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# Numerical assessment of rainwater management in historical central town square catchment with different surface sealing

## Numeryczna ocena zagospodarowania wód opadowych na obszarze zlewni historycznego placu miejskiego o zróżnicowanym uszczelnieniu powierzchni

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**Keywords:** *urban catchment, water balance, Low Impact Development, rain garden, numerical modeling, revitalization*

**Abstract**

Revitalization of historical town squares in Poland is frequently related to increase in their paved area combined with decrease in the green area and removal of trees. Taking into account increasing number of torrential rainfall events, highly sealed urban basins are prone to flooding as a results of distorted hydrologic cycle with elevated runoff, exceeding capacity of existing stormwater systems, combined with limited interception and infiltration. Thus, application of sustainable stormwater management in the historical towns centers seems to be reasonable.

This paper presents numerical assessment of changes in water cycle caused by revitalization in the basin of the Lithuanian Square in Lublin, Poland. The improvement of water balance due to installation of raingardens, as a popular Low Impact Development designs, was also proposed and numerically validated. Numerical simulations were performed in Stormwater Management Model 5.2 by EPA, USA for a period 1st April – 30th June 2024. The obtained results, covering accumulated rainwater volume, outflow hydrographs and determined runoff coefficients, indicated that rainwater management before and after revitalization performed comparably. Installation of raingardens allowed clear improvement in the rainwater balance of the whole studied basin allowing 27.7% decrease in total rainwater outflow, decrease in runoff coefficient to 0.476 and changes in hydrographs with peak flows reduced up to 47.45%.

**Słowa kluczowe:** *zlewnia zurbanizowana, bilans wodny, Low Impact Development, ogród deszczowy, modelowanie numeryczne, rewitalizacja*

**Streszczenie**

Rewitalizacja historycznych placów polskich miast jest często powiązana ze wzrostem powierzchni utwardzonej oraz zmniejszeniem udziału obszarów zielonych oraz usuwaniem drzew. Biorąc pod uwagę wzrastającą liczbę intensywnych opadów, znacznie uszczelnione zlewnie zurbanizowane stają się wysoce podatne na podtopienia wynikające z zaburzonego cyklu hydrologicznego o podwyższonym spływie powierzchniowym, przekraczającym wydajność istniejących systemów odwadniających, oraz ograniczonych intercepcji i infiltracji. Zatem, nacisk na stosowanie zrównoważonego zagospodarowywania wód opadowych w historycznych centrach miast wydaje się być uzasadniony. Niniejsza praca przedstawia numeryczną ocenę zmian bilansu wodnego spowodowaną rewitalizacją zlewni Placu Litewskiego w Lublinie, Polska. Zaproponowano także, oraz numerycznie oceniono, poprawę bilansu wodnego zlewni możliwą dzięki instalacji ogrodów deszczowych, popularnego rozwiązania Low Impact Development. Obliczenia symulacyjne przeprowadzono w programie Stormwater Management Model 5.2, EPA, USA dla okresu 1 kwietnia – 30 czerwca 2024 r. Otrzymane wyniki, obejmujące sumaryczną objętość wody deszczowej, hydrogramy odpływu oraz obliczone współczynniki spływu wykazały, że zagospodarowanie wody deszczowej przed i po rewitalizacji funkcjonowało podobnie. Natomiast, zastosowanie ogrodów deszczowych pozwoliło na wyraźną poprawę bilansu wodnego zlewni, umożliwiając 27,7% zmniejszenie odpływu wód deszczowych, obniżenie współczynnika spływu do wartości 0,476 oraz redukcję przepływów maksymalnych o 47,45%.

## Introduction

Current climate changes, combining elevated air temperature, heat waves, prolonged dry periods and increasing number of extreme torrential precipitations may cause the significant problems for urban areas and the municipal stormwater systems. In relation to the continuously increasing level of urbanization, resulting with increase in the highly sealed surfaces area in urban basins, the negative altering of water balance, resulting in increased runoff generation and limited infiltration and groundwater recharge, is possible [2, 5, 6, 8,14]. Thus, during the peak flows caused by torrential rainfall events the capacity of existing pipelines systems may be exceeded and urban flooding, dangerous for property and infrastructure, may be possible [1, 5, 40]. This problem, noted in various regions, may be particularly important in the traditional pipe-based storm water management and highly sealed historical centers of the cities, where rainwater was collected by gutters and through system of pipelines discharged to the nearest receiver, most commonly surface waters [35]. Additionally, such rainwater management may cause the serious threat by a delivered significant load of washed pollutants to quality of rainwater receiver waterbody [2]. Moreover, according to the European Water Frame Directive [11] control of quantity and quality of runoff water should be performed at the local level or as close as possible to the source. Thus, introduction of sustainable urban rainwater management allowing green cities, with reduced sensitivity to climate changes, heat and flooding seems to be necessary [40].

Green architecture, combining plants and porous filter media, is capable in restoring the alerted water balance of urban catchments [2, 5, 26]. The special attention should be given to urban bioretention systems, including raingardens, [26, 35] usually consisting of

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permeable filter bed layer (various mixtures of sand, soil, compost, gravel or demolition wastes) and vegetation layer. Raingardens, as installed directly over the soil bed, collect runoff and infiltrate rainwater through the filter layer to the existing subsoil or, as a possibility, to the drainage system. According to the guidelines [27] the area of raingardens should constitute 5-10% of the catchment. However, the different values were suggested, even up to 20% of dewatered area, according to available type of subsoil [32]. Such devices are usually associated with the several benefits to the urban basins, inter alia: increase in infiltration and evapotranspiration, limiting and delaying surface runoff, removing pollutants from rainwater, mitigating urban heat and providing biodiversity [1, 25]. The reported maximum level of runoff reduction possible duet to raingardens installation in urban basins reaches the level of 97-98% [36, 42]. However, the performance of raingardens should be assessed not only according to their environmental sustainability but also regarding the other main aspects of sustainability, economic and social. Considering main direct economic benefits of raingardens as commonly related to preventing flooding leading to damages to buildings and infrastructure while co-benefits as related to increase in public health, lower antrhoporessure on surface waters, reduced stormwater fees or taxes, outside co-founding etc. raingardens may be, under certain conditions, assumed as cost-effective. However, the result of cost and benefits analyses can be different for various locations with different climate, subsoils and economy [1, 2, 40]. Raingardens are considered as bringing also the social benefits, not only by reducing heat islands, improving air quality and benefiting human health, but also due to their high aesthetic, educational and recreational value [7, 36, 38]. The survey performed in selected locations in Australia [8] showed a very positive attitude towards raingardens presented by most of the respondents.

During the last decades in Poland, the very unfavorable for the urban rainwater balance phenomenon was observed in revitalization projects, the overuse of concrete or concrete-based pavement in a public space, commonly combined with the significant removal of green areas and trees. This phenomenon caused so strong public reactions that even the new world appeared in the popular and scientific Polish language: "betonoza", which may be loosely translated to English as "concretemania" [15, 18, 21, 23, 29]. The clear examples of "betonoza" are presented in Figure 1.

To better understand the variable possible range of selected revitalizations and their effects on the urban catchment, the comparison for three basins, before and after restoration, was presented in Figure 2.

According to a fundamental paper by Dymek and Jóźwik [10], only in Lublin Voivodship 48 projects related to revitalization of central squares in 39 towns, covering 40 town squares, were performed in 2000-2020. In all reported cases revitalization covered exchange of the existing surface cover to new, frequently based on concrete or granite pavements or various size and shape of flagstones. Nearly in all cases, the revitalization was also related to increase in highly sealed paved area at the expense of green area and trees removal. Exemplary, 80 trees were removed in Dęblin and 58 in Parczew. The mean increase in paved area of revitalized towns squares reached the value of nearly 20%, while in the following


*Fig. 1. Examples of revitalized main historical town squares in selected cities in Poland: a) Skierniewice, b) Limanowa, c) Włocławek, d) Lubaczów, modified after [22]*

*Rys. 1. Przykłady rewitalizacji historycznych placów w wybranych polskich miastach: a) Skierniewice, b) Limanowa, c) Włocławek, d) Lubaczów, opracowano na podstawie [22]*


*Fig. 2. Exemplary cases of historical parts of cities before and after revitalization: a) Rzepin, b) Kruszwica, c) Janów Podlaski, modified after [22]*
*Rys. 2. Wybrane przykłady historycznych obszarów miast przed i po rewitalizacji: a) Rzepin, b) Kruszwica, c) Janów Podlaski, opracowano na podstawie [22]*

towns after restoration paved area reached the level of 90-100%: Hrubieszów, Janów Lubelski, Krasnystaw (from over 40% to nearly 90%), Parczew (the most extreme example, from below 40% to over 90%), Poniatowa, Radzyń Podlaski, Siedliszcze [10]. The similar revitalization was also performed during 2016-2017 in the capital city of Lublin Voivodeship, where the Lithuanian Square was renovated. The green area of square after revitalization was reduced from 41.3% to 36.2%, while the increase in paved area was observed, from 57.2% to 63.7%.

The presented examples of revitalization of historical central places of numerous cities in Poland, rise concerns about unfavorable changes in water balance of urban basins resulting in increased surface runoff and possible application of manners restoring, at least partially, the distorted hydrologic cycle. Thus, the main aims of this paper may be presented as follows:

Numerical assessment of water balance of the main historical town square in Lublin, the Lithuanian Square, before and after revitalization, during the selected time duration;

Numerical assessment of proposed improvement of hydrologic cycle due to installation of raingardens in the selected subcatchments of the studied basin.

## Materials and methods

### Object description

The presented numerical calculations of water balance and rainwater outflow were performed for the selected highly sealed historical urban basin of Lithuanian Square (Plac Litewski in Polish) in Lublin, Poland. This basin is located in the central part of Lublin and covers area of approx. 35 000 $m^2$ (including surrounding buildings). The Lithuanian Square, erected in the first half of XIX century, listed in the national Register of Historical Monuments [20] is a traditional place of state ceremonies and other happenings in Lublin. During the period of 2016-17 the square underwent a serious revitalization related to extending boundaries for pedestrian movement, removal of car traffic, exchange of surface sealing, rearrangement of green areas etc.

The weather conditions in the described object area are characterized [17] by annual precipitation 560 mm and mean annual temperature 7.3 C deg.

In this paper two versions of Lithuanian Square basin spatial arrangement were considered, before and after the revitalization, both of area of 29177.7 $m^2$. The data concerning type and determined area of different surface sealing types are presented in Table 1, while the orthophotos of the square before and after reconstruction, with marked boundaries of the basin, are presented in Figures 3 and 4.

**Table 1. Types of surface sealing in Lithuanian Square, Lublin before and after revitalization**
**Tabela 1. Rodzaje uszczelnienia powierzchni na obszarze Placu Litewskiego w Lublinie, przed i po rewitalizacji**

| Surface saling type | Area before revitalization ($m^2$) | Actual area ($m^2$) |
|---|---|---|
| Green area | 12057.70 | 10572.70 |
| Concrete and granite pavement | 6923.00 | 17221.00 |
| Asphalt pavement | 4507.00 | 0 |
| Fountain | 413.00 | 1384.00 |
| Asphalt road | 5277.00 | 0 |
| Total | 29177.70 | 29177.70 |

As it can be noted in Table 1 and Figures 3 and 4 the performed revitalization resulted in decreased green area by 12.3% and increase in the sealed area by approx. 4.5%. The most important changes covered increase of fountain area and total removal of asphalt cover from the catchment, which was replaced by granite pavement. After revitalization all sealed area of the Lithuanian Square is covered by granite pavement of various sizes and shapes, presented in Figure 4.

*Fig. 3. Orthophoto of Lithuanian Square in Lublin, Poland before revitalization [22]*
*Rys. 3. Ortofotomapa Placu Litewskiego w Lublinie przed rewitalizacją [22]*

According to the actually available information [41] rainwater in this basin is collected by the PVC (polyvinyl chloride) stormwater system and delivered to the municipal network in the 3rd May and Radziwiłowska Streets. The total length of the system in the square area is 809 m, consisting of the following pipelines 400 mm – 134 m, 315 mm – 473 m, 250 mm – 152 m, 200 mm – 50 m.

*Fig. 4. Orthophoto of the actual conditions of Lithuanian Square in Lublin, after revitalization in 2016-2017 [41]*

*Rys.4. Ortofotomapa aktualnego stanu zagospodarowania Placu Litewskiego w Lublinie, po rewitalizacji w latach 2016-2017 [41]*

*Fig 5. Granite stones and slabs of the actual surface paving in Lithuanian Square, Lublin*

*Rys. 5. Granitowe kostki oraz płyty aktualnego pokrycia powierzchni Placu Litewskiego w Lublinie*

## Numerical modeling

Numerical modeling calculations of rainwater management in the area of the Lithuanian Square in Lublin were performed in SWMM (Stormwater Management Model) 5.2 by the United States Environmental Protection Agency (US EPA) for the real weather conditions registered during the period of 90 days, i.e. 3 months, 1st April – 30th June 2024.

During the tested period, the total sum of 148.00 mm of rain was registered by the DAV-6152EU Vantage Pro 2 weather station, by Davis Instruments, located in the campus of Lublin University of Technology. Table 2 presents the characteristics of notable rainfall events of depth greater than approx. 1 mm. Figure 6 shows hyetographs of selected rainfall events from the studied period.

**Table 2. Characteristics of most notable rainfall events from period 1st April – 30th June 2024**

**Tabela 2. Charakterystyki najważniejszych opadów z okresu 1 kwietnia – 30 czerwca 2024**

| Day | Time | Rain depth (mm) | Rain duration (hr:min) | Rain rate (mm/hr) | Rainwater unit outflow (dm³/(s×ha)) |
|---|---|---|---|---|---|
| 2024-04-02 | 13:50 | 8.8 | 05:15 | 1.68 | 4.66 |
| 2024-04-05 | 02:45 | 5.2 | 06:10 | 0.84 | 2.34 |
| 2024-05-22 | 17:20 | 1.6 | 01:20 | 1.20 | 3.33 |
| 2024-06-07 | 18:50 | 2.8 | 00:20 | 8.40 | 23.33 |
| 2024-06-09 | 05:35 | 8 | 02:25 | 3.31 | 9.20 |
| 2024-06-10 | 07:45 | 6.2 | 00:40 | 9.30 | 25.83 |
| 2024-06-10 | 15:10 | 6.6 | 00:35 | 11.31 | 31.43 |
| 2024-06-10 | 16:35 | 19.8 | 01:40 | 11.88 | 33.00 |
| 2024-06-13 | 08:20 | 2 | 00:40 | 3.00 | 8.33 |
| 2024-06-13 | 13:40 | 4.6 | 01:45 | 2.63 | 7.30 |
| 2024-06-13 | 18:25 | 1.8 | 00:30 | 3.60 | 10.00 |
| 2024-06-13 | 19:40 | 0.8 | 00:15 | 3.20 | 8.89 |
| 2024-06-13 | 22:10 | 1.2 | 01:05 | 1.11 | 3.08 |
| 2024-06-16 | 19:45 | 3.6 | 00:45 | 4.80 | 13.33 |
| 2024-06-16 | 21:55 | 1.2 | 00:25 | 2.88 | 8.00 |
| 2024-06-19 | 22:20 | 2.6 | 00:15 | 10.40 | 28.89 |
| 2024-06-19 | 23:20 | 1.2 | 00:30 | 2.40 | 6.67 |
| 2024-06-22 | 12:15 | 14.2 | 00:10 | 85.20 | 236.67 |

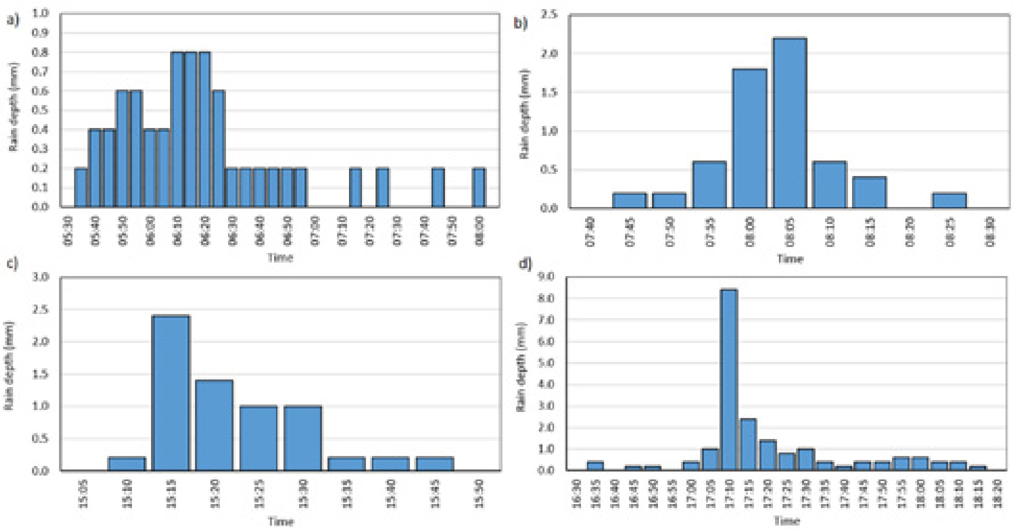


*Fig. 6. Hyetographs of selected rainfall events: a) 9th June 2024, b-d) 10th June 2024*

*Rys. 6. Hietogramy wybranych opadów: a) 9 czerwca 2024, b-d) 10 czerwca 2024*

There were three variants of rainwater management in the catchment of Lithuanian Square in Lublin tested in this paper:

Variant I, the historical variant assuming the spatial arrangement of the basin before revitalization in 2016-2017, the developed numerical model presented in Figure 7 consists of 53 subcatchments.

Variant II, the actual rainwater management, after revitalization in 2016-2017, the model, shown in Figure 8, due to more complicated spatial arrangement was divided into 87 subcatchments.

Variant III, assuming tests of possible improvement of urban basin water balance due to Low Impact Development designs, i.e. raingardens, introduction. For six highly sealed subcatchments of total area 9128 m$^2$, see Figure 9, the raingardens of total area 595 m$^2$, constituting approx. 6.5% of dewatering basin [9, 27], were designed.

**Table 3. Input data for stormwater runoff modeling**

Tabela 3. Dane wejściowe przyjęte do modelowania spływu powierzchniowego

| Parameter | Unit | Value |
|---|---|---|
| Average surface slope | (%) | 0.20 – 3.50 |
| Width of overland flow path | (m) | 1.00 – 50.00 |
| Manning's n for impervious area | (s/m$^{1/3}$) | 0.012 |
| Manning's n for pervious area | (s/m$^{1/3}$) | 0.15 |
| Depth of depression storage on impervious area | (mm) | 1.50* |
| Depth of depression storage on pervious area | (mm) | 4.50* |
| Percent of impervious area with no depression storage | (%) | 50.00* |

*Values adopted based on literature data [34]

In all tested cases the same underground system of stormwater PVC pipelines was assumed, with 47 links, 33 nodes and two outflows. The assumed Manning's coefficient of roughness for the pipes was 0.015 s/m$^{1/3}$.

The input data accepted for modeling are presented in Table 3 while the assumed infiltration rate values for the surface sealing materials were based on literature [3, 13] and are presented in Table 4. Table 5 presents assumed data for raingarden modeling. Basing on information provided by The Polish Geological Institute – National Research Institute the local soil, as a storage layer, was assumed as silt loam with particle size composition: sand 30%, silt 52%, clay 18% [16]. The raingarden was designed as 300 mm layer of ceramsite, dolomite, compost and coarse-grained sand substrate covered by vegetation layer. The scheme of proposed raingarden layout is presented in Figure 10. The initial saturation of raingarden substrate was selected as 30%, i.e. 0.3 m$^3$/m$^3$.

**Table 4 Infiltration rate values for various type of surface sealing assumed to calculations [24, 33]**

Tabela 4. Przyjęte do obliczeń wartości prędkości infiltracji uszczelnienia powierzchni [24, 33]

| Surface | Minimal Infiltration rate | Maximal Infiltration rate |
|---|---|---|
| | (mm/hr) | (mm/hr) |
| Green area | 8.57 | 75 |
| Granite paving slabs | 0.36 | 1.5 |
| Granite and concrete paving stones | 0.42 | 31.3 |
| Asphalt pavement | 0.04 | 0.36 |
| Fountain | 0 | 0 |
| Asphalt road | 0.04 | 0.36 |

**Table 5. Input data assumed to raingarden modeling, combined after [12, 34].**

Tabela 5. Dane wejściowe założone do modelowania ogrodu deszczowego, opracowano na podstawie [12, 34]

| | | |
|---|---|---|
| Surface | | |
| Berm height | (mm) | 300 |
| Vegetation volume fraction | (-) | 0.15 |
| Surface Roughness | (s/m$^{1/3}$) | 0.24 |
| Surface slope | (%) | 0.5 |
| Soil | | |
| Thickness | (mm) | 300 |
| Porosity (volume fraction) | (m$^3$/m$^3$) | 0.527 |
| Field capacity (volume fraction) | (m$^3$/m$^3$) | 0.42 |
| Wilting point (volume fraction) | (m$^3$/m$^3$) | 0.276 |
| Conductivity | (mm/hr) | 421.2 |
| Conductivity slope | (-) | 29.7 |
| Suction head | (mm) | 167.25 |
| Storage | | |
| Seepage rate | (mm/hr) | 8.57 |

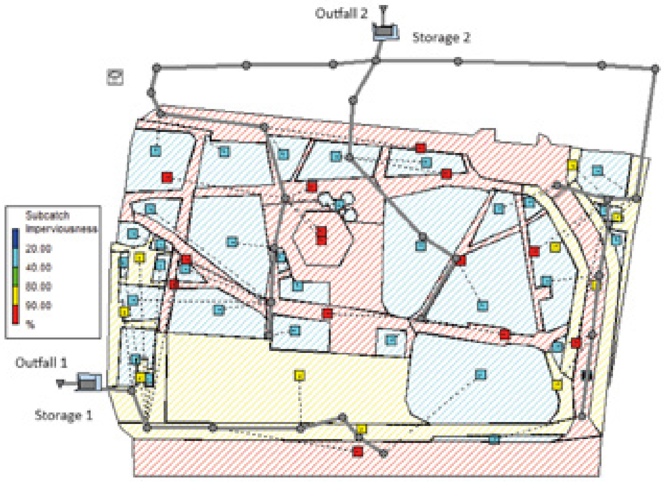


*Fig. 7. Numerical model of past spatial arrangement of studied urban catchment, before revitalization in 2016-2017*

*Rys. 7. Model numeryczny przeszłego ukształtowania przestrzennego badanej zlewni miejskiej, przed rewitalizacją w latach 2016-2017*

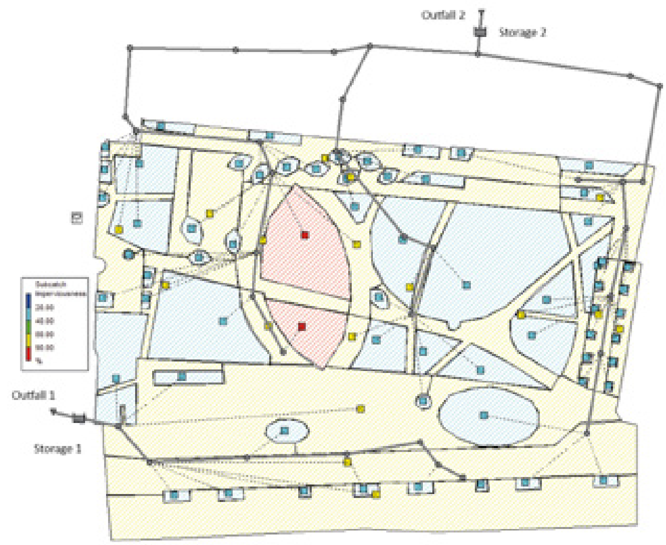


*Fig. 8. Numerical model of the actual spatial arrangement of the Lithuanian Square catchment, after restoration in 2016-2017*

*Rys. 8. Model numeryczny aktualnego ukształtowania przestrzennego badanej zlewni miejskiej, po przebudowie w latach 2016-2017*

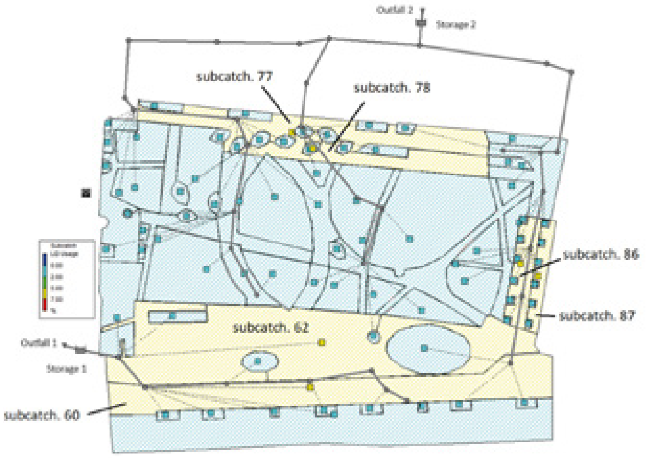


*Fig. 9. Numerical model of the actual spatial arrangement of studied catchment with proposed raingardens application in six subcatchments, marked as No. 60, 62, 77, 78, 86 and 87*

*Rys. 9. Model numeryczny aktualnego ukształtowania przestrzennego badanej zlewni miejskiej wraz z zaproponowanymi ogrodami deszczowymi w 6 zlewniach cząstkowych, oznaczonych jako 60, 62, 77, 78, 86 i 87*

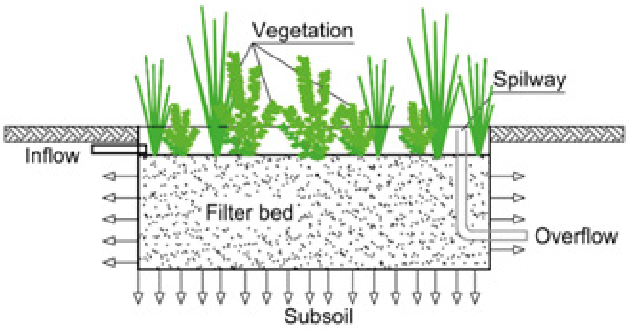


*Fig. 10. Scheme of raingarden accepted to Variant III of numerical simulations*

*Rys. 10. Schemat ogrodu deszczowego przyjętego do Wariantu III obliczeń symulacyjnych*

Analysis of urban water balance in the studied basin was based on determined volume of total rainwater outflow from the catchment and hydrographs of rainwater outflow for selected rainfall events, for all tested variants, respectively. Additionally, in order to assess the influence of raingarden introduction, the water balance of selected subcatchments was analyzed and the resultant runoff coefficient was determined. Statistical analysis of the obtained results, apart from determination of basic statistics, was, after testing the normality of variables distribution, by Shapiro-Wilk test, focused on checking the statistical significance of observed differences between time-related rainwater outflow using the suitable test. These tests were performed for two pairs of distribution: hydrographs for Variants I and II (the historical and actual surface sealing) as well as Variants II and III (the actual and modified by LIDs rainwater management).

## Results and discussion

Figure 11 shows values of accumulative volume of rainwater collected by stormwater system from the tested basin of the Lithuanian Square in Lublin for all three variants of rainwater management calculated for the period 1st April – 30th June 2024. It is visible that the difference between rainwater volume for Variants I and II, reflecting the historical and actual rainwater management, is rather low, equal approx. 3%. The significant 27.7% change in rainwater outflow volume is visible only in case of Variant III, after introducing raingardens to the selected subcatchments. Taking into account the area of studied catchment, i.e. 29177.7 $m^2$, the runoff indicator may be calculated as 100.36 mm, 97.32 mm, 70.39 mm, respectively for Variants I, II and III. Which in turn allows to determine the resultant runoff coefficient for the whole catchment, three tested variants and the studied time duration: 0.678, 0.658 and 0.476, respectively. Thus, it may be observed that the resultant values of runoff coefficient for surface sealing for the historical and actual special arrangement, before and after revitalization, are comparable, despite reduced green area after restoration. The sustaining of the comparable value of runoff indicator and runoff coefficient was possible, in our opinion, due to increase in the area of fountain and total removal of hardly permeable asphalt cover and replacing it with more permeable pavement of spaced granite blocks allowing infiltration. On the other hand, the above presented results show the significance of LIDs introduction to urban rainwater management in order to reduce the runoff generation and discharge to municipal stormwater system.

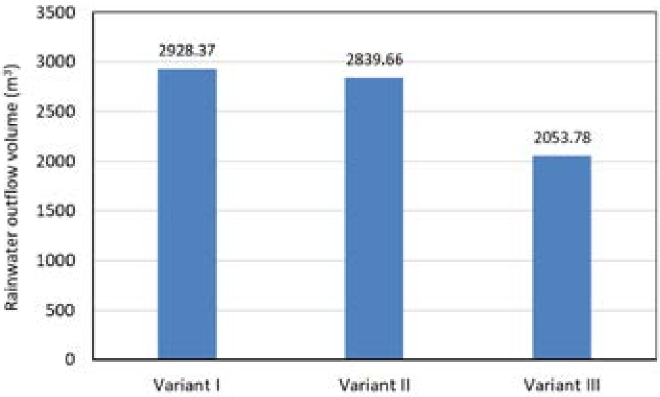


*Fig. 11. Calculated rainwater volume collected by drainage system in studied catchment during period 1st April – 30th June 2024*

*Rys. 11. Obliczona sumaryczna objętość wody deszczowej odprowadzonej przez system odwadniający badanej zlewni w okresie 1 kwietnia – 30 czerwca 2024*

Figure 12 presents hydrographs of rainwater outflow through the stormwater system from selected rainfall events of various intensity and time-related distribution for all studied variants of rainwater management. There are visible similarity in rainwater outflow distribution curves for Variant I and II for rainfall events of intensity below approx. 10 mm/hr (Figure 12 a, b and d), thus under these conditions both variants performed comparable. Visible differences in peak flows, shown also in Table 6, may be noted for rainfall events of intensity reaching over 25 mm/hr, which may be related to reduced infiltration capability of the historical surface sealing, based in huge part on asphalt cover, reflected in Variant I. In all tested cases, for all presented rainfall events, the proposed Variant III, in which raingardens were introduced, was characterized by the lowest value of simulated rainwater outflow.

**Table 6. Peak flows of rainwater outflow during rainfall events presented in Fig. 12**

**Tabela 6. Przepływy szczytowe odpływu wód deszczowych w czasie opadów przedstawionych na Rys. 12**

| Rainfall event | Peak flow ($dm^3/s$) | | | Peak flow decrease | |
|---|---|---|---|---|---|
| | Variant I | Variant II | Variant III | Variants I and II | Variants II and III |
| 2nd April | 11.69 | 11.22 | 6.53 | 4.02% | 41.80% |
| 9th June | 50.62 | 51.23 | 29.87 | -1.21% | 41.69% |
| 10th June | 593.3 | 483.33 | 334.96 | 18.54% | 30.70% |
| 16th June | 22.4 | 21.4 | 12 | 4.46% | 43.93% |
| 19th June | 161.24 | 112.44 | 59.09 | 30.27% | 47.45% |

Considering the possible improvement of the actual rainwater management in the tested basin, it should be noted, as it is visible in Table 12, that application of the typical LID devices, raingardens, to the selected highly sealed subcatchments allowed the significant

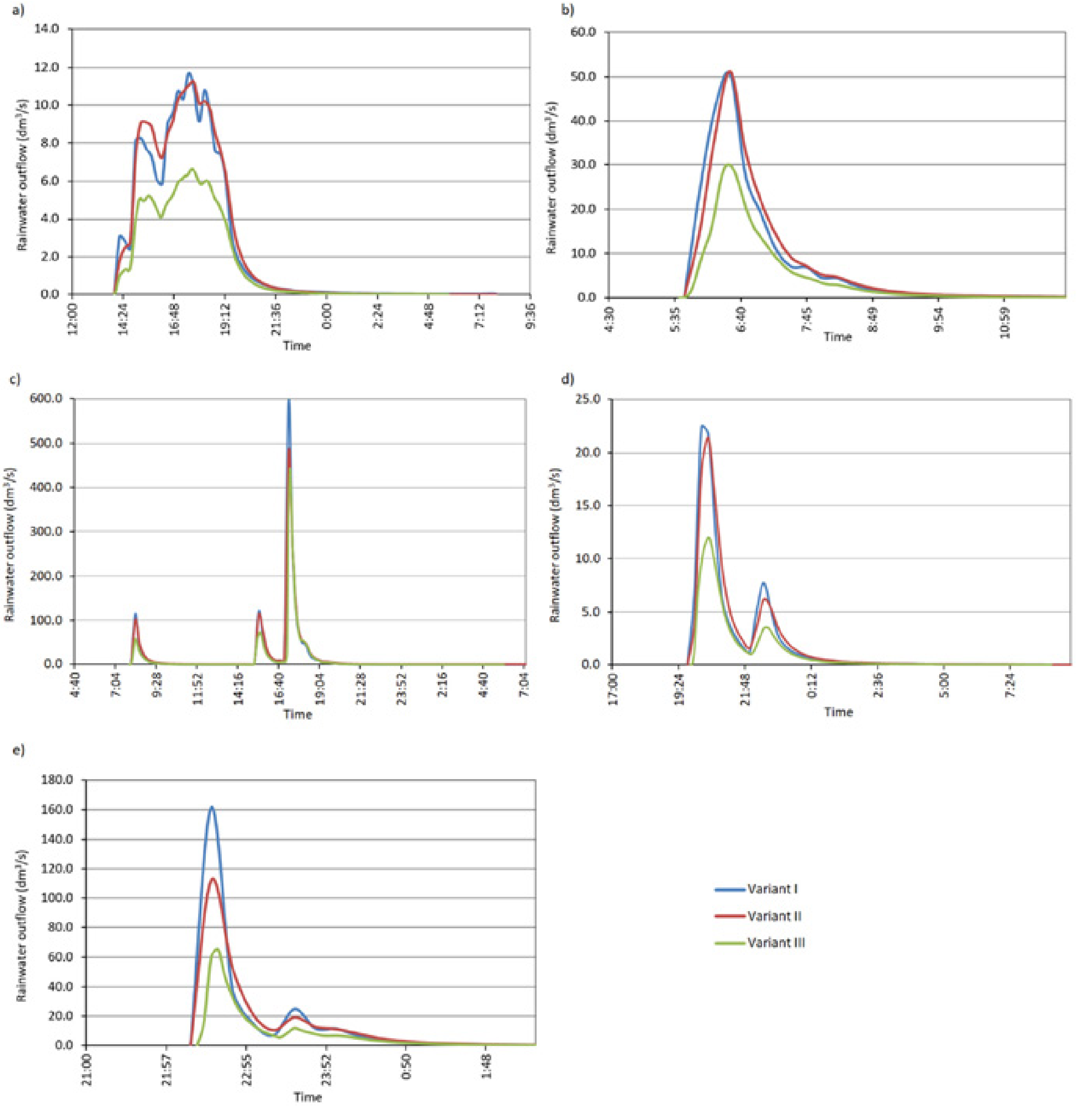


*Fig. 12. Selected simulated hydrographs of rainwater outflow from the studied catchment for all tested variants of rainwater management: a) 2nd April 2024; b) 9th June 2024; c) 10th June 2024; d) 16th June 2024; e) 19th June 2024*

*Rys. 12. Wybrane modelowe hydrogramy odpływu wód deszczowych z badanej zlewni dla wszystkich założonych wariantów zagospodarowania opadu: a) 2 kwietnia 2024; b) 9 czerwca 2024; c) 10 czerwca 2024; d) 16 czerwca 2024; e) 19 czerwca 2024*

decrease of not only the total volume of discharged rainwater (Figure 11) but also the 30.70-47.45% reduction of its peak flows. Thus, the proposed installation of raingardens should be assessed positively, during the researched time duration. The above observations are in agreement with numerous literature reports suggesting introduction of various designs of green architecture to highly urbanized basins [7, 30, 37], including also the positive, based on simulations and in-situ studies, assessment of hydrologic function of raingardens [5, 9, 26, 39].

The performed statistical analysis of variables distribution normality based on Shapiro-Wilk test showed in all cases value of $p<0.05$, thus, the null hypothesis of test was rejected and all the studied data were recognized as not normally distributed. As a result, the non-parametric Wilcoxson test for dependent samples was used to compare differences between hydrographs for two pairs of distributions: Variant I and II as well as Variant II and III. According to the obtained results the change in surface sealing after revitalization (Variants I and II) did not resulted in statistically significant change in median of rainwater outflow time-related distribution. On the contrary, changes caused in hydrographs related to raingardens introduction in the selected subcatchments (Variants II and III) were assessed as statistically significant.

To better understand the possible impacts of raingardens in highly sealed subcatchments, the components of rainwater balance for the selected basins, determined for Variants II and III, were presented in Figure 13. As it is visible, the calculated runoff for Variant II varied in the approx. range 95-98% of water balance, while the sum of evaporation and infiltration covered the remaining approx. 2-5%.

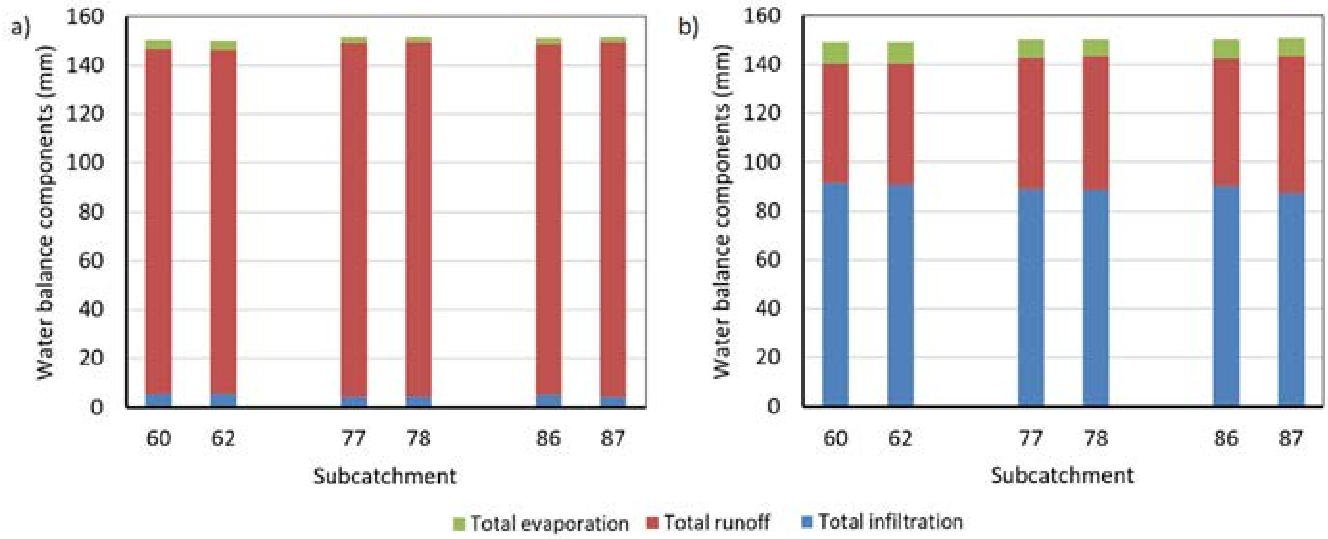


*Fig. 13. Determined components of water balance for six selected subcatchments: a) Variant II with actual rainwater management; b) Variant III with raingardens applied*

*Rys. 13. Obliczone składniki bilansu wodnego dla sześciu wybranych zlewni cząstkowych: a) Wariant II (aktualne zagospodarowanie wód opadowych); b) Wariant III (zastosowanie ogrodów deszczowych)*

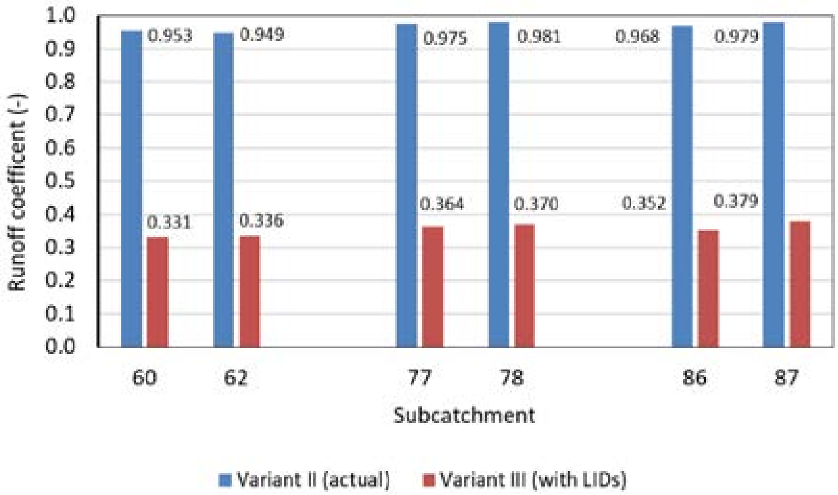


*Fig. 14. Calculated runoff coefficients for selected subcatchments with actual rainwater management and after raingardens application*

*Rys. 14. Obliczone współczynniki spływu dla badanych zlewni cząstkowych przy aktualnym zagospodarowaniu wód deszczowych oraz po instalacji ogrodów deszczowych*

After installation of the proposed raingardens the values of particular components of water balance changed clearly. The increased 88-91 mm of infiltration accompanied with 7-9 mm of evaporation were observed which resulted in runoff depth reduced to approx. 49-56 mm. Figure 14 shows determined valued of runoff coefficients for the selected subcatchments in Variant II and Variant III, i.e. the actual rainwater management and after raingardens installations. It may be noted that for the studied subcatchments and tested time duration in all cases the runoff coefficient was reduced from the level 0.95-0.98, typical for the highly sealed surface and compared to impermeable concrete and asphalt cover [28], to values in range 0.33-0.38, which may be related to typical values for single-family residential districts [4, 19, 31].

## Conclusions

The performed numerical study concerning rainwater balance for the Lithuanian Square in Lublin, Poland, for a selected time duration, the actual climatic conditions and various manners of rainwater management allowed to draw the following conclusions:

- Two tested variants of rainwater management, the historical (before revitalization in 2016-2017) and the actual (after restoration) assessed by rainwater outflow volume and time-related hydrographs performed comparably during the simulated period;
- The visible differences in rainwater hydrographs peak flows were noted only for the intense rainfall events with rain rate over 25 mm/hr for which the historical surface sealing based on asphalt cover generated greater outflow;
- The comparable values of determined runoff coefficient for the historical and the actual surface sealing, 0.678 and 0.658, respectively, were, despite reduced green area, resultant inter alia from the total replacement of hardly permeable asphalt cover by more permeable spaced granite pavement;
- Introduction of raingardens, with approx. 6.5% area share, in the selected highly sealed subcatchments clearly improved the rainwater balance of the whole studied basin allowing 27.7% decrease in total rainwater outflow, lower runoff coefficient, i.e. 0.476, changes in hydrographs and reduced by 30.70-47.45% peak flows;
- Application of raingardens in highly sealed subcatchments due to calculated clear increase in infiltration allowed reduction of their runoff coefficient values to the level 0.33-0.38 typical for single-family residential basins;
- The results of performed numerical simulations proved usefulness of Low Impact Development green architecture devices in sustainable rainwater management of urban basins allowing the partial restoration of the distorted water balance;
- In our opinion, each case of revitalization of historical basins located in centers of cities should be supported by assessment of possible resultant changes in their water balance and oriented to restoration of distorted water balance;
- The numerical model used in this study was not calibrated, due to the objective causes, thus, the presented research should be treated as preliminary;
- The presented study of possible selected LIDs application in urban basin should be extended by assessment of biodiversity improvement, urban heat island effect mitigation, social acceptance and economic efficiency to allow as full sustainability assessment as possible;

- Our studies should be continued for the longer periods with different climatic conditions and monitored rainwater outflow allowing calibration of the model.

## REFERENCES


[1] Bąk J., Barjenbruch M. 2022. "Benefits, Inconveniences, and Facilities of the Application of Rain Gardens in Urban Spaces from the Perspective of Climate Change—A Review" *Water*, 14.1153. DOI:10.3390/ w14071153.

[2] Boguniewicz-Zabłocka J., Capodaglio A.G. 2020. „Analysis of Alternatives for Sustainable Stormwater Management in Small Developments of Polish Urban Catchments" *Sustainability 12*.10189. DOI: 10.3390/su122310189.

[3] Boogaard F., Lucke T. 2019. "Long-Term Infiltration Performance Evaluation of Dutch Permeable Pavements Using the Full-Scale Infiltration Method" *Water* 11(2), 320. DOI: 10.3390/w11020320.

[4] Chao X., Mohammad R., Dagmar H., Yiping W., Meirong S., Stephan P. 2020. "Surface runoff in urban areas: The role of residential cover and urban growth form".*Journal of Cleaner Production* 262.121421. DOI:10.1016/j.jclepro.2020.121421.

[5] Chen C.F., Lin J.W., Lin J.Y. 2022. "Hydrological Cycle Performance at a Permeable Pavement Site and a Raingarden Site in a Subtropical Region" *Land 11*.951. DOI: 10.3390/land11060951.

[6] Chen Y., Zhou H., Zhang H., Du G., Zhou J. 2015. "Urban flood risk warning under rapid urbanization" *Environmental Research* 139(3).10. DOI:10.1016/j.envres.2015.02.028.

[7] Demuzere M., Orru K., Heidrich O., Olazabal E., Geneletti D., Orru H., Bhave A.G., Mittal N., Feliu E., Faehnle M. 2014. "Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure" *Journal of Environmental Management* 146.107-115. DOI:10.1016/j.jenvman.2014.07.025.

[8] Dobbie M.F., Farrelly M.A. 2022. "Using best-worst scaling to reveal preferences for retrofitting raingardens in suburban streets" *Urban Forestry & Urban Greening* 74.127619. DOI:10.1016/j.ufug.2022.127619.

[9] Dussaillant A.R., Cuevas A., Potter K.W. 2005. "Raingardens for stormwater infiltration and focused groundwater recharge: simulations for different world climates" *Water Supply* 5(3-4). 173–179. DOI:10.2166/ws.2005.0097.

[10] Dymek D., Jóźwik J. 2021. „Kształtowanie placów miejskich na przykładzie miast województwa lubelskiego" *Annales UMCS sec. B* 76.1-28. DOI:10.17951/b.2021.76.1–28, https://journals.umcs.pl/b/article/view/11415/8803.

[11] EU Water Framework Directive. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Off. J.Eur. Communities* 2000, 22, 1–73.

[12] Gdela M., Widomski M.K., Musz-Pomorska A. 2019. „Hydraulic efficiency of selected intensive green roof substrates" *Ecological Chemistry and Engineering A* 26(1-2). 37-45. DOI:10.2428/ecea.2019.26(1-2)4.

[13] Marek G. 2023. "Ocena wpływu zastosowania obiektów LID na hydrogram odpływu wód deszczowych ze zlewni kampusu Politechniki Lubelskiej". Praca magisterska, Politechnika Lubelska.

[14] Hammond M.J., Chen A.S., Djordjević S., Butler D., Mark O. 2015. "Urban flood impact assessment: a state-of-the-art review" *Urban Water Journal* 12.14–29. DOI:10.1080/1573062X.2013.857421.

[15] https://300gospodarka.pl/explainer/betonoza-nie-tylko-w-lezajsku-tlumaczymy-czemu-nie-warto-zamieniac-zieleni-na-beton

[16] https://geologia.pgi.gov.pl/mapy/

[17] https://lublin.eu/mieszkancy/srodowisko/srodowisko-przyrodnicze-lublina/klimat/

[18] https://miastojestnasze.org/betonoza-wizytowka-polskich-miast/ (accessed on 24 July 2024).

[19] https://swmm5.org/2017/11/06/runoff-coefficient-in-infosewer-and-infoswmm/

[20] https://wkz.lublin.pl/wp-content/uploads/2024/03/zalacznik-nr-1.pdf

[21] https://www.gazetakongresy.pl/betonoza-jak-rewitalizacja-polskiej-przestrzeni-miejskiej-szkodzi-wszystkim-wokol/

[22] https://www.geoportal.gov.pl/, e-mapy.net

[23] https://www.money.pl/gospodarka/betonoza-w-miastach-dlaczego-pozbylismy-sie-zieleni-z-miast-6808029991025152a.html

[24] Iwanowa A., Musz-Pomorska A., Widomski M.K. 2023. „Numerical assessment of green infrastructure and permeable pavements influence on runoff outflow in small-scale industrial catchment" *Gaz, Woda i Technika Sanitarna* 97(9).15-20. DOI:10.15199/17.2023.9.3.

[25] Jose R., Wade R., Jefferies C. 2014. "Smart SUDS: recognising the multiple-benefit potential of sustainable surface water management systems" *Water Science and Technology* 71(2).245–251. DOI:10.2166/wst.2014.484.

[26] Kasprzyk M., Szpakowski W., Poznańska E., Boogaard F.C., Bobkowska K., Gajewska M. 2022. „Technical solutions and benefits of introducing rain gardens – Gdańsk case study" *Science of The Total Environment* 835.155487. DOI:10.1016/j.scitotenv.2022.155487.

[27] Kukadia J., Lundholm M., Russell I. 2018. "Designing Rain Gardens: A Practical Guide, Urban Design London". available online https://www.urbandesignlearning.com/resources/publications/details?recordId=recOcYos3UmeZ9PMw (accessed on 24 July 2024).

[28] Lancaster B. 2006. "Guiding principles to welcome rain into your life and landscape". *Rainwater Harvesting for Drylands and Beyond*, 1. Tucson, Arizona: Rainsource Press.

[29] Mencwel J. 2020. „Betonoza. Jak niszczy się polskie miasta" Wyd. Krytyka Polityczna.

[30] Özerol G.; Dolman N.; Bormann H.; Bressers H.; Lulofs K.; Böge M. 2020. "Urban water management and climate change adaptation: A self-assessment study by seven midsize cities in the North Sea Region" *Sustainable Cities and Society* 55.102066. DOI:10.1016/j.scs.2020.102066.

[31] Pitt R.E., Clark S., Johnson P., Voorhees J. 2008. "Evapotranspiration and Related Calculations for Bioretention Devices" *Journal of Water Management Modeling* R228-19. DOI:10.14796/JWMM.R228-19.

[32] Rain gardens. Iowa Rain Garden. Design and Installation Manual, the Iowa Stormwater Partnership, Iowa Department of Agriculture and Land Stewardship-Division of Soil Conservation (IDALS-DSC). 2008. Available online: https://www.iowadnr.gov/portals/idnr/uploads/water/watershed/files/raingardens.pdf (accessed on 24 July 2024).

[33] Rammal M., Berthier E. 2020. "Runoff Losses on Urban Surfaces during Frequent Rainfall Events: A Review of Observations and Modeling Attempts" *Water* 12(10).2777. DOI:10.3390/w12102777.

[34] Rossman L. A. 2009. "Storm water management model user's manual version 5.0. National risk management research laboratory", Office of research and development. U.S. Environmental Protection Agency. Cincinnati.

[35] Sagrelius P. Ö, Blecken G., Hedström A., Ashley R., Viklander M. 2023. "Sustainability performance of bioretention systems with various designs". *Journal of Environmental Management* 340. 117949. DOI: 10.1016/j.jenvman.2023.117949.

[36] Shafique M., Kim R. 2017. "Retrofitting the Low Impact Development practices into developed urban areas including barriers and potential solution" *Open Geoscience* 9.240–254. DOI:10.1515/geo-2017-0020.

[37] Silva F.O.T., Wehrmann A., Henze H-J., Model N. 2005. "Ability of plant-based surface technology to improve urban water cycle and mesoclimate" *Urban Forestry & Urban Greening* 4(3–4).145-158. DOI:10.1016/j.ufug.2005.12.004.

[38] Siwiec E., Erlandsen A., Vennemo H. 2018. "City greening by rain gardens-costs and benefits" *Environmental Protection and Natural Resources* 29.1–5. DOI:10.2478/oszn-2018-0001.

[39] Timothy T. 2018. "Eaton, Approach and case-study of green infrastructure screening analysis for urban stormwater control" *Journal of Environmental Management* 209.495-504. DOI: 10.1016/j.jenvman.2017.12.068.

[40] Wilbers G.J., de Bruin K., Seifert-Dähnn I., Lekkerkerk W., Li H., Budding-Polo Ballinas M. 2022. "Investing in Urban Blue–Green Infrastructure—Assessing the Costs and Benefits of Stormwater Management in a Peri-Urban Catchment in Oslo, Norway" *Sustainability* 14.1934. DOI:10.3390/su14031934.

[41] www.geoportal.lublin.eu

[42] Zhang L., Ye Z., Shibata S. 2020. "Assessment of rain garden effects for the management of urban storm runoff in Japan" *Sustainability* 12(23).9982. DOI:10.3390/su12239982.