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Simulation studies of storm water drainage in Wrocław

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Abstract: In the paper were made the verification of the operation of a rainwater drainage system in the residential communities of Gaj and Tarnogaj in Wrocław, carried out in the hydrodynamic model using SWMM software. There were used two criterial precipitation: Euler's model (with a frequency of C = 3 years) and the actual precipitation (C = 5 years). The criteria of overloading the system was the specific flood volume (*SFV*). For both cases of precipitation load of catchment, the simulated calculations showed the occurrence of outflows from the channels. Due to the value of *SFV* indicator (respectively: 19 m^3/ha and 42,9 m^3/ha), it was found that the tested system needs modernization, therefor acceptable instantaneous water level above the maximum water impoundment were more often than 1 per 3 years, which leads to overflows from channels for residential areas more often than allowed once every 20 years.

1 Introduction

Extreme natural phenomena, which have increased recently, such as rapid or long rainfalls or resulting urban floods, cause major economic damages. Thus, we should aim to achieve the required standard according to PN-EN 752 from 2008 [1] for draining urbanizes areas that would be acceptable in the today's world. This standard is defined as adjusting a system to accept maximum (forecasted) flows of rainwater with a frequency equal to the socially acceptable frequency of flooding the area surface. For example, the frequency of rainfall for urban areas is 1 per 2 years (C = 2 years), and the acceptable frequency of flooding is 1 per 20 years (C = 20 years) (Tab. 1).

For the recommended rainfall rates (Tab. 1), the diameters of the channels should be selected so as the total capacity will be always higher than the calculated outflow. However, since the definition of movement of the liquid in channels is not linear, the relation between the frequency of rainfall and the frequency of flooding cannot be generalized. This can be determined in the way of hydrodynamic modeling of tested sewerage system. Here are helpful the German guidelines according to DWA-A118:2006 [2], that introduce a term of the acceptable frequency of maximum instantaneous water level up to the surface (Tab. 2). Then, the state of overloading that is the closest to the consecutive flooding can be determined indirectly.

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Table 1. Frequencies of calculated rain and acceptable frequencies of flooding from channels according to PN-EN 752:2008 [1].

Frequencies of calculated rain [1 in *C* years]	**Location**	**Acceptable frequencies of flooding from channels [1 in *C* years]**
1 per 1	rural areas	1 per 10
1 per 2	residential areas	1 per 20
1 per 5	city centres, services and industrial areas	1 per 30
1 per 10	underground transport facilities, passages and crossings under streets, etc.	1 per 50

Table 2. Acceptable frequencies of overflow for verifying calculations of the newly designed or modernized drainage systems according to DWA-A 118:2006 [2].

Frequencies of calculated rain [1 in *C* years]	**Location**	**Frequency of overflows [1 in *C* years]**
1 per 1	rural areas	1 per 2
1 per 2	residential areas	1 per 3
1 per 5	city centres, services and industrial areas	less frequently than 1 per 5
1 per 10	underground transport facilities, passages and crossings under streets, etc.	less frequently than 1 per 10*
* When the local protective measures are not applied, then: "1 per 50"		

Taking into account the current knowledge about future trends in the climate changes, design precipitation can be matched with the sizes of field drainage systems (Tab. 1 and 2) by correcting the precipitation frequency in future [3–6]. In the paper [4] showed that today's rainfall with a frequency $C = 5$ years, in the future will have a frequency of $C = 2$ years (the frequency equal to the currently recommended one for designing drainage systems in residential areas, for which the frequency of maximum acceptable instantaneous water level above the maximum water impoundment is currently $C = 3$ years). According the paper [7], a precipitation scenario of $C = 5$ years was recommended instead of $C = 3$ years for the verification of the occurrence of future overflows in residential areas and precipitation scenario $C = 100$ years to ensure the currently required admissible frequency of overflows once every 20 years (Tab. 3).

Table 3. Adjustments to DWA-A118:2006 with regard to precipitation scenarios for the identification of future drainage system overload [7].

Location	**Frequency of precipitation for simulation of:**	
	overflow	**flooding**
	[once every *C* years]	
rural areas	3 instead of 2	50 instead of 10
residential areas	5 instead of 3	100 instead of 20
city centres, services and industrial areas	10 instead of 5	100 instead of 30

The climate changes necessitates the verification of hydraulic capacity, previously dimensioned, rainwater sewerage systems in hydrodynamic modeling and taking appropriate modernization activities today [8–10].

The paper presents the verification of the operation of the rainwater drainage system in residential areas of Gaj and Tarnogaj areas in Wrocław conducted on a calibrated hydrodynamic model in SWMM for the conditions of the current precipitation load as well as for the forecasted increase in the load in the future.

2 Research methods

Rainwater catchments of the residential areas Gaj and Tarnogaj are located in the southern part of the city of Wroclaw. They cover an area of $F = 104$ ha. The system of main rainwater collector KD1 of the length 2712 m, is built with concrete channels with a diameter ranging from 0.30 to 1.20 m. The total length of the channels is 17 730 m, and the number of manholes is 509 [9, 10]. The sealed area of the catchment is 61.5 ha. In this model, 75 sub-catchment areas were identified and the hydraulic width of them was determined as $W_i = 1.6 F_i^{0.5}$.

The calibrated model in SWMM software has the following parameters: roughness coefficient of the concrete channels 0.020 s/m$^{1/3}$, roughness coefficient of the paved areas 0.02 s/m$^{1/3}$, roughness coefficient of the non-paved areas 0.30 s/m$^{1/3}$, field retention height on the paved areas 2.0 mm, and field retention height on the non-paved areas 5.0 mm. The infiltration parameters adopted for the Harton's model: initial infiltration intensity 90 mm/h, final I_{ink} =10 mm/h, recession constant 4 1/h, and complete soil drying time 7 d [10–12].

Two criteria precipitation types were used to generate a load on the catchment area: Euler's type II – with a frequency in Wrocław of $C = 3$ years (for the current supply conditions of the catchment area) and intensive actual convective rainfall of 19 July 2015 - with a frequency in Wrocław of $C = 5$ years (for the future supply conditions).

The specific flood volume (*SFV*) was used to assess the system overload [6, 10, 13, 14]. Parameter *SFV* concerns the flood volume from channels (eg. $V = 10$ m^3/ha corresponds to rainfall of height 1 mm):

$$SFV = \sum V / \sum F_s \qquad (1)$$

where:

V – flood volume, m^3,

F_s – sealed catchment area, ha.

Limit value of *SFV* parameter accepted according to paper [13], where determined $SFV >$ 13 m^3/ha indicate an urgent need to adjust the system to the climate changes.

3 Simulations of model precipitation

Precipitation models are histograms compiled based on the local formulas for depth-duration frequency (DDF) or intensity-duration frequency (IDF). Under the hydrological conditions of Wroclaw, applied a probabilistic model of the type DDF range for the duration of rainfall $t \in [5; 4320]$ minutes and a probability of exceedance $p \in [1; 0.01]$, in the following form [16]:

$$h_{\max}(t,p) = -4.58 + 7.41 t^{0.242} + (97.11 t^{0.0222} - 98.68)(-\ln p)^{0.809} \qquad (2)$$

where:

$h_{\max}$ – maximum precipitation amount, mm,

t – rainfall duration, min,

p – probability of higher rainfall: $p = 1/C$,

C – frequency of higher rainfall, years.

As an example take Euler's type II model precipitation recommended for modelling drainage systems in Germany [2] as well as in Poland [6]. This model is based on an observation that the highest instantaneous rainfall intensity occur at the end of one third of its duration.

In order to verify the flow capacity of the tested rainwater drainage system, in accordance with the recommendations of DWA-A 118:2006 [2], the tested catchment in housing area,

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should be loaded by the rain with the incidence of $C = 3$ years during the period exceeding the flow of double time in the system. Since the time of flow in the main collector KD1 is approx. 45 min, model precipitation for a time of $t = 90$ min and a frequency of $C = 3$ years was prepared. The procedure for creating a model of precipitation is given in Figure 1.

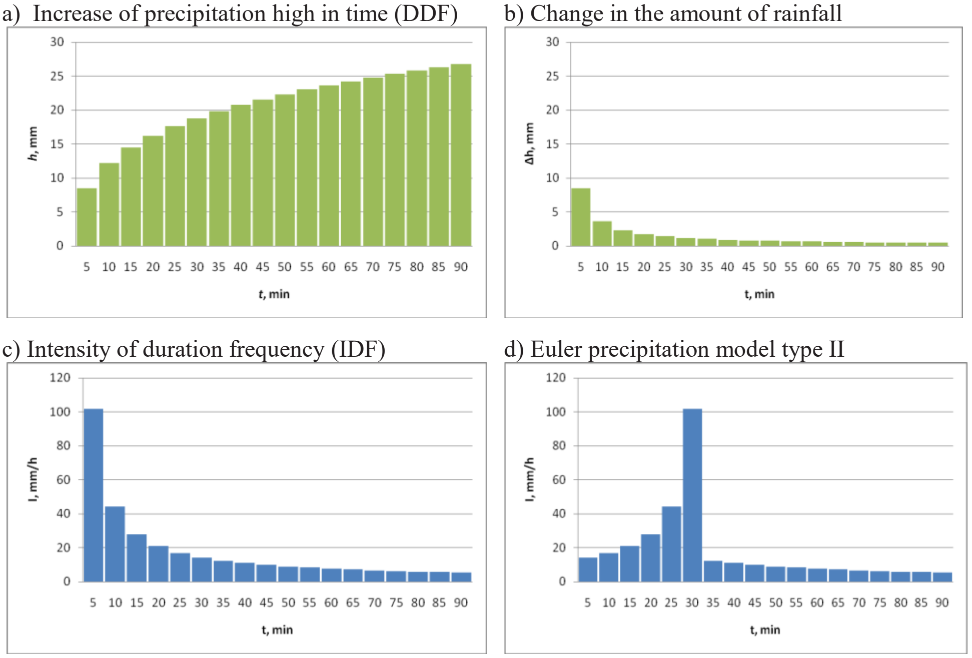

Fig. 1. Precipitation phases of the Euler model type II of $t = 90$ min and $C = 3$ years for Wroclaw.

In order to verify the flow capacity of the tested rainwater drainage system, the catchment area was loaded with Euler's type II model precipitation. Figure 2 shows the profile of the main collector (KD1) with maximum acceptable instantaneous water levels above the maximum water impoundment at the 35th minute of the rainfall.

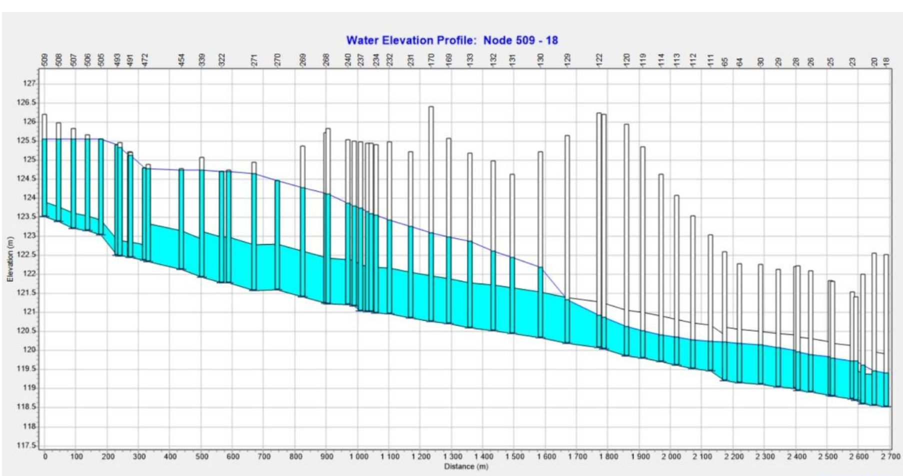

Fig. 2. Operation of sewer KD1 at 35th minute of Euler's model precipitation.

As it can see in the Figure 2, the flow of sewerage along 2/3 of the length of the sewer KD1 was under pressure. Along the route of the sewer KD1, there are a few critical points, e.g. points with overflow levels reaching to the ground surface. Important hazards can be caused by spills above the volume 100 m^3. There are 4 such critical points. An extremely large flood volume was found in the area of node 423 of 481 m^3 and lasting about 25 minutes (Tab. 4).

Table 4. Locations and volumes of floods from drainage system for Euler's model precipitation.

Number of manhole	Flood duration	Flood start time	Flood volume
-	**h**	**h:min**	**m^3**
423	0.41	00:35	481
75	0.37	00:35	254
99	0.36	00:35	232
45	0.5	00:35	204

Figure 3 shows the location of 4 areas of overflows and significant floods in the tested sewage system.

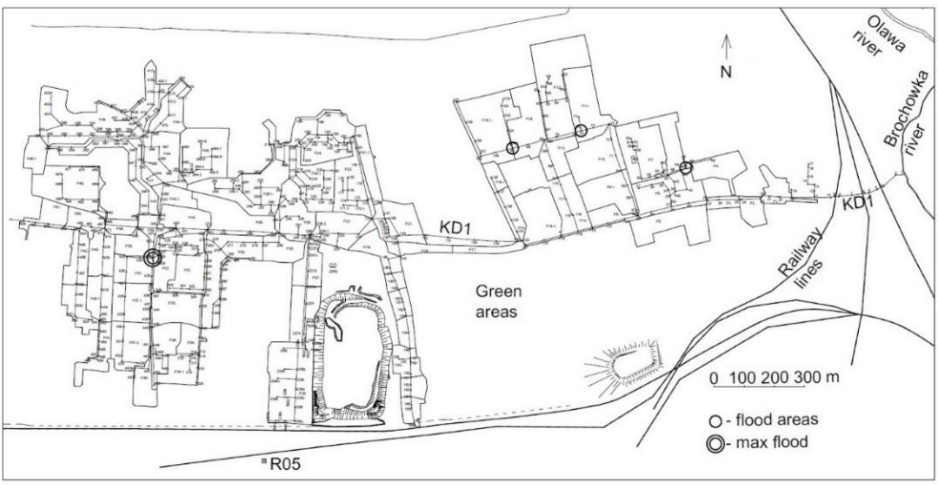

Fig. 3. Location of floods from channels for Euler's model precipitation (C = 3 years and t = 90 min).

Based on the formula (1), the specific flood volume was calculated SFV = 19 m^3/ha, for ΣV = 1171 m^3 and F_s = 61.5 ha. According to the paper [13], the calculated value SFV > 13 m^3/ha indicates an urgent need to make adjustments to the climate changes. Here we can argued that the overflow and flooding on the tested settlements area, occur in the frequency more than once every 3 years. The reasons for this situation are mainly too small diameters and drops of ducts, i.e. in insufficient hydraulic capacity of the sewage system.

4 Simulations of actual precipitation

At the second stage of the tests, the verification of the operation of the drainage system for Gaj-Tarnogaj under climatic changes was conducted using actual precipitation of 19 July 2015 with height h = 23,778 mm. It is a precipitation with frequency of occurrence in Wroclaw C = 5 years (for a duration t = 42 min). Its episode intensity - for t = 15 min, i.e. I_{15} = 88,4 mm/h (q_{15} = 245,6 dm^3/(s·ha)), corresponds to the frequency of C_{15} = 18 years and considering the Chomicz scale it is classifies to heavy rains [12]. The actual precipitation histogram, in 5-minute intervals of time, is shown in Figure 5.

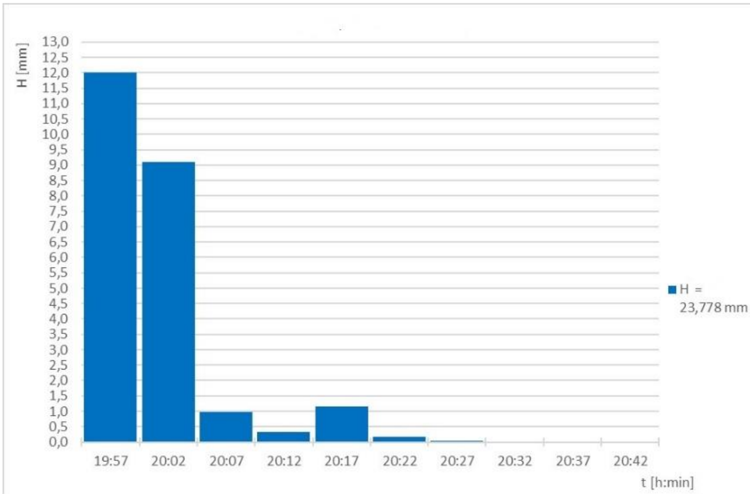

Fig. 5. Actual precipitation histogram of 19 June 2015 (*C* = 5 years and *t* = 42 min).

Figure 6 shows the profile of the KD1 collector with fill during the 20th minute of the real rainfall. In the showed temporary simulation sewage flows worked under the pressure along 2/3 of the length of the channel (similar to the Euler model type II of *C* = 3 years and *t* = 90 min). Also a few critical points occur, where the level of rain sewage reaches the ground level (in the area of manholes no 270, 322 and 472).

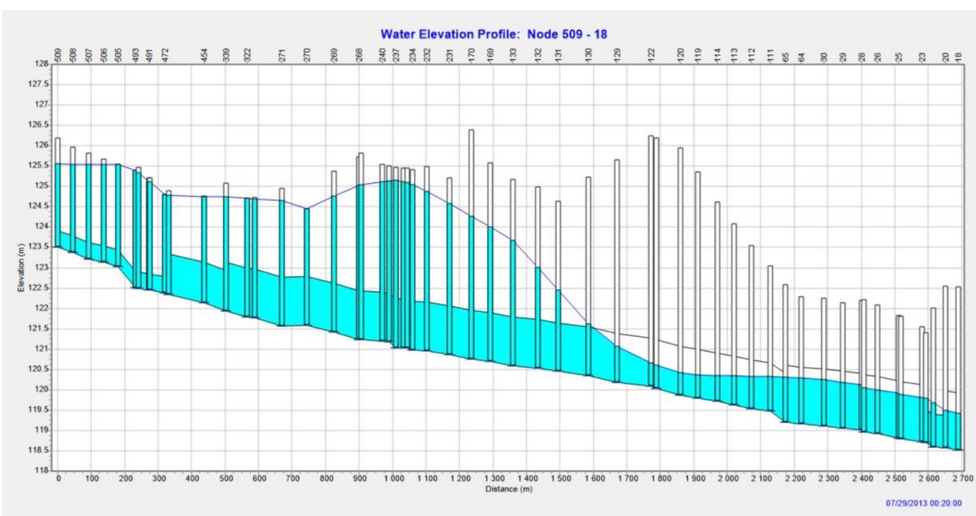

Fig. 6. Profile of sewer KD1 at 20th minute of actual precipitation (*C* = 5 years and *t* = 42 min) of 19 June 2015.

For precipitation with *C* = 5 years, potential risks result from floods even in 8 areas (with *V* > 200 m^3), given in Table 5. The highest simulated floods occurred in the area of the manholes No.: 423 (515 m^3), 75 (359 m^3), 99 (354 m^3), 43 (327 m^3), 270 (299 m^3), 45 (272 m^3), 80 (262 m^3) and 427 (253 m^3). The flood duration was between 10 and 26 min.

Table 5. Locations and volumes of floods from drainage system for actual precipitation (C = 5 years and t = 42 min).

Number of manhole	Flood duration	Flood start time	Flood volume
-	h	h:min	m^3
423	0.38	00:19	515
75	0.35	00:20	359
99	0.37	00:20	354
43	0.25	00:20	327
270	0.17	00:22	299
45	0.43	00:20	272
80	0.28	00:20	262
427	0.42	00:20	253

Figure 7 illustrates the location of significant floods in 8 areas shown in Table 5.

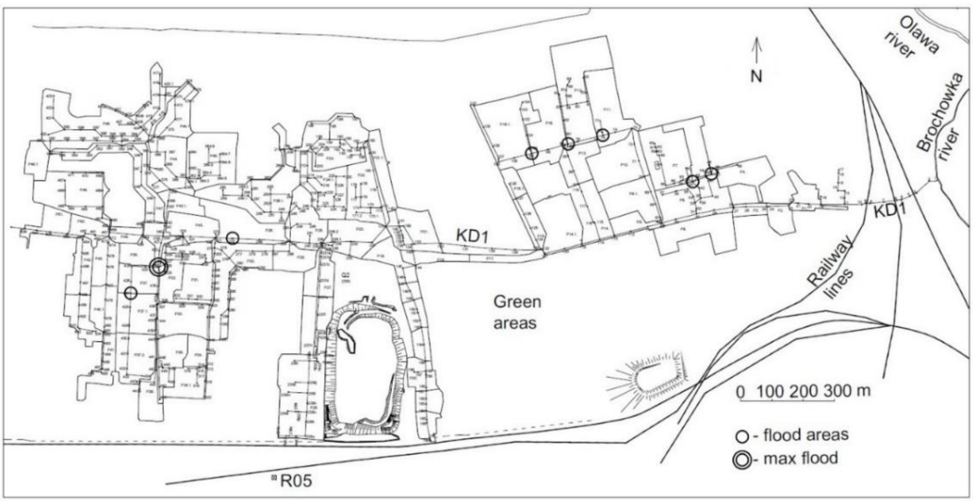

Fig. 7. Location of floods from channels for actual precipitation of 19 June 2015 (C = 5 years and t = 42 min).

For actual precipitation with C = 5 years, the calculated specific flood volume $SFV = 2641/61.5 = 429$ m^3/ha (for $\Sigma V = 2641$ m^3 and $F_s = 61.5$ ha). Value of $SFV > 13$ m^3/ha indicates a very urgent need to adjust the water drainage system in the tested residential areas to the climatic changes (as in case of model precipitation), according to the adopted criteria [15].

5 Conclusions from the study

The paper shows the results of an verifications of the operation of the rainwater drainage system in the residential areas Gaj and Tarnogaj in Wrocław. The tests were conducted on a calibrated hydrodynamic model of the system, in SWMM. Two criteria precipitation types were used to generate a load on the catchment area: Euler's type II model precipitation - with a frequency in Wrocław of C = 3 years (for the current supply conditions of the catchment area) and intense actual precipitation of 19 July 2015 - with a frequency in Wrocław of C = 5 years (for the supply conditions in the future). Criteria used to describe the overloads of the system was the specific flood volume (SFV).

For model precipitation with a frequency of $C = 3$ years, the value of $SFV = 19$ m^3/ ha > 13 m^3/ha indicates an urgent need to make modernizations. For actual precipitation with a frequency of $C = 5$ years, the value of the parameter $SFV = 42.9$ m^3/ha in particular indicates an even more urgent need to modernization of tested system to the climate changes.

The carried out simulations showed the rainwater drainage system does not comply with PN-EN 752. Multiple overflows to the ground level and resulting significant floods from the channels (with $V > 200$ m^3) occur in the tested residential areas considerably often than 1 per 3 years, which in consequence may lead to potential risks more frequently than 1 per 20 years, particularly in the future. A cause for this are too small diameters and slopes of the channels, and thus insufficient flow capacity of the existing rainwater drainage system sized in the past with methods that are not applicable any more.

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