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DIMENSIONING OF THE SEWERAGE SYSTEM

WYMIAROWANIE KANALIZACJI DESZCZOWEJ

Abstract: The paper presents verification of selected flow time methods in terms of usability for sewerage systems design and sizing on the example of a model municipal flat drainage area of 2 km^2. Namely, the sewerage system network was sized using three methods, that is, MGN with Blaszczyk's formula, MGN with the precipitation model for Wroclaw and MWO with the precipitation model for Wroclaw, and then, the network functioning was verified for damming up on the area surface and flooding from drains using the hydrodynamic model SWMM 5.0. It was shown that the safe flow time method for sewerage system sizing is MWO using the criterion for the lack of damming up for the area and flooding from drains.

Keywords: sewer flooding, rain model, storm water management model

Introduction

The sizing of sewerage systems or combined sewerage systems in Poland presents difficulties resulting from the lack of a reliable precipitation model. The most frequently used model of Blaszczyk from 1954 lowers calculation results for rainfall intensities by 40%, which has been show on the example of precipitation measured at the IMGW meteorological station in Wroclaw in the period of 1960-2009 [1]. This affects the design of drainage areas in Poland according to the latest European standard of PN-EN 752 related to permissible frequencies of sewerage system flooding. The safe design of sewerage systems aims at ensuring a proper standard of an area drainage, which is defined as a sewerage system adaptation to take forecast precipitation water flows with a frequency equal to the permissible - socially acceptable frequencies of flooding occurrences (Table 1).

Table 1

The recommended design frequencies of rainfall and permissible
flooding occurrence frequencies according to PN-EN 752:2008

Design rainfall frequency [1 per C years]	The area drainage standard	Flooding occurrence frequency [1 per C years]
1 per 1	Out of town areas (rural)	1 per 10
1 per 2	Residential areas	1 per 20
1 per 5	City centers, service and industry area	1 per 30
1 per 10	Underground transportation facilities, underpasses, etc.	1 per 50

The application of hydrodynamic run-off models for the verification of sewerage system functioning requires a previous sizing of drainage systems by the so-called flow time methods. In such methods, the sewerage system or combined sewerage system sizing is based on a number of simplifying assumptions - constant block precipitation in a drainage basin, uniform steady flow in channels. Larger sewerage systems sized using these methods (in particular, with drainage basin areas of $F > 2$ km^2) are now recommended

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to be verified for hydraulic flow capacity based on calibrated simulation models to meet the requirements of PN-EN 752:2008.

Initial assumptions and investigation methods

Partial drainage basins of the areas of 2.25 ha were assumed and the model basin of the dimensions of 750 x 2700 m and the total area of $F = 202.5$ ha was proposed. The drainage basin consists of 90 modules - integrated partial drainage basins. It was assumed that the drainage basin for a residential area is located on a flat surface in Wroclaw. Assuming the mean weighted coefficient of surface run-off from the drainage basin $\psi = 0.25$, its reduced area amounts to $F_{zr} = 50.625$ ha. It has also been assumed that side channels being designed, to the number of 36 (Fig. 1), will have the length of 300 m each. The interceptor will have the total length of 2700 m. The channel wall coarseness is assumed at the level of $n_k = 0.013$ s/m$^{1/3}$.
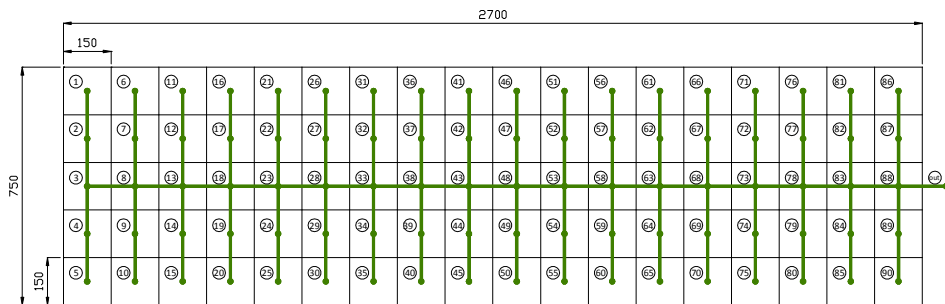

Fig. 1. The schematic diagram of the model drainage basin of the area of $F = 202.5$ ha

In SWMM 5.0, a partial drainage basins is represented with a rectangle of a set area and width (W). The stream of rainfall sewage flowing into a network design node is calculated using the model of a non-linear reservoir:

$$Q_m = W \frac{\left(d - d_p\right)^{5/3}}{n} i^{1/2}$$

where: Q_m - model run-off from a drainage basin [m^3/s]; W - hydrological width of a drainage basin [m]; d - precipitation amount [m]; d_p - surface retention height [m]; n - Manning's surface roughness coefficient [s/m$^{1/3}$]; i - mean drainage basin area slope [-].

The following has been assumed for hydrological simulations: a substitute surface slope value $i = 1\%$ a substitute roughness coefficient (for Manning's formula) for sealed drainage basin surfaces $n = 0.02$ s/m$^{1/3}$ and hydrological width of a drainage basin $W = 300$ m [2-7].

Sizing of example rainwater sewerage systems

When designing channel pits, 1.4 m has been assumed as a minimum soil covering for side channels and 1.9 m for an interceptor. Channels of a circular cross-section, arranged

with a minimum bottom slope selected from the formula $1/D$ have been used. The hydrological and hydraulic computations have been conducted for three network sizing variants (three flow time methods):

I. MGN with Blaszczyk's precipitation model.
II. MGN with the maximum precipitation model for Wroclaw.
III. MWO with the maximum precipitation model for Wroclaw.

In the MGN method used in Poland, it is assumed that the design volume flow of rainwater sewage (Q) in the channel cross-section in question occurs with a certain delay in relation to the precipitation beginning moment, by the time necessary for: terrain concentration (t_k), channel retention (t_r) and flow in the channel (t_p) - from the beginning to the design cross-section. Hence, the rainwater run-off time from the drainage basin is assumed to be equal to the dependable rainfall duration: $t_{dm} = t_k + t_r + t_p$. In any channel cross-section, the design volume flow Q [dm^3/s] is written by the following formula:

$$Q = q(t_{dm}) \cdot F_{zr} = \frac{6.631\sqrt[3]{H^2 C}}{t_{dm}^{2/3}} F_{zr}$$

where: $q(t_{dm})$ - a rainfall intensity for a dependable duration according to Blaszczyk's formula [dm^3/(s·ha)]; H - a mean annual precipitation amount: $H = 590$ mm for Wroclaw [1]; C - a design rainfall frequency [years]; F_{zr} - a reduced rainfall drainage basin area [ha].

In the MWO method used in Germany, the time of sewage flow (t_p) in a channel is assumed as dependable rainfall duration (t_d). Thus, terrain and channel retention times are omitted mainly due to the network operational safety at precipitation occurrence frequencies C more seldom than the design frequencies. The rainwater run-offs determined in this manner are higher in comparison with values computed according to MGN [8]. The volume flow Q (in [dm^3/s]) in MWO is calculated using the following formula

$$Q = q(t_d) \cdot F_{zr}$$

where $q(t_d)$ - a rainfall intensity for a duration equal to a flow time ($t_d = t_p$) [dm^3/(s·ha)].

In the paper [1], the probabilistic model of maximum precipitations in the conditions of Wroclaw has been formulated for the range of $t_d \in$ [5; 4320] minutes and occurrence probability $p = 1/C \in$ [1; 0.01] in the following form:

$$h(t_d) = -4.58 + 7.41 t_d^{0.242} + \left(97.11 t_d^{0.0222} - 98.68\right)(-\ln p)^{0.809}$$

where $h(t_d)$ - the maximum rainfall amount (for the duration t_d) [mm].

Table 2

The initial assumptions for sizing example networks of a rainwater sewerage system

Design variant	Design rainfall frequency C [years]		Terrain concentration time t_k [min]		Channel retention time t_r [min]	Minimum dependable rainfall duration t_d [min]
	side channels	interceptor	side channels	interceptor		
I.	1	2	10	5	0.2 t_p	10
II.	1	2	10	5	0.2 t_p	10
III.	2	2	0	0	0	15

The breakdown of initial assumptions for 3 different design variants of the rainwater sewerage system has been shown in the Table 2.

The cumulative breakdown of sizing results has been given in the Table 3.

Table 3

The sizing results of example sewerage networks [9]

Design variant	Run-off stream Q [m³/s]	Design flow time [min]	Channels and interceptor dimensions [m]	Channels and interceptor burial depths [m bgl]	Network volume V_K [m³]
I.	1.95	45.60	0.3-1.6	1.70-5.99	4849
II.	3.05	43.85	0.4-2.0	1.80-5.91	7234
III.	3.70	43.33	0.4-2.2	1.80-5.33	9825

Taking the design volume flow of rainwater sewage run-off from the I. variant of the sewerage system (Table 3): $Q_{(I)} = 1.95$ m³/s as the relative basis for comparisons (100%), then, the flow in the III. variant: $Q_{(III)} = 3.70$ m³/s is higher by as much as 90%.

Creation the model precipitation of Euler's type II

The concept of the model precipitation is to yield a typical precipitation distribution of an intensity variable in time in a manner close to reality. An example of model precipitations is the Euler type II model, recommended for modeling of sewerage in Germany [10-12]. The model is based on the observation that the highest momentary rainfall intensity occurs at the end of the third part of its duration. The Euler model precipitation is recognized as corresponding to real measured series of annual storm rainfalls, which are typically not easily accessible for a designer.
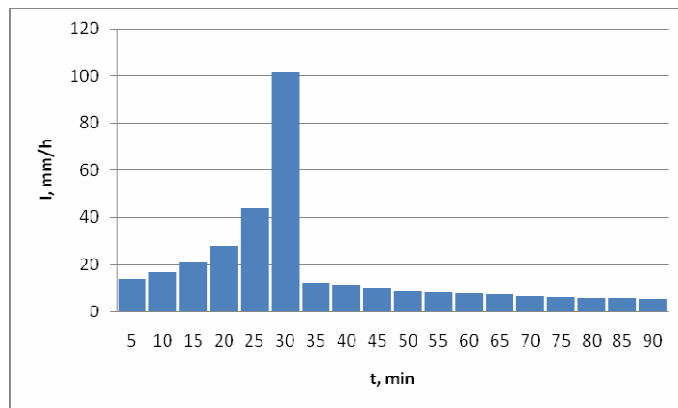

Fig. 2. The model precipitation of Euler type II for Wroclaw ($C = 3$ years and $t = 90$ min)

In order to verify the occurrence of damming up in channels, in example designer networks, the model drainage basin should be loaded with rainfall of the occurrence frequency of $C = 3$ years and with duration twice as long as the network flow time according to the recommendations ATV-A118 [10]. Since the mean flow time in designed

model drainage basins is of the order of 45 min (Table 3), the model precipitation with the duration of $t = 90$ min (Fig. 2) has been developed based on the formula for the maximum precipitation amount in Wroclaw [1].

The model precipitation developed for the conditions of Wroclaw for $t = 90$ min and $C = 3$ years ($p = 0.33$) is characterized by the maximum intensity of 101.71 mm/h, occurring between the 25th and 30th minute. The mean precipitation intensity amounts to 17.83 mm/h, which corresponds to 26.75 mm of the precipitation height.

Modeling the operation of example sewerage system

In order to verify the hydraulic flow capacity - sized in the 3 variants - of the rainfall sewerage system, the drainage basin has been loaded with the model precipitation of Euler type II for the conditions of Wroclaw. From the total precipitation amount (26.75 mm), its forth part ($\psi = 0.25$) has been transformed into the surface flow and reached the sewerage system. As a result of hydrodynamic simulations carried out, the information on volume flows and fills in specific sewerage sections in the time of the model precipitation duration was obtained. The interceptor profile in a selected precipitation duration time (the 31st minute) for the sewerage system sized in the I. variant has been shown in the Figure 3.
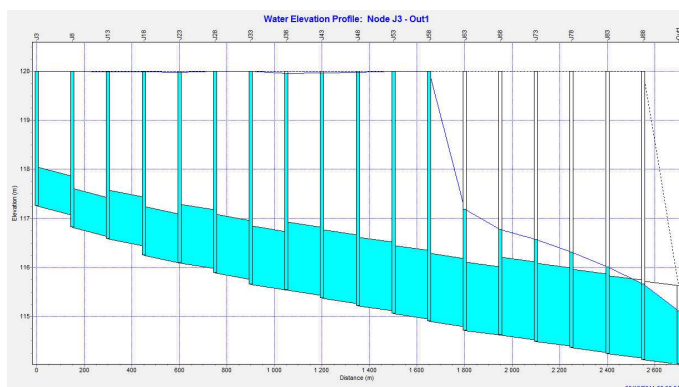

Fig. 3. The interceptor profile in the 31st minute of the precipitation duration modeled in the I. variant

The rainwater sewerage system designed in this variant does not have appropriate hydraulic flow capacity to discharge modeled rainwater run-offs without damming up to the ground level. The damming ups of a few meters - including to the ground surface and flooding - occur in most interceptor design nodes. The total sewage volume, which was not contained or flowed out of the network amounts to 1291 m^3 during the model precipitations. The flooding were observed in the total of 71 design nodes. In the I. variant of the sized sewerage system, the maximum model volume flow in the last interceptor section amounted to $Q_{m(I)} = 5.16$ m^3/s.

In order to verify the hydraulic flow capacity of the sewerage system designed in the II. variant, the drainage basin has been loaded with the model precipitation similarly to the I. variant. The inceptor profile with fills in the selected time of the precipitation duration (the 33rd minute) has been shown in the Figure 4.
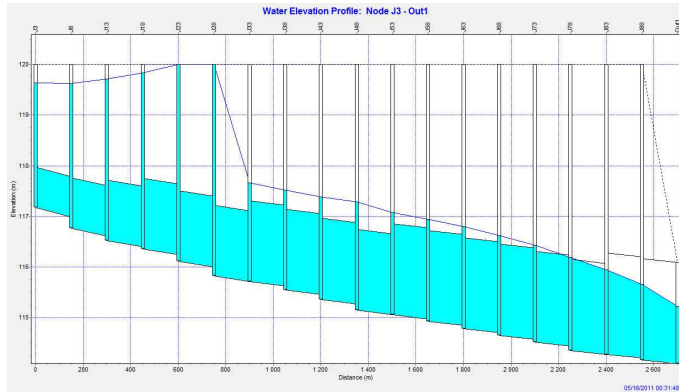
Fig. 4. The interceptor profile in the 33rd minute of the model precipitation duration in the II. variant

As it can be seen in the Figure 4, the damming ups in the beginning interceptor sections - in nodes J23 and J28, in the presented time moment of the simulation, reach the ground level (flooding). The middle and partially ending interceptor sections operate under small pressure. In case of the beginning side channels, we also have damming ups to the ground level, however for the further side channels, where the interceptor is buried considerably deeper, the damming ups to the ground level do not occur. The total sewage volume, which flowed out from the sewerage system during the model rainfall, amounts to 20 m^3 only. All in all, the flooding was observed in 12 nodes only. The maximum model volume flow reached $Q_{m(II)} = 6.11$ m^3/s.

In order to verify the hydraulic flow capacity of the sewerage system designed in the III. variant, it has also been loaded with the model precipitation of Euler type II. The interceptor profile with fills in the selected time of the precipitation duration (the 34th minute) has been shown in the Figure 5.
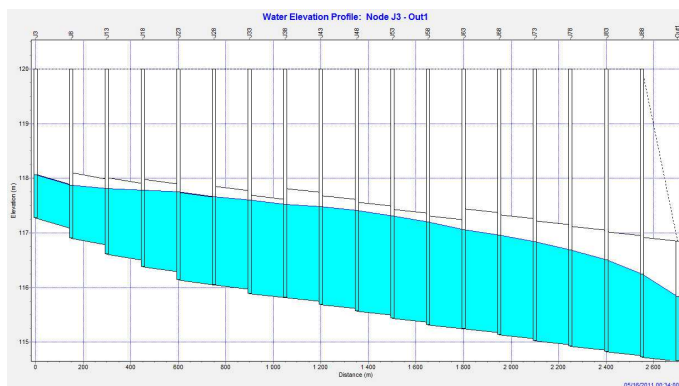

Fig. 5. The interceptor profile in the 34th minute of the model precipitation duration in the III. variant

As it follows from the Figure 5, practically the entire interceptor operates with a free sewage table during the set model rainfall, except for the interceptor section J23-J28

operating with a several-centimeter damming up above the channel vaulting. Damming up to the ground level are also absent in the case of all side channels - the lack of flooding from channels. Only damming up of a several dozen centimeters in relation to vaults occur on the first two sections, the two side channels. The maximum model volume flow (in the III. variant) on the last interceptor section reached $Q_{m(III)} = 6.95$ m^3/s. The cumulative breakdown of the operation analysis of the model sewerage systems (sized in the three variants) has been shown in the Table 4.

Table 4

The results of operation modeling of example sewerage systems

Design variant	Model flow Q_m [m^3/s]	Number of flooding	Volume of flooding [m^3]	Run-off and network emptying time [hours]
I	5.16	71	1291	4.7
II	6.11	12	20	5.1
III	6.95	0	0	5.3

The maximum values of the simulated volume flows rise with the increase in the network flowability, that is, the channel diameters and network volume (Table 4): from $Q_{m(I)} = 5.16$ m^3/s - in the I. variant (with numerous flooding) to $Q_{m(III)} = 6.95$ m^3/s (without flooding). The high volume of the storm channels in the III. variant of the sewerage system sizing $V_{K(III)} = 9825$ m^3 is then a considerable buffer in relation to the water run-off volume of the model precipitation from the drainage basin.

Summary and conclusions

The investigations described in this paper have been carried out to verify the selected flow time methods for usability in the safe designing of sewerage systems. The verification was conducted on the example of the model drainage basin located on the flat land in the hydrological conditions of Wroclaw. To simulate the functioning of sewerage system sized in this manner, the application SWMM 5.0 was deployed, in which the precipitation model of Euler type II was assumed as the precipitation load, while damming up and flooding were assumed as the criterion of the correct network operation.

The analyses carried out have unequivocally shown that the safe sewerage system sizing method is the MWO with the maximum precipitation model for Wroclaw due to the lack of damming up to the ground level and flooding from the sewerage system. Blaszczyk's formula and MGN in general considerably underrates the storm sewage volume flow necessary for sewerage system sizing, causing in consequence numerous damming up to the ground level and flooding (Table 4). The number of damming ups and flooding volumes from the sewerage system sized in the I. variant amount to: 71 and 1291 m^3, respectively. The attempt to substitute Blaszczyk's formula in MGN with the new maximum precipitation formula for Wroclaw (in the II. variant) has also failed to give satisfying results - the number of damming ups and flooding volume have only decreased (12 and 20 m^3, respectively). The third rainwater sewerage system sizing variant - according to MWO with the maximum precipitation model for Wroclaw - ensures the safe network sizing results for the model drainage basin in the conditions of Wroclaw - the lack of damming ups to the ground level and flooding (Table 4).

When the model precipitation has decreased, the rainwater run-off time, and mainly channel emptying time keeps lasting for a few hours from the moment the precipitation ends - the longer the time, the bigger the channel diameters and lower required bottom slopes. In this time, the sewerage system (sized for $C = 2$ years at $t_d = t_p = 45$ minutes) is not fully ready to take the rainfall of similar intensity and duration as the model precipitation ($C = 3$ years and $t_d = 2t_p = 90$ minutes), since channels are still partially filled. Thus, flooding from channels is inevitable, even when using correct flow time methods for the sizing of drainage networks, and then for the verification of their operation in hydrodynamic modeling due to the stochastic nature of rainfall. Thus, this breaks down to the limiting of damming up and flooding occurrence probability, which can only be obtained in safely sized sewerage systems.

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WYMIAROWANIE KANALIZACJI DESZCZOWEJ

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Abstrakt: W pracy symulowano działanie kanalizacji deszczowej zwymiarowanej trzema metodami czasu przepływu, tj.: MGN z wzorem Błaszczyka, MGN z wzorem opadów dla Wrocławia i MWO z wzorem opadów dla Wrocławia, dla modelowej zlewni miejskiej o powierzchni 2 km² w terenie płaskim. Do symulacji hydrodynamicznych działania systemów kanalizacyjnych wybrano program SWMM 5.0 (Storm Water Management Model), opracowany przez Amerykańską Agencję Ochrony Środowiska (US EPA). Wskazano na bezpieczną metodę wymiarowania kanalizacji deszczowej (MWO) przy kryterium braku wylewów z kanałów.

Słowa kluczowe: wylania z kanalizacji, opad modelowy, model zarządzania wodami opadowymi