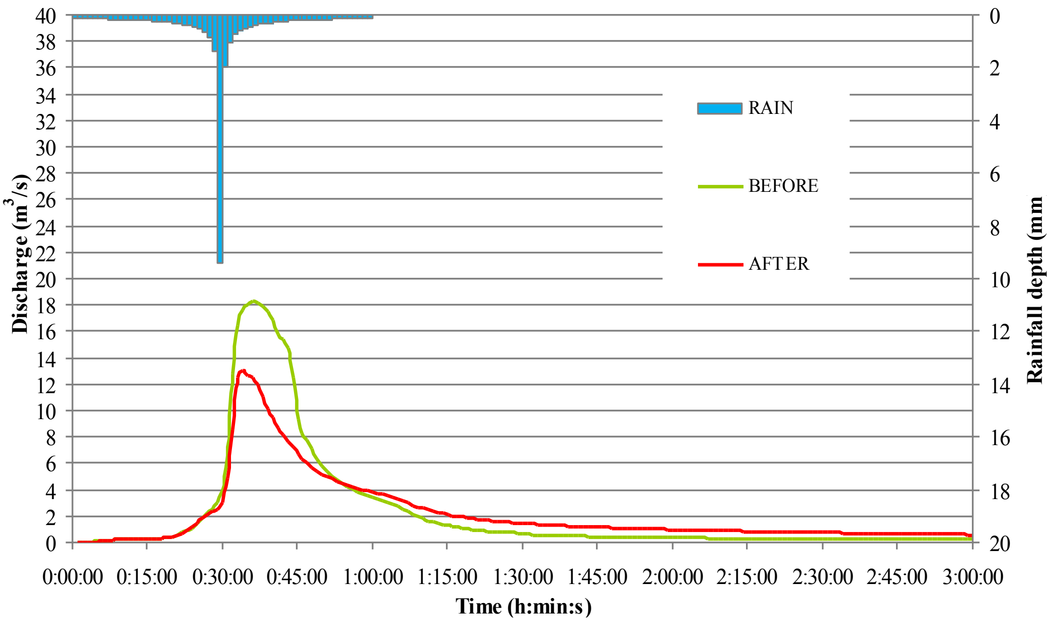

Figure 5. Detail of the hydrograph of the 10-year, 1-hour storm at the exit of the combined sewer system before and after the implementation of the detention ponds (Scenario 2)

From the model results, it is clear that in the case of sewer enlargement the drainage capacity of the combined sewer system increases by 61%, while in the case of installation of detention ponds the peak discharge at the exit of the system reduces by 29%. In the first case, 60 pipes (from 79 combined sewer pipes) must be replaced, while in the second scenario 29 detention ponds must be installed at various parts of the drainage system. For both solutions, major earthwork must be undertaken. The construction of detention ponds next to the combined sewer system is very difficult to be implemented because of the significant number required and the great cost (land acquisition, construction, etc.) and the inconvenience that this entails. Thus, it may be unrealistic. In future research, additional scenarios combining sewer enlargement and minimizing detention ponds should be tested and an optimization to minimize cost should be considered.

4. CONCLUSIONS AND RECOMMENDATIONS

This paper has presented the analysis, simulation and proposal of conventional measures for the combined drainage network of Zone D of Athens. SWMM model was selected for the hydrologic and hydraulic simulation. Overall, the SWMM is a useful and easy to apply tool in testing the adequacy of existing drainage systems and the design of mitigation measures. Moreover, SWMM can be used effectively for the simulation of pluvial flooding, and, by comparing existing and proposed solutions, it can be a very useful tool to test mitigation measures even for a region there has been no flow monitoring.

Focusing on the combined sewer system of Athens, some ideas can be proposed for further research. The first one is the analysis and the modelling of all the Zones of the combined sewer system. The second one is the implementation of rainfall runoff monitoring in major systems. Moreover, other measures could be proposed, such as Low Impact Development (LID) or Best Management Practices (BMPs), which should be examined and evaluated. Finally, it is essential to identify the best methodologies for the selection of the optimum combinations between the various mitigation measures, which would be able to achieve sustainability goals at the minimum cost.

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RERERENCES

Bathrellos G.D., Karymbalis E., Skilodimou H.D., Gaki-Papanastassiou K., Baltas E.A., 2016. Urban flood hazard assessment in the basin of Athens Metropolitan city, Greece. Environmental Earth Sciences, 75(4): 1-14

Damodaram C., Giacomoni M.H., Prakash-Khedun C., Holmes H., Ryan A., Saour W., Zechman E.M., 2010. Simulation of combined best management practices and low impact development for sustainable stormwater management. Journal of the American Water Resources Association, 46(5): 907-918

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

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

Jang S., Cho M., Yoon J., Yoon Y., Kim S., Kim G., Kim L., Aksoy H., 2007. Using SWMM as a tool for hydrologic impact assessment. Desalination, 212(1): 344-356

Lee S.B., Yoon C.G., Jung K.W., Hwang H.S., 2010. Comparative evaluation of runoff and water quality using HSPF and SWMM. Water Science and Technology, 62(6): 1401-1409

Mimikou M., Baltas E., Varanou E., 2000. A study of extreme storm events in Athens greater area. The extreme of extremes. Extraordinary Floods, Proceedings of a Symposium, Reykjavik, Iceland, July, IAHS Publ. No. 271

Ouyang W., Guo B., Hao F., Huang H., Li J., Gong Y., 2012. Modeling urban storm rainfall runoff from diverse underlying surfaces and application for control design in Beijing. Journal of Environmental Management, 113: 467-473

Park S.Y., Lee K.W., Park I.H., Ha S.R., 2008. Effect of the aggregation level of surface runoff fields and sewer network for a SWMM simulation. Desalination, 226(1): 328-337

Pistrika A., Tsakiris G., 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 Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency 276p.

Salvadore E., Bronders J., Batelaan O., 2015. Hydrological modelling of urbanized catchments: A review and future directions. Journal of Hydrology, 529: 62-81

Selvalingam S., Liong S.Y., Manoharan P.C., 1987. Use of RORB and SWMM models to an urban catchment in Singapore. Advances in Water Resources, 10(2): 78-86

Smith D., Li J., Banting D., 2005. A PCSWMM/GIS-based water balance model for the Reesor Creek watershed. Atmospheric Research, 77(1): 388-406

Tsihrintzis V. A., Hamid R., Fuentes H.R., 1995. Calibration and verification of watershed quality model SWMM in subtropical watersheds. Proceedings of the First International Conference on Water Resources Engineering, ASCE, San Antonio, Texas, August 14-18: 373-378

Tsihrintzis V.A., 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., He P., 2016. Approach for evaluating inundation risks in urban drainage systems. Science of the Total Environment, 553: 1-12