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Modelling the impact of design rainfall on the urban drainage system by Storm Water Management Model

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Abstract

Flood modelling is an effective way to manage the stormwater network in cities. It aims to understand and predict the behaviour of stormwater network so that it can test and evaluate effective solutions to structural and operational problems. So simulation modelling stays a preoccupation for building a successful hydraulic modelling in urban areas. This study investigates the impact of the design rainfall on the hydraulic modelling results for the Azzaba stormwater network located in the North-East of Algeria by using the Storm Water Management Model (SWMM). Four scenarios of design rainfall events were compared for 10, 25 and 50-year return periods, where we used double triangle and composite curves for the design rainfall event definition. The results show the impact of the choice of design rainfall on the behaviour of the stormwater network, from which the results of simulation by the double triangle method for the short durations represents a great risk on the probability that the stormwater network can overflow and flood the city, with a difference in peak discharge estimated at 62.97% and 58.94% for 2 h and 3 h events compared to the peak discharge simulated by the composite rainfall method.

Key words: *composite rainfall, double triangle rainfall, flood, hydraulic modelling, Storm Water Management Model (SWMM), stormwater network*

INTRODUCTION

Urban flooding can occur through floods of rivers or coastal floods or flash floods, whereas the cause is a lack in the design of the stormwater network. The problem of urban flooding in recent years is a major danger that has attracted the attention of many researchers in recent years [CHEN *et al.* 2015; LIU, CHENG 2014; ZHU *et al.* 2016]. Flood prevention due to heavy rainfall due to lack of adequate stormwater network has become a critical issue due to the development of urban areas and climate change [DUAN *et al.* 2016]. Floods are one of the natural disasters that affect urban areas with high population density, and cause socio-economic and infrastructural problems [BELLOS, TSAKIRIS 2015; CHEN *et al.* 2013; HOANG *et al.* 2016].

It is worth knowing that all stormwater networks are designed to a set of criteria that are subject to economic, social and environmental considerations. Stormwater networks are usually designed to meet performance criteria based on historical events that are supposed to be fixed [PECK *et al.* 2012]. Stormwater networks design may be linked to technical criteria which cannot account for any possible rainfall event. The probability to obtain extreme rainfall event for the stormwater network design is extensively related to the intensity duration frequency (IDF) relationships [NOTARO *et al.* 2015], for which the relation between the design rainfall and the hydraulic flow modelling results remains uncertain [BEZAK *et al.* 2018]. According to MAILHOT and DUCHESNE [2009], the introduction of information on extreme events climate projections, performance level and lifespan of the stormwater network

represent a process of revising the design criteria of the stormwater network design, GULBAZ, KAZEZYILMAZ-ALHAN [2012] used extreme rainfall event to detect the sensitivity of Storm Water Management Model (SWMM) parameters.

In this study SWMM is used to rainfall-runoff simulating process, and flood routing in the stormwater network. Many researchers have used SWMM model for simulating urban flooding [FRENI *et al.* 2010; GIRONAS *et al.* 2010; JIANG *et al.* 2015; ROSSMAN 2010; WALSH *et al.* 2014]. The dynamic wave routing model in SWMM is used for modelling the variations of flow in the pipes, water levels in nodes, backwater effects, and pressurized flow [ROSSMAN 2015]. ŚCIERANKA [2013] used the dynamic wave model for testing the performance of the hydraulic model, where ROSSMAN [2006] compared dynamic wave routing in both SWMM 5 and SWMM 4 for 20 sewer patterns.

Therefore, the objective of this study is to look at the relationship between the design rainfall definition, and hydraulic modelling results. For this purpose, the Azzaba urban catchment was selected as the case study. The fixed objectives are as follows: (1) to account the effect of rainfall duration on hydraulic modelling results, (2) to compare the differences between hydraulic flow modelling results as flow frequency rate, maximum flow, and total volume for the events with 10, 25 and 50-year return periods. In this work, model calibration and model verification against the observed data were not performed, because the study is based only on the qualitative analysis of the models and not on the quantitative scale.

STUDY METHODS

STUDY AREA

The study area is located in the northeastern of Algeria exactly in Azzaba city department of Skikda (36°44'48.91" to 36°45'9.15" N latitudes, and 7°6'52.10" to 7°7'48.69" E longitude) and occupying an area of 42 hectares (Fig. 1).



Fig. 1. The study area location; source: own elaboration

THE SWMM MODEL

SWMM is one of the strongest hydrological models [LOWE 2010], which consists of a dynamic model of rainfall-runoff simulation [BURGER *et al.* 2014] used to plan, analyse and design infrastructure related to rainfall-runoff, combined sewage and sanitation, and other urban drainage networks [HUBER *et al.* 2005; ZHAO *et al.* 2009]. Therewith, it may be emphasized that SWMM is a physically based discrete time simulation model that uses principles of mass conservation, energy and momentum [HUBER *et al.* 2005]. The platform consists of infiltration model, surface runoff concentration model and pipe hydraulic dynamic model, and an interface where the stormwater network can be constructed using elements such as pipes, channels, storage units, sub-catchments, etc. Static elements such as weirs and outlets, designed to reduce water levels along the system, act as barriers that reduce flow energy. Dynamic controls, such as orifices and gates, can be programmed to operate using either logical or rule-based control. In this study, the catchment is almost urbanized in its totality, and the Soil Conservation Service – curve number (SCS-CN) was the method widely used to estimate losses and direct runoff, from a given rainfall event [NRCS 2008]. Runoff that changes over time was calculated using the combined continuity equation and Manning's equation.

Two different methods were applied in order to construct the design rainfall hyetograph: namely, the composite rainfall method and the double triangle method. For modelling purposes, the Azzaba stormwater network composed of 306 underground stormwater pipes with 306 junctions connecting the 97 sub-catchments to a single outlet (Fig. 2) was used. The SCS-CN equation is used to simulate the infiltration loss from pervious surfaces in SWMM. For the flow routing computation, the dynamic wave theory is adopted.

DESIGN RAINFALL

The design rainfall intensities and depths were calculated according to the rainfall intensity-duration-frequency (IDF) equations for Montana [DEMARÉE, VAN DE VYVER 2013] from observed rainfalls of the Azzaba rainfall station from the period of 1995 to 2014.

$$i_{T,t_d} = \frac{a(T)}{(t_d + c)^b} \quad (1)$$

Where t_d is the length of the precipitation and T is the return period of the event; $a(T)$ is independent of the aggregation time so that the family of curves in T are parallel; $a(T)$ is specified by the inverse function of $a(T)$ [KOUTSYOIANIS *et al.* 1998]. The Montana IDF curve coordinates $(t_d + c)^b$ provides the shape of the IDF curves, the parameters c and b describe the dynamics of the extreme rainfall process in function of the duration t_d and are related to climate.

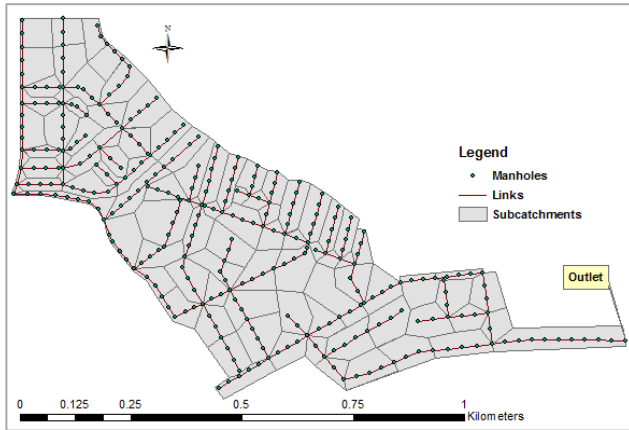


Fig. 2. The storm water management model (SWMM) configuration for the study area; source: own elaboration

Design rainfall was defined based on the composite and double triangle rainfall for duration of 2 and 3 h, consecutively. All four scenarios were conducted for rainfall with 10-, 25-, and 50-year return periods. Thus, in total, 12 different combinations were evaluated and analysed.

After designing the depth and duration of rainfall, a representative hydrograph should be selected to distribute design rainfall over time. To examine the effects of rainfall duration on hydraulic modelling results at the outlet of the catchment, 4 hyetographs were used.

Composite rainfall hyetograph

The concept of a composite rainfall pattern is closer to the reality than the uniform rainfall [MUSY 1988]. The return period of the composite precipitation method depends on the IDF curves. The basic assumption of the composite precipitation method is that the maximum intensities calculated over a given period is the same as that obtained from the IDF curves. The composite rainfall intensity is presented as following:

$$i_{\Delta t} = h_{t_1} \frac{t_d}{\Delta t} \quad (2)$$

Where: h_{t_1} = the cumulated depth of rainfall (mm); t_d = duration of the rainfall (min); Δt = a constant time step (min).

The 2- and 3-h design rainfalls (Fig. 3) calculated using the composite rainfall method for 10-, 25-, and 50-year return periods are also used to quantify the effect of rainfall duration on hydraulic modelling results. The corresponding total rainfall depths for the 2-h design rainfalls are 36.96, 42.10 and 45.99 mm for 10-, 25- and 50-year return periods, respectively. Moreover, the corresponding total rainfall depths for the 3-h design rainfalls are 40.90, 46.59 and 50.89 mm for the same return periods, respectively. Peak rainfall for three design rainfalls for the 2- and 3-h design rainfalls occurs in 60 and 80 min respectively (Fig. 3) for 10-, 25-, and 50-year return periods.

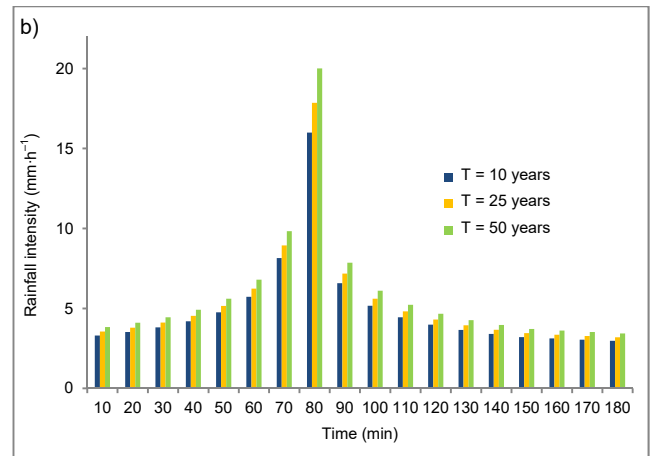
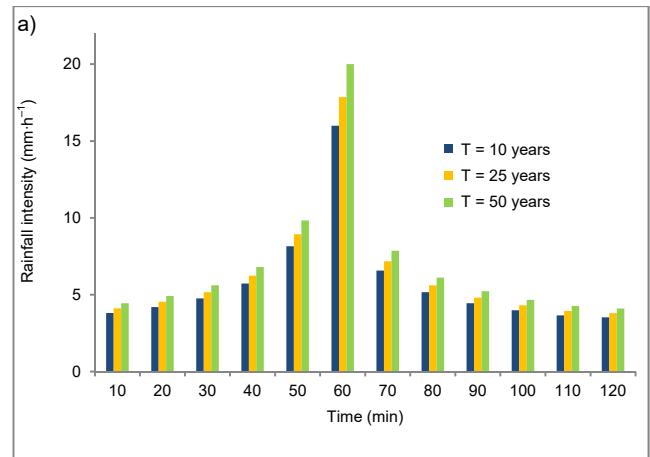


Fig. 3. Composite rainfall hyetograph: a) for 2 h, b) for 3 h; source: own elaboration

Double triangle rainfall hyetograph

The double triangle rainfall hyetograph derived from the IDF curves was proposed in this study to account for the rainfall characteristics. The distribution of the design hyetograph can be determined from an IDF curve as follows [LEE, HO 2008]:

$$i(t) = \begin{cases} (d - d_m) \frac{t}{t_1 t_2}, & 0 \leq t < t_2 \\ 4d_m \frac{t - t_1}{(t_d - 2t_1)^2}, & t_2 \leq t < \frac{t_d}{2} \\ 4d_m \frac{t_d - t_1 - t}{(t_d - 2t_1)^2}, & \frac{t_d}{2} \leq t < t_d - t_2 \\ (d - d_m) \frac{t_d - t}{t_1 t_2}, & t_d - t_2 \leq t \leq t_d \end{cases} \quad (3)$$

in which,

$$t_1 = \frac{1}{2}(t_d - t_m) \quad (4)$$

$$t_2 = t_1 + (d - d_m) \frac{t_m^2}{4t_1 d_m} \quad (5)$$

Where: $i(t)$ is the rainfall intensity at time t ; t_d is the total rainfall duration; d is the total rainfall depth for duration t_d ; t_m is the duration of the central triangular hyetograph; d_m is the rainfall depth corresponding to duration t_m . For data, t_d and t_m , the corresponding values of d and d_m can be obtained from an IDF curve for a specified return period.

The 2- and 3-h design rainfalls (Fig. 4) calculated using the double triangle method for 10-, 25-, and 50-year return periods are also used to quantify the effect of rainfall duration on hydraulic modelling results. The corresponding total rainfall depths for the 2-h design rainfalls are 36.96, 42.10 and 45.99 mm for 10-, 25- and 50-year return periods, respectively. Moreover, the corresponding total rainfall depths for the 3-h design rainfalls are 40.90, 46.59 and 50.89 mm for the same return periods, respectively. Peak rainfall for three design rainfalls for the 2- and 3-h design rainfalls occurs in 60 and 90 min respectively (Fig. 4) for 10-, 25-, and 50-year return periods.

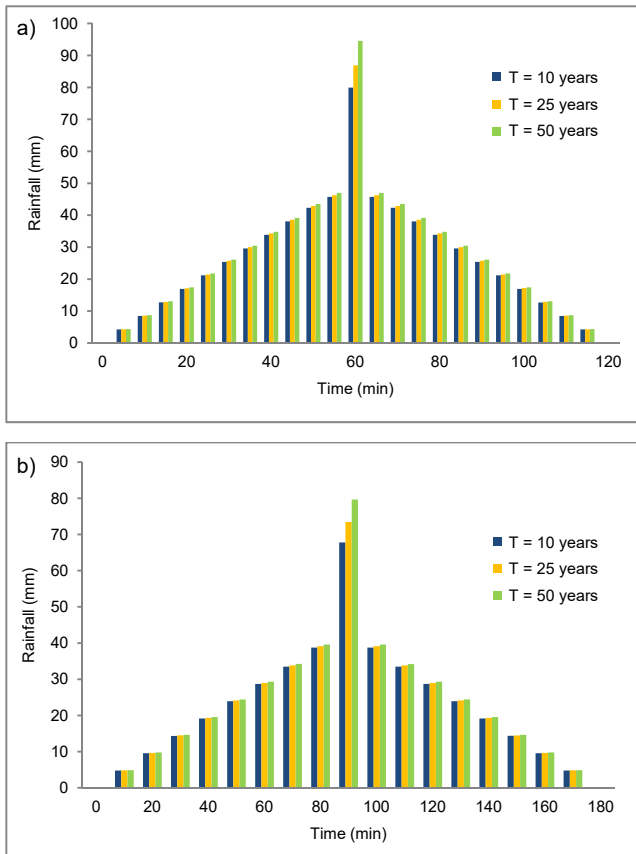


Fig. 4. Double triangle rainfall hyetograph: a) for 2 h; b) for 3 h; source: own elaboration

HYDRAULIC MODEL

Results of the hydrological modelling were used as inputs to the hydraulic model. The pipe network performance is analysed with the SWMM model software, which simulates unsteady flow in both free surfaces and pressurized conditions. The computations of the flow conditions in the network are performed by solving the complete Saint-Venant equations in several points of the pipes and manholes. The Equations (1) and (2) represent the conservation of mass and momentum, respectively.

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{6}$$

Where: Q = the discharge ($m^3 \cdot s^{-1}$), A = the cross sectional area of flow (m^2), x = the distance along the channel (m), and t = the time (h). The momentum equation is given by:

$$\frac{1}{g} \frac{\partial V}{\partial t} + \frac{V}{g} \frac{\partial V}{\partial x} + \frac{\partial h}{\partial x} + (S_f - S_0) = 0 \tag{7}$$

Where: g = acceleration due to gravity ($m \cdot s^{-2}$), V = the velocity ($m \cdot s^{-1}$), h = the depth of flow (m), S_f and S_0 = friction and bed slopes ($m \cdot m^{-1}$), respectively.

RESULTS AND DISCUSSION

In order to assess the impact of design rainfall on the results of hydraulic modelling, the following four scenarios (design rainfall events) were identified and applied as inputs in the hydrological model used to calculate hydrograph flow at outflows from individual sub-catchments.

10-year return period event. In the first step of the study, we obtained hydraulic modelling results for the 10-year return period. Cases for the selected four scenarios were computed, and the results were compared. Figure 5a illustrates a comparison among the outflow hydrographs for the applied scenarios considering the 10-year return

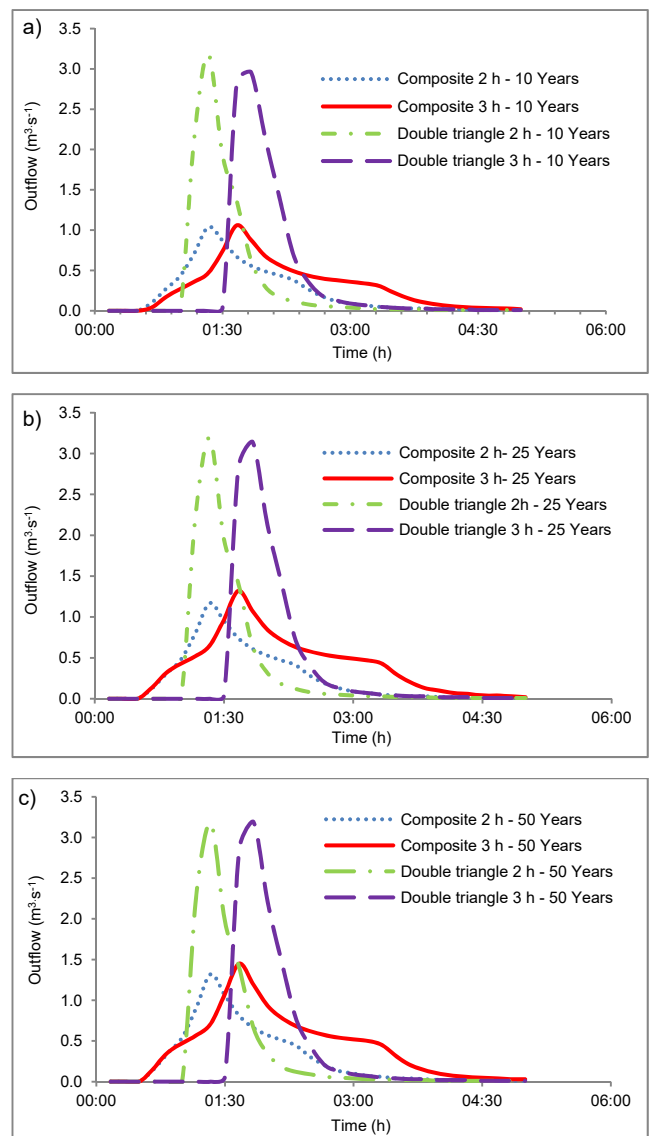


Fig. 5. Comparison of outflow hydrographs for four selected scenarios for: a) 10-year return period, b) 25-year return period, c) 50-year return period; source: own study

period. It can be seen that rainfall duration has a significant influence on the outflow hydrograph. The scenario that represents the double triangle curve with rainfall duration of 2 h yields larger peak discharge and smaller time of peak values than the scenario applying the same double triangle curve with rainfall duration of 3 h. However, the scenario that represents the composite curve with rainfall duration of 2 h yields more close peak discharge and smaller time of peak values than the scenario applying the same composite curve with rainfall duration of 3 h.

In the next step, we compared flow frequency, maximum flows, and total volume calculated from the hydraulic model simulations for the four selected scenarios for the 10-year return period (Tab. 1). The results show the impact of design rainfall with short duration on hydraulic modelling results.

Table 1. Comparison of the results of hydraulic modelling for different scenarios for the 10-, 25- and 50-year return period

Return period years	Rainfall method	Rainfall duration (h)	Flow frequency (%)	Max flow ($\text{m}^3 \cdot \text{s}^{-1}$)	Total volume (m^3)
10	double triangle rainfall	2	89.14	3.208	6 102.00
		3	87.38	2.987	6 700.00
	composite rainfall	2	94.96	1.040	4 159.00
		3	96.57	1.059	5 268.00
25	double triangle rainfall	2	89.33	3.211	6 236.00
		3	87.60	3.204	6 861.00
	composite rainfall	2	94.98	1.187	4 569.00
		3	96.25	1.340	6 967.00
50	double triangle rainfall	2	89.46	3.209	6 365.00
		3	87.79	3.210	7 017.00
	composite rainfall	2	95.00	1.338	5 035.00
		3	96.27	1.473	7 544.00

Source: own study.

25-year return period event. The simulation of the four scenarios was carried out also for the 25-year return period. Figure 5b illustrates a comparison of outflow hydrographs for the considered scenarios for the 25-year return period. In the case of the four scenarios, the peak flows were more closed, as illustrated in (Fig 5b). A comparison between flow frequency, maximum flow, and the total volume was shown in Table 1. The scenario based on the double triangle method for the 25-year return period, yields larger peak flow with duration rainfall of 2-h than the same scenario of duration rainfall of 3-h. On the other hand, the total volume of the double triangle of duration rainfall of 2h for the 25-year return period yields smaller than the same scenario of duration of 3-h. This finding reveals that the short duration rainfall for the double triangle method increase peak flow and decrease the volume. For the second method namely composite rainfall for the 25-year return period, the peak flow with duration rainfall of 2-h yields was smaller than the peak flow with duration rainfall of 3h for the same method (Tab. 1). The flow frequency rate in the case of the double triangle method indicates, that the peak flow will increase with decreasing of duration rainfall, in contrast in the case of the composite rainfall method, the results indicate that the frequency flow rate increases with the increasing of duration rainfall.

50-year return period event. Finally for 50-year return period, we have also applied all four scenarios. Figure 5c illustrates a comparison of outflow hydrographs for the considered scenarios for the 50-year return period. The scenario that represents the double triangle curve with rainfall duration of 2-h yields larger peak flow and smaller time of peak values than the same scenario applying with rainfall duration of 3-h (Tab. 1). Likewise, the maximum peak flow value was calculated for the scenario based on the double triangle curve for 25-year return period and duration rainfall of 2-h. However, the smallest peak flow was obtained for the scenario based on composite curve for 10-year return period and duration rainfall of 2-h. Thus, the larger volume value was calculated for the scenario based on the composite curve for 50-year return period and duration rainfall of 3-h. Likewise, the smallest volume was obtained for the scenario based on composite curve for 10-year return period and duration rainfall of 2-h.

The results indicate that for the same total rainfall depth and the same return periods, the rainfall duration was a major factor of the stormwater network outlet. Table 1 shows a slight variation in flow rates with double-triangle rainfall method for return periods of 10, 25 and 50 years. This slight variation is due to the overflow of some manholes of the stormwater network during the return periods 25 and 50 years, which prevents the amount of water, pushed back by the manholes to reach the outlet. LEE and HO [2008] used double triangle rainfall method for design discharge estimation and showed that the error of the estimated peak discharge was limited around 10% in the higher return period cases.

It can be seen in Figures 5a and b and Table 1 that the application of the scenario of double triangle rainfall method with rainfall duration of 2-h yields larger peak discharge and smaller time of peak values than the other scenarios. Likewise GONG *et al.* [2016] indicate that the simulated discharge at the outlet for the 2-h rainfall greater and reach higher peaks upon a time, than measures made for 3-h rainfall durations, when applying Pilgrim and Cordery rainfall method. On the contrary for the composite rainfall method, where the peak discharge with rainfall duration of 3-h represents the large value compared to the peak discharge with rainfall duration of 2-h. Same results was obtained by GONG *et al.* [2016] with application of Chicago rainfall method [KEIFER, CHU 1957].

CONCLUSIONS

This study was conducted for analysing the impact of design rainfall on the flood properties in Azzaba new city catchment using Storm Water Management Model (SWMM). Soil Conservation Service – curve number (SCS-CN) and dynamic wave routing approaches were applied to analyse losses and flow routing processes successively, whereas two design rainfalls namely double triangle rainfall and composite rainfall methods used to simulate hydrological model as input for hydraulic model. The case study of Azzaba new city showed that SWMM is well suited for urban catchments and can perform the hydraulic modelling for different rainfall events duration and differ-

ent return periods. The comparisons of the hydraulic modelling results under the design rainfall conditions highlighted that the double triangle method with the short duration and different return period increase the peak flow and decrease the total volume. In particular, extreme rainfall events due to climate change affect the performance of the stormwater network, which leads us to change future design criteria to allow the stormwater network to maintain its capacity until the end of its expected life. The novelty of this paper is a visualization of the impact of changes in inputs parameters of design rainfalls on the stormwater network model predictions.

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Modelowanie wpływu projektowanego opadu na system miejskiego drenażu z użyciem modelu zarządzania wodami burzowymi

STRESZCZENIE

Modelowanie jest skuteczną metodą zarządzania siecią kanalizacji deszczowej w miastach. Umożliwia sprawdzenie działania oraz prognozę funkcjonowania sieci kanalizacji deszczowej, testując i oceniając skuteczność przyjętych rozwiązań. Dlatego modelowanie symulacyjne stanowi wstępny etap konstruowania modeli hydraulicznych dla obszarów miejskich. W niniejszej pracy przedstawiono wpływ projektowanego opadu na wyniki modelowania hydraulicznego sieci kanalizacji deszczowej Azzaba w północno-wschodniej Algierii z zastosowaniem modelu zarządzania wodami burzowymi (SWMM). Porównano trzy scenariusze zdarzeń opadowych dla okresów powtarzalności 10, 25 i 50 lat. Kształty hietogramu opadu, opisano przy pomocy metody podwójnych trójkątów oraz krzywych syntetycznych. Stwierdzono wpływ doboru projektowanego opadu na wyniki symulacji sieci kanalizacji deszczowej. Wyniki modelowania wskazują, że w przypadku metody podwójnych trójkątów dla krótkotrwałych epizodów opadowych występuje ryzyko przepełnienia sieci kanalizacyjnej i zalania miasta. Różnica pomiędzy maksymalnymi odpływami obliczonymi dla deszczy dwu- i trzygodzinnych modelowanych metodą podwójnych trójkątów oraz metodą krzywych syntetycznych wynosiła odpowiednio 62,97% i 58,94%.

Słowa kluczowe: *metoda podwójnych trójkątów, model zarządzania wodami burzowymi, modelowanie hydrauliczne, powódź, sieć wód burzowych, złożony opad*