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Numerical assessment of green infrastructure and permeable pavements influence on runoff outflow in small-scale industrial catchment

Numeryczna ocena wpływu zielonej infrastruktury i pokryć wodoprzepuszczalnych na spływ powierzchniowy w niewielkiej zlewni przemysłowej

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Keywords: *green roofs, permeable pavements, LID, SWMM, rainfall runoff, modeling*

Abstract
Increased number of extreme rainfall events, related to currently observed climate changes, in combination with the limited capacity of existing stormwater systems may pose a significant threat of rapid flooding in urbanized catchment. Thus, the growing popularity of Low Impact Development techniques, including green roofs and permeable pavements allowing to collect, evaporate and infiltrate rainwater directly in the urbanized catchment is understandable. This paper presents an attempt of numerical assessment of green roofs and permeable pavements efficiency in limiting the peak flows and volume of rainwater runoff generated in a selected urbanized industrial catchment. Four variants of rainwater management were studied, including no LID application and variable installation of extensive green roofs and permeable pavements. The numerical calculations were performed in SWMM 5.2, EPA, USA software for three real rainfall events of different intensity. The proposed manners of LID installation allowed to significantly reduce runoff peak flows and volume, in mean ranges of 13.4 – 58.9% and 22.6 – 70.8%, respectively.

Słowa kluczowe: *zielone dachy, powierzchnie wodoprzepuszczalne, LID, SWMM, odpływ wód opadowych*

Streszczenie
Zwiększona liczba deszczy nawalnych, wynikająca z obserwowanych aktualnie zmian klimatycznych, w połączeniu z ograniczoną przepustowością istniejących systemów odprowadzania wód deszczowych może stwarzać znaczne zagrożenie powodziami błyskawicznymi w zlewniach miejskich. Dlatego też zrozumiała jest wzrastająca popularność rozwiązań Low Impact Development, w tym zielonych dachów i pokrycia z betonów wodoprzepuszczalnych, umożliwiających powstrzymywanie, odparowanie i infiltrację wód deszczowych bezpośrednio w zlewani zurbanizowanej. Niniejsza praca przedstawia próbę numerycznej oceny efektywności zastosowania zielonych dachów i pokryć wodoprzepuszczalnych do obniżenia przepływów szczytowych oraz objętości spływu powierzchniowego w wybranej zurbanizowanej zlewni przemysłowej. Rozważono cztery warianty zagospodarowania wód deszczowych, bez instalacji LID oraz dla wariantowej instalacji ekstensywnych zielonych dachów i powierzchni wodoprzepuszczalnych. Obliczenia symulacyjne przeprowadzono za pomocą programu SWMM 5.2, EPA, USA dla trzech rzeczywistych opadów deszczu o różnym natężeniu. Zaproponowane warianty wykorzystania LID w badanej zlewni pozwoliły na znaczne obniżenie przepływów szczytowych i objętości spływu powierzchniowego, odpowiednio w zakresie 13.4 – 58.9% i 22.6 – 70.8%.

1. Introduction

Recent climate changes, resulting in heat waves, increased drought periods and extreme rainfall events, combined with the developing rapid urbanization may pose a significant threat to the urbanized areas [1, 13, 21, 29]. Urbanized catchments, with the significant share of hardly pervious sealed surfaces, are nowadays characterized by the distorted water balance, with increased runoff generation and evaporation and decreased infiltration and groundwater sources recharge [25]. Thus, urban basins, as a result of limited capacity of stormwater systems are prone to frequent rapid flooding, posing a significant threat to urban population's health and wealth [9, 14, 17]. Minimizing this threat requires decrease in the values of rainwater outflow peak flows and volume of runoff.

Low Impact Development (LID) is the engineering practice orientated towards restoring, or preserving, the pre-development water balance of the urbanized catchment by rainwater retention directly in the catchment [4, 28] using various techniques allowing to collect, infiltrate or evaporate the rainwater. The commonly applied LID green and blue architecture solutions allowing to reduce the runoff peak flows and outflow volume are green roofs and permeable pavements [3, 18, 27]. Green roofs usually consist of three layers, vegetation, substrate and drainage. The main general differences between two distinguished types, extensive and intensive, green roofs are thickness of substrate layer and maximal acceptable possible angle of roof inclination [5, 27]. Generally, the extensive green roofs have substrate layer up to 150 mm and they can be installed on steep roofs, even up to 45 degrees, while the

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intensive green roofs with substrate layer thicker than 150 mm can be installed only on roofs of inclination ≤10 degrees. Permeable pavements are surface sealing manners allowing water infiltration into soil, through gaps allowing water flow (Classic Permeable Pavements) or through pervious materials (Designed Permeable Pavements), including plates and surfaces made of permeable concrete or porous asphalts [6, 24, 26, 30].

This paper presents the study covering an attempt of numerical assessment of green architecture (extensive green roofs) and permeable pavements application influence of runoff generation in the selected urbanized industrial catchment in Lublin, Poland allowing assessment of the hydrologic efficiency of the proposed designs. The aim of this study was to numerically evaluate the possible effects of green roofs and permeable pavements installation on the hydrographs peak flows and runoff volume reduction for the selected different rainfall events.

2. Materials and methods

The numerical studies of green architecture hydrologic effects were performed in SWMM 5.2 simulation software for four variants of rainwater management in the selected urbanized basin under conditions of three real rainfall events of different depth and intensity registered in 2020 and 2021.

2.1. Catchment description

The numerical calculations of rainfall runoff generation in the small-scale urbanized industrial catchment were performed for a selected food industry basin in Lublin, Poland, presented in Figure 1. The total area of catchment was 2.48 ha with terrain inclination slopes in range 0.1 – 9.9%. The actual surface cover is in approx. 87% impermeable and consists of roofs and concrete pavements and roads (see Table 1). The remaining 13% of area are occupied by grass and trees.

Fig. 1. Studied industrial urbanized catchment

Rys. 1. Wybrana do badań przemysłowa zlewania zurbanizowana

Table 1. Surface sealing characteristics in the studied catchment

Tabela 1. Charakterystyki uszczelnienia powierzchni badanej zlewni

Surface	Area [ha]	Runoff coeffcient, ψ [-]
Roofs	1.01	0.90
Impermeable concreto sealing	1.15	0.85
Green	0.32	0.10

Rainwater system in the studied catchment consists of PVC-U pipelines of dimeters from 160 mm to 315 mm. The total length of rainwater pipelines is 805 m (d=315mm – 315 m; d=250 mm – 76 m; d=200 mm – 229 m; d=160 mm – 185 m).

2.2. Hydraulic model

The numerical simulations of runoff generation in this study were performed in the SWMM 5.2 by EPA, USA, modeling software. The characteristics of catchment and rainwater system, including surface sealing, inclination pipelines materials, diameters, length etc. were obtained from the technical documentation. The developed model consisted of 80 subcatchments, 42 nodes, one reservoir and outflow (see Figure 2). The division of total area of model into subcatchments was based on the sealing degree of particular types of surface. The width of runoff strip was determined according to the formula [23]:

$$W = \frac{A_{red}}{L_d} \tag{1}$$

where: A_{red} – reduced catchment area [m^2], L_d – calculation length of flow path from partial catchment area [m].

Fig. 2. Scheme of developed model including assumed subcatchments of different imperviousness for the actual rainwater management

Rys. 2. Schemat opracowanego modelu przedstawiający przyjęte stopnie uszczelnienia zlewni dla aktualnego sposobu zagospodarowania wód opadowych

The following assumptions were made for the numerical calculations: i) dynamic model wave was selected, ii) outflow through OUTLET node from all types of subcatchments, pervious and impervious, iii) rainwater infiltration to soil according to Horton's model, iv) time duration of simulation 24 hours.

The input data to the developed model are presented in Table 2. The required infiltration rate values for the permeable concrete paving was determined in situ using 300 mm polypropylene infiltrometer rings, according to ASTM C1701/C1701M-09 [2].

Table 2. Input data assumed to numerical calculations of runoff generation in SWMM software

Tabela 2. Dane wejściowe przyjęte do obliczeń spływu powierzchniowego w programie SWMM

Input data	Subcatchment area type		
	Roof	Pavement	Green area
% impervious	90	85	10
Max infiltration rate (mm/h)	0.12	5.0	100
Min. infiltration rate (mm/h)	0.04	1.0	4.0
Decay constant (1/h)	4		
Drying time (day)	7		

2.3. Variants of calulations

The following four variants of rainwater management in the industrial catchment were introduced to the presented study:

- Variant 1 – the actual rainwater management, without green infrastructure or permeable pavements;
- Variant 2 – introduction of extensive green roofs on approx. 86% of conventional roofs area, i.e. 0.869 ha;
- Variant 3 – introduction of permeable surface sealing instead of approx. 82% (0.942 ha) of impervious concrete;
- Variant 4 – combination of variants 2 and 3, i.e. simultaneous application of 0.869 ha green roofs and 0.942 ha of permeable pavements.

All assumed variants were tested under conditions of three different rainfall events, of different depth and intensity, registered in the nearest weather station in Radawiec, Lublin, Poland at 23 may 2020, 29 may 2021 and 1 august 2021, respectively. The data concerning the assumed rainfall events are presented in Table 3 and in Figure 3. The Euler's model of rainfall distribution was assumed to our studies.

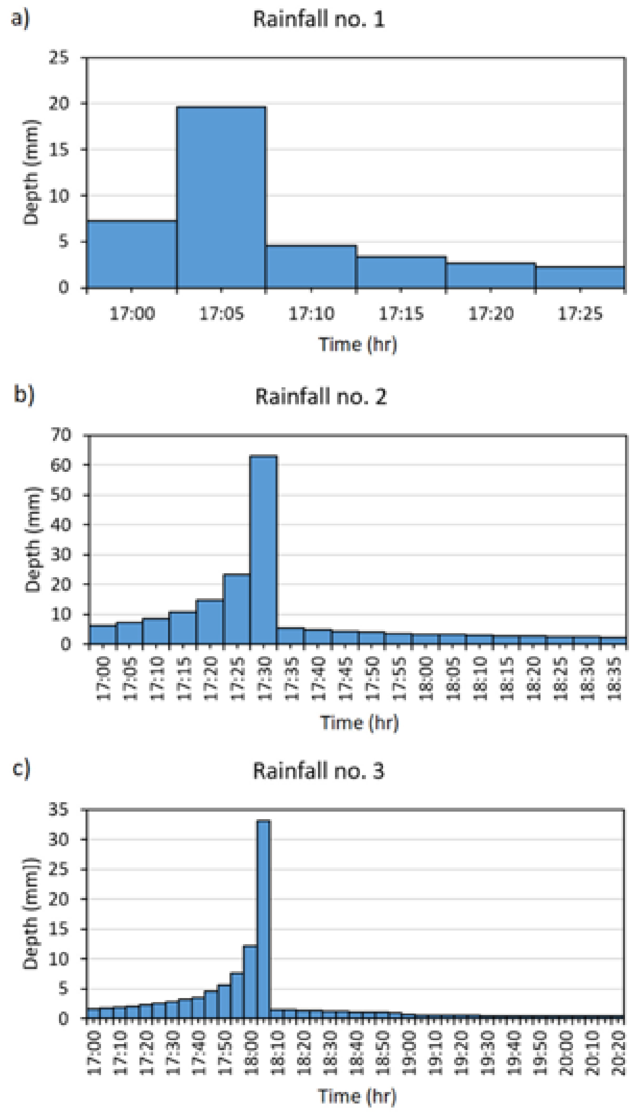

Fig. 3. Assumed rainfall events hyetographs: a) rainfall no. 1, b) rainfall no. 2, c) rainfall no. 3

Rys. 3. Przyjęte do obliczeń hietogramy opadów: a) opad nr 1, b) opad nr 2, c) opad nr 3

Table 3. Characteristics of assumed rainfall events

Tabela 3. Charakterystyki opadów przyjętych do obliczeń

Rainfal no.	Rainfall height (mm)	Time duration (min)	Rainfall intensity (mm/hr)
1	39.60	25	95.04
2	177.60	95	112.17
3	105.30	200	31.59

The typical construction of extensive green roof was assumed in our studies, covering: i) grass vegetation layer; ii) 8 cm commercially available extensive substrate, in agreement with German FLL and GRO UK green roof guidelines [11, 12, 16]; iii) standard polypropylene geotextile infiltration layer; iv) 25 mm HDPE mat (high-density polyethylene) drainage layer; v) reinforced PVC (polyvinyl chlorine) membrane hydro insulation layer; vi) 0.5 mm LDPE (low-density polyethylene) foil root protection barrier. Table 4 presents particle size distribution of the selected substrate while Figure 4 shows its water retention abilities described by the pF curve, where pF=log H, where H–pressure head in cm. The detailed SWMM input data concerning green roof construction and its hydraulic properties are presented in Table 5. The initial saturation or green roofs substrate and permeable pavement soil layer was assumed as 30%.

Table 4. Particle size distribution of assumed substrate [16]

Tabela 4. Uziarnienie substratu ekstensywnego przyjęte do obliczeń [16]

Particle size fraction	Particle content (%)
Stones (> 8 mm)	4.9
Coarse gravel (8–4 mm)	34.6
Fine gravel (4–2 mm)	4.7
Very coarse sand (2–1 mm)	3.4
Coarse sand (1–0.5 mm)	12.1
Medium sand (0.5–0.25 mm)	23.6
Fine sand (0.25–0.125 mm)	11.9
Very fine sand (0.125–0.05 mm)	1.1
Silt (0.05–0.002 mm)	2.4
Clay (< 0.002 mm)	1.4

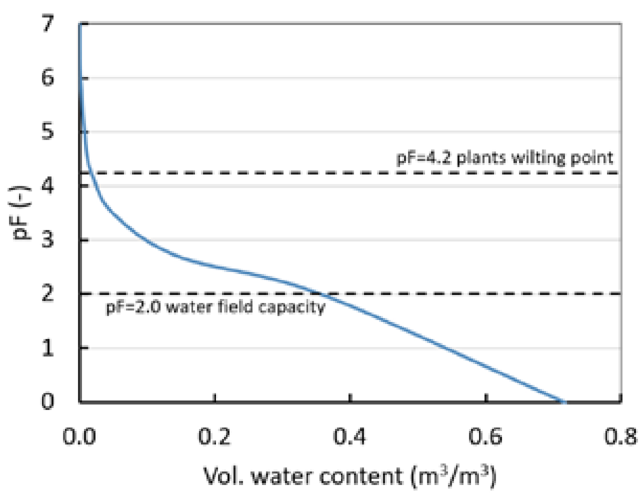

Fig. 4. Water retention curve of selected substrate, developed after [16]

Rys. 4. Krzywa retencyjna wybranego substratu, opracowano na podstawie [16]

The main hydraulic and retention characteristics of permeable surface sealing and subsurface soil and storage layers assumed to calculations are presented in Table 6. Results of numerical calculations concerning volumetric flow rate of runoff outflow from the tested urbanized catchment were statistically verified using the standard methods including basic statistics, correlation matrices, Shapiro-Wilk normality tests and non-parametric one-way Kruskal-Wallis ANOVA with a post-hoc test.

Table 5. Hydraulic and water retention characteristics of selected extensive green roof assumed to calculations

Tabela 5. Charakterystyki hydrauliczne i retencyjne ekstensywnego zielonego dachu przyjętego do obliczeń

Characteristics	Value
Extensive substrate	
Saturated hydraulic conductivity (cm/min)	21.30
Total porosity (m^3/m^3)	0.717
Water field capacity (m^3/m^3)	0.357
Plants wilting point (m^3/m^3)	0.019
Hydraulic conductivity slope (-)	46.86
Surface layer	
Berm height (mm)	50
Vegetation volume fraction	0.05
Surface roughness Manning's coefficient ($s/m^{1/3}$)	0.24
Surface slope (%)	5%
Drainage layer	
Thickness (mm)	25
Void fraction (-)	0.3
Roughness Manning's coefficient ($s/m^{1/3}$)	0.2

Table 6. Hydraulic and water retention characteristic of permeable pavement assumed to numerical calculations

Tabela 6. Charakterystyki hydrauliczne i retencyjne powierzchni wodoprzepuszczalnej przyjętej do obliczeń

Characteristics	Value
Surface	
Manning's roughness coefficient ($s/m^{1/3}$)	0.24
Pavement	
Thickness (mm)	100
Void ratio (-)	0.15
Impervious Surface Fraction (-)	0
Permeability (mm/hr)	30.83
Soil layer (sand)	
Thickness (mm)	60
Porosity (-)	0.420
Field Capacity (-)	0.292
Wilting Point (-)	0.003
Conductivity slope (-)	48.00
Suction Head (mm)	48.25
Conductivity (cm/min)	0.534
Storage layer	
Thickness (mm)	250
Void ratio (-)	0.5
Seepage rate (mm/hr)	18.96

3. Results and discussion

Figure 5 presents calculated runoff outflow hydrographs for all tested manners of rainwater management in the studied catchment and all three applied rainfall events. It is visible that in all cases, for each applied rainfall event, application of green roofs and permeable pavements, or their combination, resulted in changes in hydrograph shape, affecting clearly its maximal peak value. The modeled values of peak flow reduction possible due to application of the proposes LID devices are presented in Table 7. The lowest efficiency in peak flow reduction, from 7.8% to 21.9%, was determined for Variant 2 assuming sole application of permeable pavements. Installation of the proposed extensive green roofs allowed to significantly reduce the runoff peak flow rate by 29.8-47.6%. The highest calculated hydraulic efficiency, from range 47.4-69.2%, was observed for the Variant 4 assuming combination of extensive green roofs and permeable pavements.

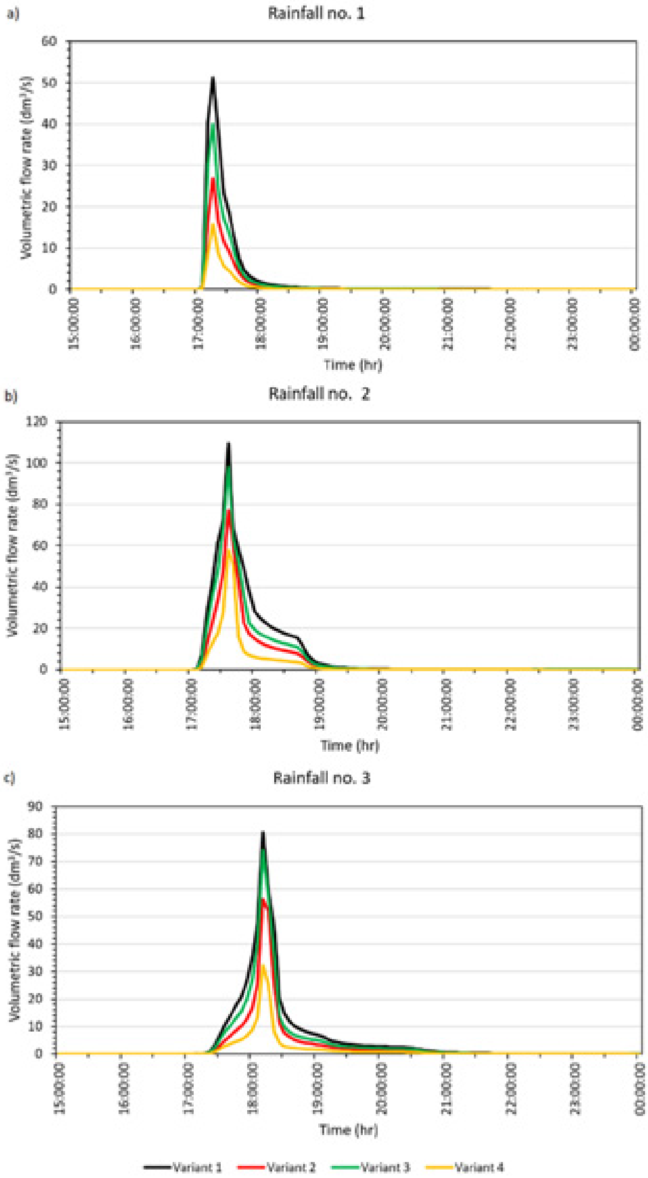

Fig. 5. Time-related rainwater outflow volumetric flow rate for different rainfall characteristics and all studied variants of rainwater management

Rys. 5. Natężenie objętościowe odpływu wód deszczowych z badanej zlewni dla różnych charakterystyk opadów oraz założonych sposobów zagospodarowania wody deszczowej

Table 7. Determined reduction of rainwater runoff peak flow

Tabela 7. Obliczona redukcja przepływów szczytowych spływu powierzchniowego ze zlewni

Variant	Peak flow rate (dm^3/s)			Peak flow rate reduction (%)			
	Rainfall no. 1	Rainfall no. 2	Rainfall no. 3	Rainfall no. 1	Rainfall no. 2	Rainfall no. 3	Mean reduction (%)
1	51.25		80.48	-	-	-	-
2	26.83	76.97	56.3	47.6	29.8	30.0	35.8
3	40.03	97.96	74.2	21.9	10.6	7.8	13.4
4	15.77	57.62	32.18	69.2	47.4	60.0	58.9

Figure 6 presents calculated accumulated volume of runoff outflow determined for all studied variants of rainwater management and three applied rainfall events. As it could be expected, application of the proposed LID techniques allowed to significantly reduce the volume of generated runoff, up to approx. 75%. Again, the highest efficiency in runoff volume reduction, from range 65.8-74.8% for the applied rainfall events was observed for the fourth variant, assuming combination of green roofs and permeable pavements. Similarly, the lowest calculated runoff reduction, i.e. 20.5-25.9%, was determined for the Variant 3, assuming the sole application of permeable pavements.

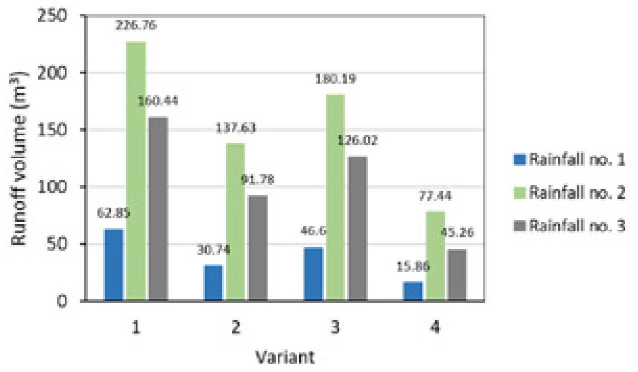

Fig. 6. Calculated accumulated runoff volume for all studied manners of rainwater management and three tested rainfall events

Rys. 6. Obliczona sumaryczna objętość spływu powierzchniowego dla wszystkich badanych wariantów zagospodarowania wód opadowych oraz trzech przyjętych opadów

Table 8. Calculated runoff volume reduction

Tabela 8. Obliczona redukcja objętości spływu powierzchniowego

Variant	Runoff volume (m^3)			Runoff volume reduction (%)			
	Rainfall no. 1	Rainfall no. 2	Rainfall no. 3	Rainfall no. 1	Rainfall no. 2	Rainfall no. 3	Mean reduction (%)
1	62.85	226.76	160.44	-	-	-	-
2	30.74	137.63	91.78	51.1	39.3	42.8	44.4
3	46.6	180.19	126.02	25.9	20.5	21.5	22.6
4	15.86	77.44	45.26	74.8	65.8	71.8	70.8

The performed statistical analysis of obtained results of simulations show that despite the fact that all runoff outflow hydrographs for a particular rainfall and all tested manners of rainwater management are described by very strong correlations (see Table 9), the observed differences in hydrographs distributions, tested by non-parametric one-way Kruskal-Wallis ANOVA are statistically significant. The determined p-value level for a post-hoc test, presented in Table 10, showed that these differences are generated by Variant 4.

Table 9. Correlation matrices for rainwater runoff outflow hydrographs

Tabela 9. Macierze korelacji wyznaczone dla hydrogramów odpływu wód deszczowych ze zlewni

Rainfall no. 1				
	Variant 1	Variant 2	Variant 3	Variant 4
Variant 1	-	0.994	0.997	0.986
Variant 2	0.994	-	0.996	0.997
Variant 3	0.997	0.996	-	0.991
Variant 4	0.986	0.997	0.991	-
Rainfall no. 2				
	Variant 1	Variant 2	Variant 3	Variant 4
Variant 1	-	0.981	0.994	0.916
Variant 2	0.981	-	0.993	0.967
Variant 3	0.994	0.993	-	0.943
Variant 4	0.916	0.967	0.943	-
Rainfall no. 3				
	Variant 1	Variant 2	Variant 3	Variant 4
Variant 1	-	0.977	0.994	0.962
Variant 2	0.977	-	0.992	0.989
Variant 3	0.994	0.992	-	0.983
Variant 4	0.962	0.989	0.983	-

Table 10. Determined p values of post-hoc test for one-way non-parametric ANOVA test of rainwater runoff hydrographs

Tabela 10. Wyznaczone wartości p dla testu post-hoc do nieparametrycznego testu ANOVA hydrogramów odpływu

Rainfall no. 1				
	Variant 1	Variant 2	Variant 3	Variant 4
Variant 1		0.266448	0.901979	0.000000
Variant 2	0.266448		1.000000	0.000883
Variant 3	0.901979	1.000000		0.000075
Variant 4	0.000000	0.000883	0.000075	
Rainfall no. 2				
	Variant 1	Variant 2	Variant 3	Variant 4
Variant 1		0.390556	0.977948	0.000015
Variant 2	0.390556		1.000000	0.024941
Variant 3	0.977948	1.000000		0.005488
Variant 4	0.000015	0.024941	0.005488	
Rainfall no. 3				
	Variant 1	Variant 2	Variant 3	Variant 4
Variant 1		0.310297	1.000000	0.000175
Variant 2	0.310297		1.000000	0.152508
Variant 3	1.000000	1.000000		0.011201
Variant 4	0.000175	0.152508	0.011201	

The results of preformed numerical simulations of hypothetical installation of selected LID devices in the studied small-scale urbanized industrial catchment showed clear hydrologic benefits expressed by significant reduction of runoff peak flow and volume. The determined efficiency of green roofs and permeable pavements application in the studied catchment was comparable to previously described in the literature considering in-situ monitoring or numerical simulations of retention abilities of LIDs [7, 8, 10, 15, 19, 20]. Moreover, the calculated retention abilities of applied LID devices were in some cases greater that for the similar solutions applied in several residential or educational services basins, under various climatic conditions, due to the significant share area of sealed surfaces in industrial catchments which could be replaced by LIDs [19, 22, 27, 29].

4. Conclusions

The performed numerical simulations of hydrologic efficiency of selected variants of LID, i.e. extensive green roofs and permeable pavements, applied in the small-scale urbanized industrial catchment allowed the following conclusions:

- All suggested LID devices, green roofs and permeable pavements, allowed significant reduction of peak flows and volume of generated rainwater runoff outflow from the studied industrial catchment.
- The mean LID reduction degree of rainwater outflow hydrograph peak flows varied between 13.4 and 58.9%, while mean reduction of accumulated runoff outflow volume reached the level 22.6 – 70.8%.
- The highest efficiency in restoring the water balance of urbanized catchment was determined for simultaneous application of extensive green roofs and permeable pavements, in this case peak flow and runoff volume reduction reached the level of 47.7%–69.2% and 65.8%–74.8%, respectively.
- The lowest degree of peak flows and runoff volume decrease was determined for the sole application of permeable pavements, i.e. 7.8%–21.9% peak flow and 20.5%–25.9% of runoff volume reduction.
- Numerical modeling studies allow the possibility to assess hydrologic effects of hypothetical variants of LIDs installation, thus, in our, opinion, should be commonly implemented to decision-making process in LID designing. ■

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