https://doi.org/10.3311/PPci.12668

Periodica Polytechnica Civil Engineering, 63(2), pp. 641–646, 2019

Verification of the Stormwater Drainage System Overloads in Wrocław for an Assessment of Climate Change Effects

Monika Nowakowska[1*], Katarzyna Wartalska[1], Bartosz Kaźmierczak[1], Andrzej Kotowski[1]

[1] Faculty of Environmental Engineering,
Wroclaw University of Science and Technology,
27 Wybrzeże Wyspiańskiego Street, 50-370 Wrocław, Poland
[*] Corresponding author, e-mail: monika.nowakowska@pwr.edu.pl

Received: 11 June 2018, Accepted: 11 January 2019, Published online: 13 February 2019

Abstract

This paper presents a verification of the performance of the stormwater drainage system in Gaj and Tarnogaj residential developments in Wrocław with regard to climate changes, by means of a calibrated hydrodynamic model created within the SWMM software. The verification was carried out for two criterial rainfalls: the Euler model rainfall with occurrence frequency C = 3 years and an actual rainfall with C = 5 years. Two parameters: degree of flooding (*DOF*) and specific flood volume (*SFV*) were adopted to indicate potential system overloads. The simulations showed numerous outflows from the sewers, which means, that the investigated system needs adapting to climate changes. The causes of this should be sought in the too small diameters of the sewers and so in the insufficient hydraulic capacity of the sewerage system dimensioned in the past using methods which are inadequate today.

Keywords

urban hydrology, rainwater, hydrodynamic modelling, stormwater management model

1 Introduction

Because of the random character of precipitation, the operation of stormwater drainage or combined sewer systems cannot be entirely reliable. Extreme natural phenomena (intensifying in recent years), such as torrential or persistent rains, and the resulting urban floods cause substantial economic losses [1–2]. According to EN 752, efforts should be made to achieve the currently required water drainage standard for urban areas, defined as the adaptation of the drainage system to receiving the maximum (forecasted) rainfall water streams occurring with a frequency equal to the allowable (socially acceptable) frequency of occurrence of a terrain surface flooding (Table 1 and Table 2).

Table 1 Recommended frequency of designed computational rain and limit the frequency of spill in accordance with EN 752:2008

Design rainfall frequency	The area drainage standard category	Flooding occurrence frequency
1 per 1 year	Rural areas	1 per 10 years
1 per 2 years	Residential areas	1 per 20 years
1 per 5 years	City centres/industrial/ commercial areas	1 per 30 years
1 per 10 years	Underground railway/ underpasses	1 per 50 years

Table 2 Examples of design sewer flooding criteria for standing floodwater in accordance with EN 752:2017

Impact	Example locations	Return period*
Very low	Roads or open spaces away from buildings	1 per 1 year
Low	Agricultural land (depending on land use, e.g. pasture, arable)	1 per 2 years
Low to medium	Open spaces used for public amenity	1 per 3 years
Medium	Roads or open spaces adjacent to buildings	1 per 5 years
Medium to high	Flooding in occupied buildings excluding basements	1 per 10 years
High	Deep flooding in occupied basements or road underpasses	1 per 30 years
Very high	Critical infrastructure	1 per 50 years

* Return period should be increased (probabilities reduced) where the floodwater is fast moving. When undertaking rehabilitation of existing systems and where achieving the same design criteria for a new system would entail an excessive cost, a lower value may be considered.

Stormwater sewers should have such diameters that their total capacity will always be greater than the design runoff (Table 1). But the dependence between the frequency of the assumed rainfall and the flooding frequency (Table

Cite this article as: Nowakowska, M., Wartalska, K., Kaźmierczak, B., Kotowski, A. "Verification of the Stormwater Drainage System Overloads in Wroclaw for an Assessment of Climate Change Effects", Periodica Polytechnica Civil Engineering, 63(2), pp. 641–646, 2019. https://doi.org/10.3311/PPci.12668

1 and Table 2) cannot be generalized since the description of the motion of the liquid in sewers is nonlinear. The dependence can be determined only through the hydrodynamic modelling of a given sewerage system. German recommendations DWA-A118 of 2006, introducing the concept of the frequency of surcharging up to the ground level in sewerage system performance check calculations (Table 3), can be helpful in this regard. Then in an indirect way one can determine the overload state closest to the subsequent flooding. A serious flooding hazard will occur when water exceeds the level of street kerbs and enters the adjacent properties, the basements of the buildings, etc.

Considering the current knowledge of the future trends in climate change [3–9], the design rainfalls can be adjusted to terrain drainage dimensioning (Table 1 and Table 3) by correcting the current rainfall intensities or by changing the frequencies of their occurrence in the future. In [10] it was shown that today's rainfall events with a statistical repeatability of, e.g., five years, in the future will be events with a frequency of occurrence $C = 2$ years. Therefore a scenario of rainfalls with $C = 5$ years instead of $C = 3$ years is recommended for verifying the occurrence of future surcharging events in housing areas and a scenario of precipitation with $C = 100$ years is recommended to ensure the currently allowable flooding frequency of once every 20 years (Table 4).

A considerable number of stormwater drainage systems in Poland was dimensioned using rainfalls intensity formulas which are inadequate today. As a result, the systems are likely to be unable to meet the requirements concerning the allowable frequency of sewer overflows (especially in the future) [12, 13].

This paper presents a verification of the stormwater drainage system performance in Gaj and Tarnogaj residential developments in Wrocław for the present and forecasted future rainfalls.

Table 3 Recommended frequencies for calculations testing the stormwater drainage performance in accordance with DWA-A118:2006

Design rainfall frequency	The area drainage standard category	Acceptable surcharging frequency
1 per 1 year	Rural areas	1 per 2 years
1 per 2 years	Residential areas	1 per 3 years
1 per 5 years	City centres/industrial/ commercial areas	Less than 1 per 5 years
1 per 10 years	Underground railway/ underpasses	Less than 1 per 10 years*

* When local security measures are not applied, then: „1 per 50"

Table 4 Recommended changes in rainfall frequency for identification of future sewage systems overloads [11]

The area drainage standard category	Design rainfall frequency for overloads verification [1 per *C* years]	Design rainfall frequency for floodings verification [1 per *C* years]
Rural areas	3 instead of 2	50 instead of 10
Residential areas	5 instead of 3	100 instead of 20
City centres/ industrial/ commercial areas	10 instead of 5	100 instead of 30

2 Model drainage area and research methodology

A hydrodynamic model of the stormwater drainage system, created within the SWMM software, was used for this study. The drainage area is $F = 104$ ha. The main stormwater sewer (KD1) network consists of concrete sewers 0.30–1.20 m in diameter. The total length of the sewers amounts to about 17730 m and the number of manholes to 509. Seventy five drainage sub-catchments were distinguished in the model [14].

Calibration of the hydrodynamic model included the following hydraulic and hydrological parameters: roughness coefficient of the sewer's interior, roughness coefficient of runoff area, depth of depression storage, and hydraulic width of the overland flow path. For the calibration and validation of the model, rainfall data from the two-year observation period (5 precipitation for calibration and 3 for validation), with the amounts from 9.7 to 28.4 mm and durations from 42 to 1486 minutes were used. The rain gauge, from which rainfall data were applied, is located only 620 m from the center of gravity of the analyzed catchment. The aim of the calibration was to achieve the highest possible compliance between simulated and measured values for the runoff volume balance.

Two parameters: degree of flooding (*DOF*) and specific flood volume (*SFV*) were adopted to indicate potential system overloads.

$$DOF = \sum N_f / \sum N \qquad (1)$$

where:

N_f – number of flooded manholes,
N – total number of manholes.

$$SVF = \sum FV / \sum SS \qquad (2)$$

where:

FV – flood volume, m^3,
SS – sealed surface, ha.

The limit values of parameters (1) and (2) should be set individually. For example in [15], for three sewerage systems in North Rhine-Westphalia, the limit values of the parameters were determined to be: $DOF = 0.33$ and $SFV = 13$ m^3/ha.

The Euler model rainfall type II with occurrence frequency $C = 3$ years and an intensive rainfall (of 19.07.2015) with the frequency of occurrence in Wrocław $C = 5$ years were assumed as the drainage area load for respectively the current supply conditions and the future supply conditions.

The model rainfalls are synthetic rainfall histograms created on the basis of local formulas for rainfall depth-duration-frequency (*DDF*) or intensity-duration-frequency (*IDF*). In the hydrological conditions of Wrocław, the *DDF* model is applied. The model has the form:

$$h = -4.58 + 7.41t^{0.242} + (9711t^{0.0.222} - 98.68)(-\ln p)^{0.809} \tag{3}$$

where:

h – precipitation amount, mm,
t – precipitation duration, min,
p – occurrence probability, $p = 1/C$.

The idea of the model is to most closely represent the pattern of typical rainfalls characterized by time-variable intensity. An example here is the Euler model rainfall type II recommended by DWA-A118:2006 for modelling sewerage in Germany, and also in Poland [12, 17].

3 Verification of overloads for model rainfall

In order to verify the occurrence of surcharging in sewers in accordance with DWA-A 118:2006 one should load the investigated residential development drainage area with rainfall with occurrence frequency $C = 3$ years and duration at least twice longer than the time of the flow in the network. Since in main sewer KD1 this time amounted to 45 minutes, the Euler model rainfall for $t = 90$ min and $C = 3$ years was adopted. Fig. 1 shows the main sewer profile with the maximum overloads.

In the simulation instant shown in Fig. 1, at 2/3 of the length of main sewer KD1 sewage flows under pressure. Several critical points with up to the ground level surcharges, and floodings occur along the route of KD1. In this study, it was assumed that outflows with a volume of over 100 m^3 can pose potential hazards. Then assuming the water height to be at the level of pavement kerbs (0.15 m), the inundation would cover an area larger than 25 m × 25 m = 625 m^2, which corresponds to a typical drainage gully spacing of 25 m [12]. There are 14 such nodes in the investigated network (Table 5). In the analysis of surface flooding, the default SWMM program settings were used in this area - no special methods were used.

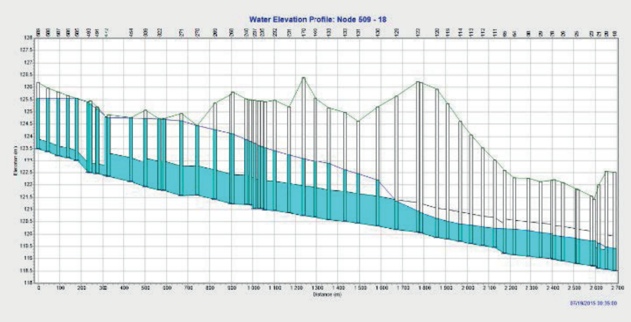

Fig. 1 KD1 trunk sewer operation at 35th minute of Euler model rainfall duration

Table 5 Localizations and volumes of floodings from stormwater drainage for Euler type II model rainfall

Node	Hours flooding, h	Time of flooding occurrence, h:min	Flooding volume, m^3
423	0.41	00:35	481
75	0.37	00:35	254
99	0.36	00:35	232
45	0.50	00:35	204
238z	0.45	00:37	196
168	0.82	00:45	195
427	0.51	00:35	176
270	0.14	00:37	164
80	0.29	00:35	160
43	0.21	00:35	158
47	0.84	00:48	146
103	0.59	00:28	118
456	0.22	00:32	117
430	0.28	00:35	111

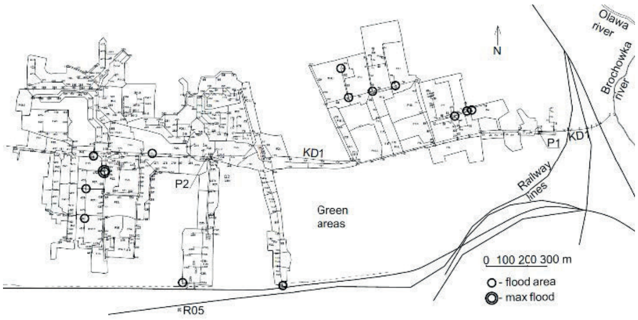

Fig. 2 Localization of floodings from stormwater drainage system for Euler model rainfall type II for $C = 3$ years and $t = 90$ minutes

The longest duration (about 50 minutes) outflows occurred in nodes no. 47 and 168 (with a volume of 146 and 195 m^3, respectively). An extremely large outflow volume, amounting to 481 m^3 and lasting for 25 minutes, was found to occur in the node no. 423 area.

Fig. 2 shows the locations of the 14 areas in which sewerage surcharges and substantial floodings occur.

The indicators: *DOF* and *SFV* were used to describe the overload of the system. They were calculated from formulas (1) and (2) to amount to: $DOF = 0.16$ ($N_f = 79$, $N = 509$) and

$SFV = 44.1$ m^3/ha ($FV = 2712$ m^3, $SS = 61.5$ ha). According to the criteria in [15], $DOF < 0.33$, while $SFV > 13$ m^3/ha indicates the system should be upgraded right now.

4 Verification of overloads for actual rainfall

The actual rainfall of 19.07.2015 was used to verify the performance of the sewerage system in climate change conditions. The rainfall histogram for five minute time intervals is shown in Fig. 3.

Fig. 4 shows the KD1 main sewer profile at the 20th minute of rainfall duration, i.e. when the maximum overloads occur. At this instant at 2/3 of the length of trunk sewer KD1 the sewage flows under pressure (similarly as for the Euler model rainfall type II). There are numerous critical points where storm sewage reaches the ground level.

For the rainfall with $C = 5$ years, floodings in 17 nodes (Table 6) can pose potential hazards. Similarly, as in the case of the Euler model rainfall, the longest lasting (about 30 min) flooding in the network occurred in 2 critical nodes: no. 47 and 168. The largest simulated outflow volumes occurred in 8 nodes.

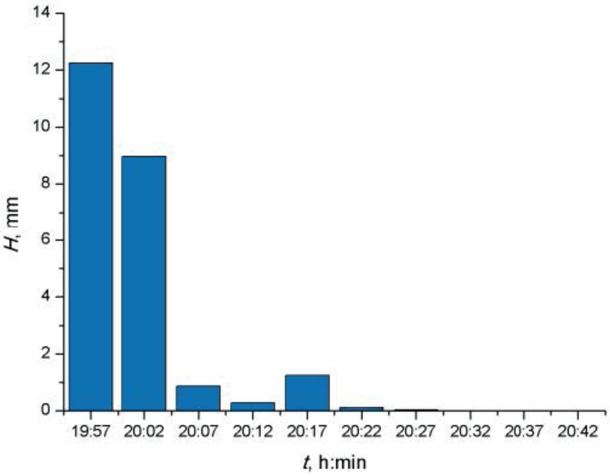

Fig. 3 Actual rainfall histogram of 19.07.2015 with $C = 5$ years and $t = 42$ minutes

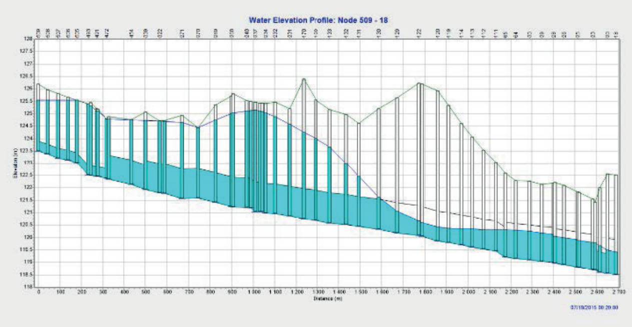

Fig. 4 Profile of the KD1 main sewer at 20th minute of actual rainfall duration with $C = 5$ years and $t = 42$ minutes

Table 6 Localizations and volumes of floodings from stormwater drainage for actual rainfall

Node	Hours flooding, h	Time of flooding occurrence, h:min	Flooding volume, 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
430	0.25	00:20	197
382	0.21	00:20	191
73	0.19	00:20	158
168	0.51	00:13	157
456	0.22	00:16	139
238z	0.45	00:21	132
153	0.19	00:20	131
322	0.10	00:20	110
47	0.51	00:28	104

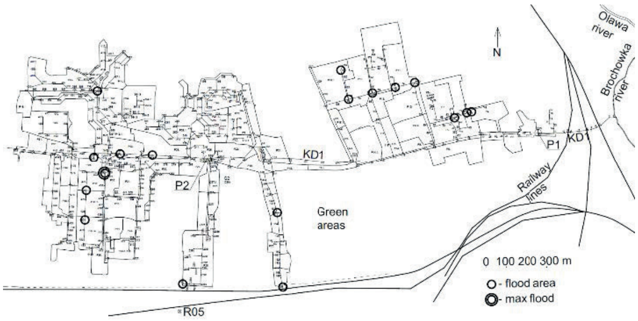

Fig. 5 Localization of floodings from stormwater drainage system for actual rainfall with $C = 5$ years and $t = 42$ minutes

Fig. 5 shows the locations of the outflows in the areas of the 17 nodes listed in Table 6.

The values of the criterial parameters are: $DOF = 87/509 = 0.17$ (for $N_f = 87$ and $N = 509$) and $SFV = 3960/61.5 = 64.4$ m^3/ha (for $FV = 3960$ m^3 and $SS = 61.5$ ha). According to the criterion in [15], the SVO value >> 13 m^3/ha indicates an urgent need to adapt the stormwater drainage system in the residential developments to climate changes.

5 Conclusions

The verification of the performance of the stormwater drainage system in Gaj and Tarnogaj residential developments in Wrocław has been presented. The verification was carried out using a calibrated hydrodynamic model of the system, created within the SWMM software. Two rainfalls: the Euler model rainfall type II with the frequency of occurrence in Wrocław $C = 3$ years for the current drainage area supply conditions and an actual intensive rainfall with occurrence frequency $C = 5$ years for the supply conditions in the future were used as the catchment load.

The degree of flooding (*DOF*) and the specific flood volume (*SFV*) were adopted as the criteria for describing the system overload. In the case of the model rainfall (with frequency $C = 3$ years) for $SFV = 44.1$ m^3/ha > 13 m^3/ha the system was found to be in need of upgrading. In the case of the actual rainfall (with frequency $C = 5$ years) for $SFV = 64.4$ m^3/ha > 13 m^3/ha the system was also found in need of adapting to climate changes.

Thus the simulations showed that the investigated system does not meet the current standards. The causes of this should be sought in the too small diameters of the sewers and so in the insufficient hydraulic capacity of the sewerage system dimensioned in the past using methods which are inadequate today. In the unvaried (flat) terrain where the considered residential developments are located, outflows with a volume > 100 m^3 in most cases occurred in the areas with the smallest sewer diameters: 0.30, 0.40 and 0.50 m.

In the case when local system overloads are identified, further risk assessments are necessary [18]. They can be carried out on the basis of GIS or in-situ evaluations as part of an additional system performance simulation combined with a digital terrain model. This is recommended particularly when the criterial evaluation parameters (*DOF* and *SFV*) indicate an urgent need of adaptation [12]. A detailed analysis of the results of such simulations will enable one not only to demarcate the boundaries of floodplains, but also to specify the water depths and consequently, to determine the actual flooding hazard. In the hazardous areas, one should consider locating stormwater tanks or use other ways of relieving the network (e.g. drainage on individual premises) [19–23].

Acknowledgement

The work was realized within the allocation No. 0401/0006/17 awarded for Faculty of Environmental Engineering Wrocław University of Science and Technology by Ministry of Science and Higher Education in years 2017–2018.

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