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Numerical Assessment of Green Infrastructure Influence on Hydrologic Effectiveness in a Suburban Residential Development

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ABSTRACT

Applying green infrastructure measures helps to retain water in the land during wet periods, which in turn makes it more available during periods of drought. Water retention reduces the volume of rainwater that transforms into surface runoff, allowing for the increase in the intensity of evapotranspiration and infiltration, which helps to establish a catchment with a balanced hydrologic cycle that's effectively more resistant to the consequences of climate change. With increasing popularity of introducing low impact development (LID) solutions in highly urbanised catchments characterised by a high runoff coefficient, it is important also to reduce rainwater runoff in residential areas with lower density of housing. This work presents a numerical assessment of green infrastructure (green roofs, raingardens, permeable paving and rainwater harvesting) performance in increasing retention in a catchment area consisting of single-family houses. The numerical model of potential residency in Ożarów, Poland was developed in SWMM 5.2. software, replicating local conditions with input infiltration data collected through on site and laboratory testing, as well as data gathered during a period of registering local evaporation and precipitation conditions. After running a series of simulations of three rain events, varying in their duration and intensity, the model was enhanced with green infrastructure solutions by the utilisation of LID Controls option in SWMM. With rainfall simulations resulting in varying rainwater outflow hydrographs and with differences in the volume of collected rainwater outflow, the results of LID application were consistent with the reduction of the peak rainwater outflow (reduction rate 61.90–67.99%), as well as the decrease in rainwater outflow volume (reduction rate 61.17–62.12%). This research promotes the hydrologic effectiveness of introducing green infrastructure in low density housing establishments.

Keywords: green infrastructure, hydraulic modelling, rainfall outflow modelling, rainwater drainage, rainwater harvesting, water retention, SWMM.

INTRODUCTION

The development of suburban housing establishments in Poland, with its significant increase in intensity dating back to the last decade of the 20th century, has been described as rapid and uncoordinated, resulting in poor spatial planning of areas peripheral to major Polish cities (Koj, 2020). The integration of proper land use and responsible water resource management has proven to be crucial in ensuring sustainable development of urban areas facing the negative effects of global increase in temperature (Kalfas et al., 2024). Restoring a more sustainable balance of hydrological processes that make up the water cycle, dictating the performance of solar radiation absorption through latent heat of vaporisation, has been a topic of intense research in recent years. With counteracting the hydrologic effects of climate change in mind, the introduction of green infrastructure in urban catchments, which decreases its high runoff coefficient by increasing local rainwater retention while also enhancing the intensity of evaporation and infiltration, has become a crucial factor in sustainable urban development in Poland (Szeląg et al., 2022a).

The general aim of the application of green infrastructure is to decrease the volume and peak flows of surface runoff, in means not to surpass the hydraulic capacity of stormwater drainage system during an event of intense rainfall, which could lead to urban flooding. Retained rainwater can be then gradually released into the environment by allowing for the intensification of processes that make up a more balanced hydrological cycle, mainly evapotranspiration and infiltration, the delay making the resource accessible during periods of drought. Green infrastructure, through extensive research, continuously proves to be an effective tool in mitigating the effects of climate change in urban areas (Demuzere et al., 2014; Manso et al., 2021; Szeląg et al., 2022b; Szeląg et al., 2021). In addition to hydrological advantages of LID solutions in communal spaces, developing urban infrastructure with a greater share of greenspaces helps to improve health and overall well-being of the local community. Considering the utilization of green infrastructure techniques in urban planning provides a range of economic benefits, both on individual level (by reducing costs of heating during colder season and reducing air conditioning expenses during summer months, as well as lowering the water and sewage bill with rainwater harvesting) as well as on administrative level (reducing the volume of rainwater outflow leading to lowering the cost of transporting and treating rainwater that is collected from a catchment) (Shakya and Ahiablame, 2021).

There is an abundance of research providing proof of the hydrologic effectiveness of green infrastructure measures in developing a more sustainable eco-hydrological water management system in highly urbanised areas with high percentage of sealed surfaces. When choosing from a selection of available LID solutions, the aspects that have to be taken into account are their individual preferable climatic and geo-hydrological conditions in which they would be most effective as well as the anticipated environmental, economic and social results from delivering certain projects to completion.

Increasing the share of biologically active surfaces in urban areas by developing green roofs and raingardens helps to increase biodiversity, mitigate the urban heat island effect through preservation of humidity in the air as well as to abate the traffic noise and reduce the spreading of dust (Shishegar, 2012). Vegetation introduced in urban areas also serves as a bio-filter for airborne particles that contribute to air pollution, while also absorbing heavy metals and nutrients washed out from the atmosphere and migrating across the surface after a rainfall event (Shakya and Ahiablame, 2021; Shafique et al., 2018; Kasprzyk et al., 2022). Selection of the hydrophyte plant species for the vegetation layers should be consistent with incorporating green life that is native to the investment area in order to preserve local biodiversity (Fenoglio et al., 2023). Green roof is usually designed as a five constituent structure with its layers consisting of: waterproof membrane, isolation, drainage mat, substrate and vegetation. There are three pivotal characteristics that define its retention capacity: the basic type of green roof (intensive, extensive or semi-intensive), the physical and chemical properties of selected substrate layer as well as the slope of the roof on which the structure is to be installed. Lower maintenance costs and smaller structural load determine the extensive green roof as the standard solution for single-family buildings (Shishegar, 2012). Rain garden can be defined as a landform which is shallowly depressed below the level of the surrounding area and is covered with vegetation. Its design allows for the collection, storage, infiltration and evapotranspiration of rainwater (Kasprzyk et al., 2022). The hydrological performance of raingardens is determined by the factors such as: construction and maintenance of selected bioretention system, the area of the investment, selected plant species, as well as the type and depth of soil and drainage layer (Burszta-Adamiak et al., 2023).

Reduction in the volume of rainwater that transforms into runoff can also be achieved through increasing the permeability of surfaces that cover the communication routes in an urbanised area. Permeable pavement is a solution that combines road infrastructure with water infrastructure, providing additional storage and drainage of stormwater as a result of its higher porosity in comparison to more traditional materials, such as asphalt and concrete. Depending on the combination of mineral fractions of the native soil, the implementation of pervious pavement can increase infiltration or allow for the deliberate exfiltration of rainwater by a drainage system into the nearest retention basin. Due to the overtime buildup of dust and fine particles in the pores of the material, regular maintenance is required in order to keep the hydrological capacity of permeable surfaces (Singer et al., 2022). Pervious paving also serves as an effective tool in improving the quality of stormwater. The research on pollutant removal performance of permeable pavements has been consistent with achieving a reduction of total suspended solids, total nitrogen, ammonia, total phosphorus, dissolved metals such as zinc, copper and iron, as well as *Escherichia coli* (Abdollahian et al., 2018).

Managing stormwater at its source through the practice of rain water harvesting (RWH) is a sustainable solution in limiting the volume of outflow and reducing the risk of pluvial flooding, all while providing additional water supply in urbanised areas. Collected rainwater can be used for toilet flushing, laundering, as well as backyard maintenance work. Recent research emphasizes the importance of exploring the dual-use of RWH, ensuring a sustainable balance between the water supply and rainwater retention potential of the installation, which in turn helps to establish a catchment that is more invulnerable to climate change related intense rainfall events (Quinn et al., 2021). Domestic RWH can be integrated with green roofs and infiltration systems such as seepage boxes or basins, enhancing the overall hydrologic effectiveness of green infrastructure by adapting multiple solutions simultaneously (Raimondi et al., 2023). The choices in design of RWH system are dependent on the hydrological regime of the investment area (rainfall intensity and duration, dry periods), the type and characteristics of a surface from which rainwater is collected (area, slope and runoff coefficient) and water demand, which is connected to the living standard of the population (Raimondi et al., 2023).

When developing climate change mitigation strategies, it is equally important to account for the differences in challenges faced by urban and rural settlements, and suburban areas with lower density of housing often serve as a transitional zone between these agglomerations, with climate risks overlapping those characteristic of both developments (Hincks et al., 2023). With majority of rainwater management studies focusing on urban areas with high population density, there is a dearth of similar research for agglomerations with a more dispersed infrastructure, as indicated by Piasecki and Pilarska (2023). According to the typology of climate risk for European cities and regions provided by the European Climate Risk Typology (ECRT), majority of Eastern Europe, including Lublin voivodeship, is classified as Inland Hinterland, and the area studied in this research (Ożarów, Jastków county) falls under the sub-class Inland Hinterland 1. This cluster is characterised by high percentage of peri-urban and rural areas, with dominant climate hazards consisting of rising temperatures, heat waves and risk of fluvial flooding, with relatively small amounts of critical infrastructure to prevent damage to public spaces as well as private property in case of an intense rainfall event (Hincks et al., 2023). This study presents a numerical assessment of the efficiency of green infrastructure applications (green roofs, raingardens, permeable paving and RWH) in mitigating the hydrologic effects of climate change in a low density housing estate catchment. The aim of this research is to promote the importance of restoring a more sustainable balance of hydrological processes in a suburban basin by increasing its local retention capacity, resulting in reduced outflow and enhanced rainwater infiltration and evapotranspiration.

MATERIALS AND METHODS

Study area

The study area reported in this paper is located in Ożarów, Jastków county (N: 51°17’43.46” E: 22°16’42.66”), which is a settlement with predominantly rural areas that is peripheral to Lublin, the ninth largest city in Poland. The process of selecting the potential investment area for a developing project was determined by the possibility of conducting soil permeability tests as well as by providing constant access to the equipment installed at the research site for the duration of the data registering period. The average annual precipitation in this region of Poland is estimated at 600 mm, the average annual temperature ranges from 7 to 8 degrees Celsius. The development of a housing estate design consisted of spatial planning of single-family houses with garages and utility buildings, connecting all of the designed plots by determining the layout of communication routes, and arranging a centrally located common area with public gardens and community playground. The potential investment area was then equipped with a water supply network and an electrical power supply. For domestic sewage management, each house was equipped with individual sewage treatment plants with draining pipelines. The final residential development design covered the total area of 0.98 hectares and consisted of 6 private plots, each ranging in size from 0.13 to 0.15 ha, and a public common space with the area of 0.10 ha. The layout for the potential housing estate development in Ożarów is presented in Figure 1. The implementation of the proposed design with traditional construction solutions and material selections would result in the increase of the runoff coefficient in the investment area. In order to mitigate this hydrologic imbalance, the design of this housing estate was supplemented with green infrastructure solutions such as: green roofs, raingardens, permeable pavements and RWH systems.

Numerical runoff modelling

The object of this study is to numerically asses the influence of adopting green infrastructure solutions on a hydrologic performance of a suburban catchment through the analysis of rainwater outflow hydrograph and rainwater outflow volume. This study assumes the application of green roofs and RWH systems on private real estate as well as the application of raingardens and permeable paving on common areas, with the goal of creating a single- family residential development that is self-sufficient on a hydrological level. Numerical model of selected suburban catchment was developed in US EPA (United States Environmental Protection Agency) SWMM (Storm Water Management Model) 5.2 software. SWMM is a physically based dynamic wave simulation model that determines rainwater outflow and storage within a catchment that consists of subcatchments with assigned properties. For modelling infiltration, the Horton method was assumed (Niazi et al., 2017). Dynamic wave was selected as the flow routing method. Since the developed project of the settlement is only conceptual, the results achieved for this hydrodynamic model cannot be validated due to the lack of the possibility of calibrating the model with measured data (Fatone et al., 2021).

The developed numerical model of the object consisted of 83 subcatchments, including 12 roofs, 12 driveways, 16 green areas and 43 communication routes, with a stormwater drainage system of 0.3 m diameter PVC pipelines (assumed Manning's roughness coefficient n = 0.009), with 7 links and 6 nodes and a total length of 380 m. Figure 2 shows the numerical surface runoff model developed in SWMM 5.2. In order to committedly represent local soil properties and meteorological conditions during the numerical runoff modelling in SWMM, a series of measurements were conducted along with constant data registering for the selected location. Soil hydraulic conductivity was measured directly using the double ring infiltrometer (by falling head method), and laboratory methods (determining the saturated hydraulic conductivity coefficient using the constant flow method in a modified Wit apparatus). As a result of this analysis, the maximum infiltration rate was estimated at 104.94 mm/h, and minimum infiltration rate was estimated at 9.17 mm/h. Constant data recording conducted by the A-Ster company's EWP-1010R evaporometer, installed at

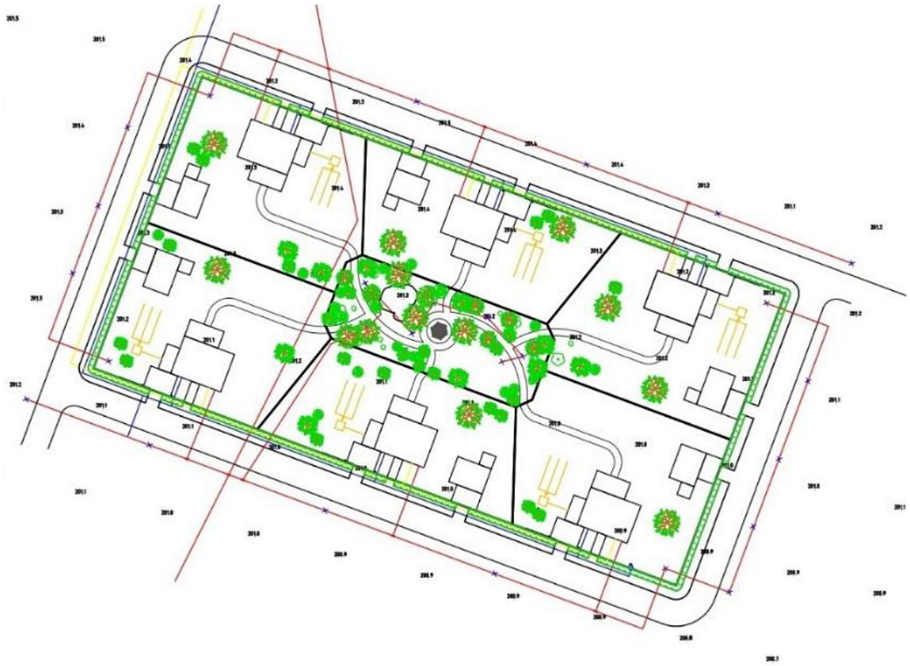

Figure 1. The developed design of a single-family suburban housing estate

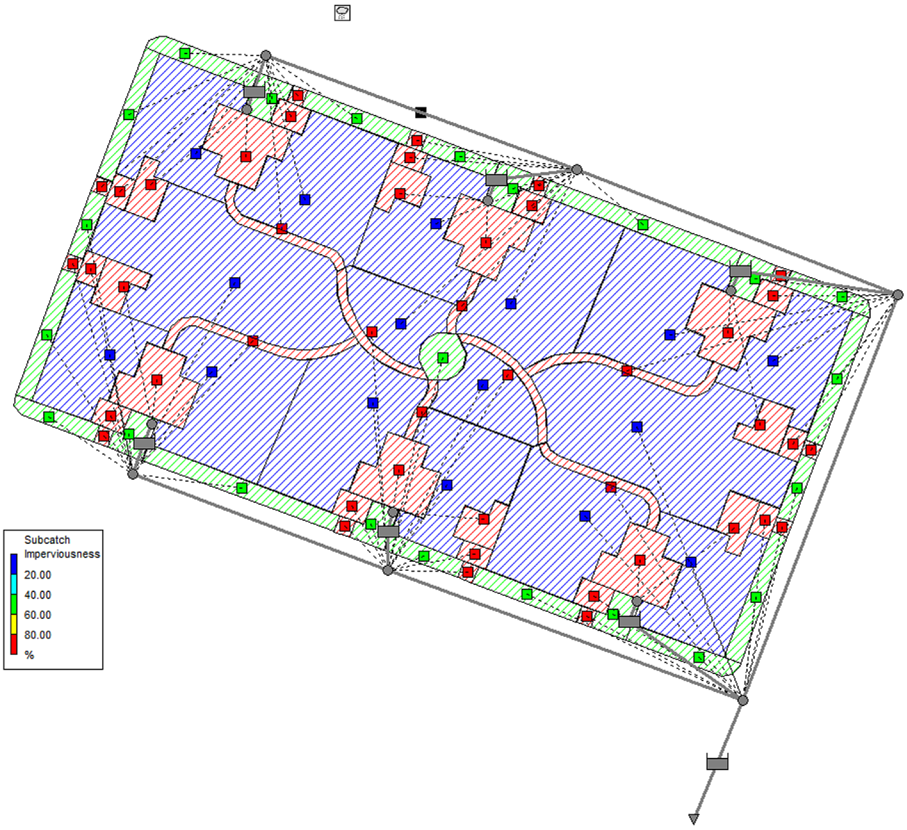

Figure 2. The numerical model of the studied catchment developed in SWMM 5.2

the potential investment site along with a rain gauge, enabled the consideration of evaporation as another parameter reflecting the actual meteorological conditions typical to the study area. The device remained on location for the duration of registering period, and was collecting data with a monitoring frequency of 1 minute.

Study variants

In order to assess the influence of green infrastructure application on rainwater outflow hydrograph and rainwater outflow volume, numerical modelling of surface runoff was performed for 2 cases: variant "zero" (wo_LID) without any LID applications and variant w_LID with the application of green roofs, raingardens, permeable paving and RWH systems.

During the process of determining the wo_LID variant subcatchment properties, the materials prescribed for covering each surface were assumed to align with traditional selection of sealing materials. Roofs were assumed to be lined with flexible metal sheet, driveways and pavements were selected to be covered with concrete paver blocks. The total area of roofs was calculated as 0.13 ha, the total area of communication routes and driveways covered in concrete materials was also estimated at 0.13 ha, while green areas made up the total area of 0.72 ha. The properties of each subcatchment type, as determined by the selected sealing material, are characterised in Table 1. The introduction of various green infrastructure measures when modelling surface runoff for the w_LID variant was performed with the utilisation of LID Controls option in SWMM 5.2. software.

Green roofs

Out of 12 subcatchments characterised as sheet metal lined roofs, 6 were modified with green roof feature in SWMM. Each of these identical gable roofs was tilted at 20 degrees, with an area of 0.016 ha, green roof was assumed to cover 95% of the area, in consideration of providing space for chimneys and other potential instalments such as photovoltaic panels. Selected subcatchments were assigned with properties characteristic to extensive green roof type, which is a typical choice for smaller area roofs in single-family housing developments (Shishegar, 2012). Two constituents of green roof design that predetermine its hydraulic and water retention

Table 1. The properties of subcatchment types assumed during numerical modelling in SWMM

Subcatchment type	% Impervious [%]	Manning's n [s/m$^{-1/3}$]	Slope [%]	Depression storage [mm]	% Zero depression storage [%]
Roof (sheet metal)	95	0.012	17.6–36.4	0.05	90
Driveways and pavements (concrete blocks)	85	0.012	0.5–5.0	0.5	70
Green areas (short grass)	15	0.025	0.5–1.5	1.5	25

properties the most are substrate layer and drainage layer. Their characteristics were assigned based on manufacturers' catalogues and previous research (Widomski et al., 2023). Main attributes of each layer of the green roof design are described in Table 2.

Raingardens

Two of the central common grounds were modified with LID controls raingarden feature in SWMM. The total area intended for the development of raingardens was estimated at 0.044 ha. The applied solution for raingardens was designed as self-contained, with no underdrain system, slow water discharge rate was instead provided by incorporating a drainage layer with suitable thickness and an appropriate particle size gravel. Hydraulic and water retention properties of substrate layer were derived from infiltration rate testing conducted on the potential investment site. Main properties of each constituent of the proposed raingarden design in SWMM are characterised in Table 3.

Permeable pavements

Each area which was previously characterised as pavement or driveway subcatchment type was modified using permeable pavement LID controls option in SWMM. The total amount of 55 subcatchments were altered with the utilisation of this feature, this number consisted of 43 communication routes and 12 driveways. The properties of individual layers of the designed permeable paving solution defined in the program were based on manufacturer's catalogues. The water infiltration rate data was determined in a series of on-site tests conducted in accordance with the ASTM C1701/C1701M-09 standard method with 300 mm infiltration rings, which were performed on the campus of Lublin University of Technology. The main attributes of each layer of the proposed permeable pavement design in SWMM are described in Table 4.

Rain water harvesting system

The proposed individual RWH system was designed to collect rainwater from two roofs on each private plot into underground storage tanks with the capacity of retaining a calculated stormwater volume of 4.2 m^3. The selection of the appropriate storage tank volume was determined by the assumption of providing enough water to flush toilets, do laundry, wash cars and watering the grass-covered areas on individual plots and retain rainwater storage for 21 days. The total area designed for collecting rainwater for each storage tank was calculated at 0.022 ha and consisted of a green roof with an area of 0.016 ha, tilted at 20 degrees with a runoff coefficient $\Psi = 0.35$, and a sheet metal lined roof with an area of 0.006 ha, tilted at 10 degrees with a runoff coefficient $\Psi = 0.95$. In an event of intense rainfall, any resulting rainwater overflow is directed into stormwater drainage system.

Meteorological data

The runoff calculations were performed for three rainfall events, which were characterised by different durations and rain intensities, in order to test the influence of variable precipitation conditions on hydraulic performance of presented solutions. Two of selected rainfall events (27.10.2023 and 31.10.2023) were registered by a meteorological station located on Lublin University of Technology campus. The third rain event was derived from the Chicago pattern model and was assigned the date of 24.10.2023. This model of rain distribution is recommended for designing sustainable stormwater management systems in Poland, and is characterised by an unit outflow of 177 dm^3/(s·ha), a duration of 15 minutes, a probability of 20%, and an appearance of once in a 5 year period (Widomski et al., 2023). The assumed rainfall characteristics are presented in Table 5, the rain intensity curves for these rain events are presented in Figure 3.

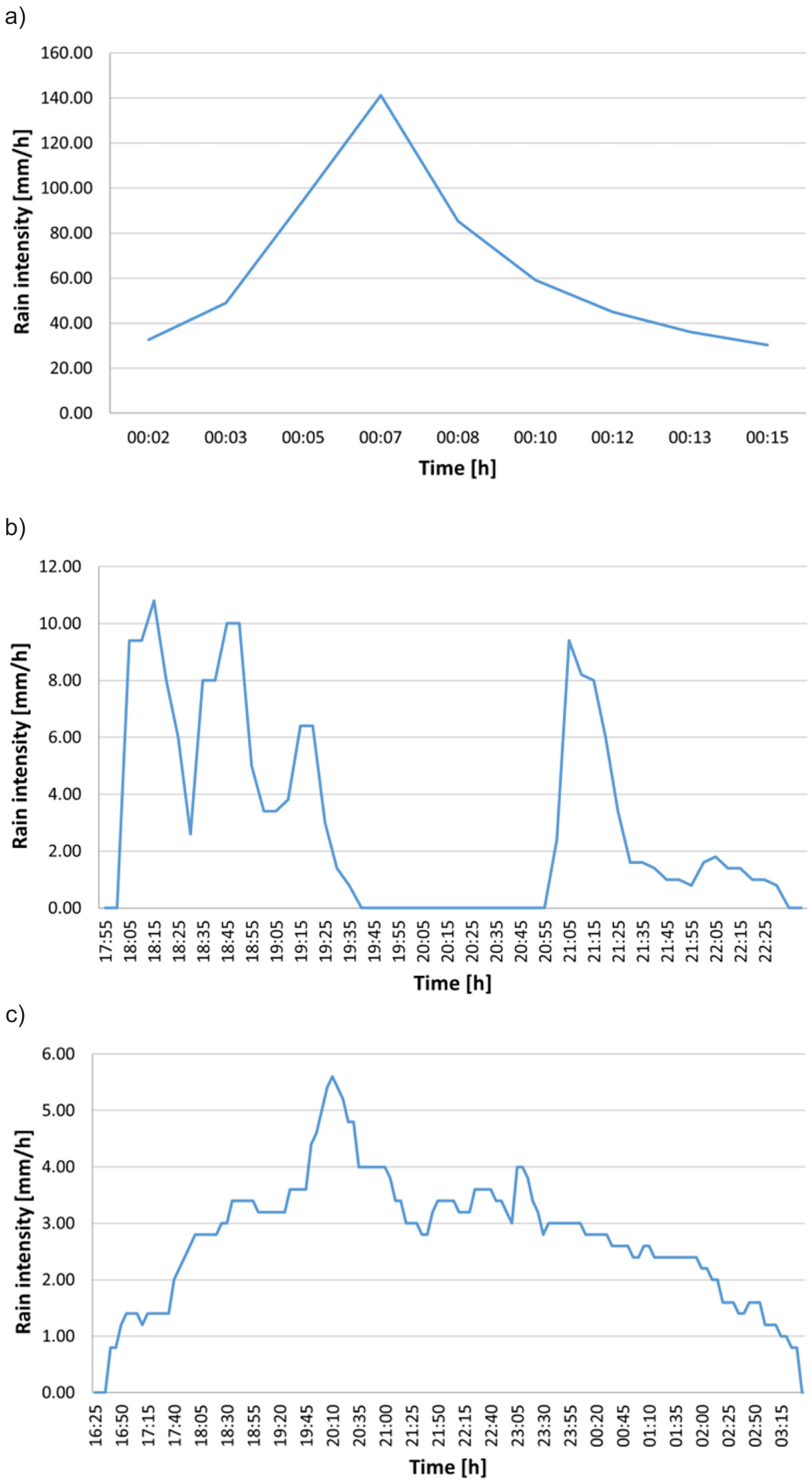

Figure 3. Rainfall intensity curves for selected rain events: a) 24.10.2023, b) 27.10.2023, c) 31.10.2023

Table 2. The hydraulic and water retention properties of green roof LID controls feature in SWMM

Surface - vegetation layer	
Berm height	50 mm
Surface roughness	0.1 s/m$^{-1/3}$
Surface slope	36.4 %
Soil - extensive roof substrate	
Thickness	80 mm
Porosity	0.464 m^3/m^3
Field capacity	0.376 m^3/m^3
Wilting point	0.031 m^3/m^3
Conductivity	2880 mm/h
Conductivity slope	41.8
Drainage mat	
Thickness	25 mm
Void fraction	0.5 m^3/m^3
Roughness	0.1 s/m$^{-1/3}$

Table 3. The hydraulic and water retention properties of raingarden LID controls feature in SWMM

Surface - vegetation layer	
Berm height	300 mm
Vegetation volume fraction	0.15
Surface roughness	0.24 s/m$^{-1/3}$
Soil	
Thickness	200 mm
Porosity	0.437 m^3/m^3
Field capacity	0.105 m^3/m^3
Wilting point	0.047 m^3/m^3
Conductivity	29.97 mm/h
Conductivity slope	49.3
Suction head	61 mm
Drainage	
Void ratio	0.75
Seepage rate	8.57 mm/h
Clogging factor	0

RESULTS

Rainwater outflow hydrograph

Rainwater outflow hydrographs for two variants of numerical calculations (without LID and with LID applications) and three simulated rainfall events are presented in Figure 4. The descriptive statistics of determined hydrographs are presented in Table 6. It can be observed that the application of green roofs, raingardens, permeable paving and RWH has impacted the shape of the outflow hydrograph curves in each of the studied cases, resulting in decrease in individual values as well as in peak flows. The application of LID and RWH has resulted in 61.90–67.99% decrease in peak flow values. From all simulated rain events, the biggest reduction in outflow values and peak flow has been observed for rain event with the assigned date 24.10.2023, which was derived from the Chicago pattern model and is characterized by short duration and high intensity. For two remaining rainfall events (27.10.2023 and 31.10.2023) with similar rain intensity, the reduction rate was comparable (61.9 and 62.59%, respectively) despite the differences in their other characteristics (depths and durations). The performed Wilcoxon matched-pairs test for calculated values of rainwater outflow for each studied rainfall event, presented in Figure 4, showed that the determined differences in medians are statistically significant.

Rainwater outflow volume

The calculated rainwater outflow volumes for two studied variants and three rainfall events are presented in Figure 5. The application of green infrastructure has resulted in a decrease in the volume of rainwater that entered the stormwater drainage system. The reduction in rainwater outflow volumes was calculated at 62.12, 61.23 and 61.70%, respectively. Thus, the determined results are comparable for each of the simulated rain events

DISCUSSION

The performed numerical calculations for the conceptual suburban housing estate catchment located in Ożarów, Poland demonstrate the hydrologic benefits of introducing LID solutions and RWH systems in low density housing establishments. The application of green infrastructure resulted in 61.90–67.99% decrease in peak stormwater outflow and 61.17–62.12% decrease in rainwater outflow volume, which validates LID and RWH as competent means to establishing a catchment that can effectively mitigate the effects of climate change in peri-urban areas. Despite the different duration, intensity and depth characteristics of simulated rainfall events, the calculated rainwater outflow volume reduction rate remained consistent. The aim of the application

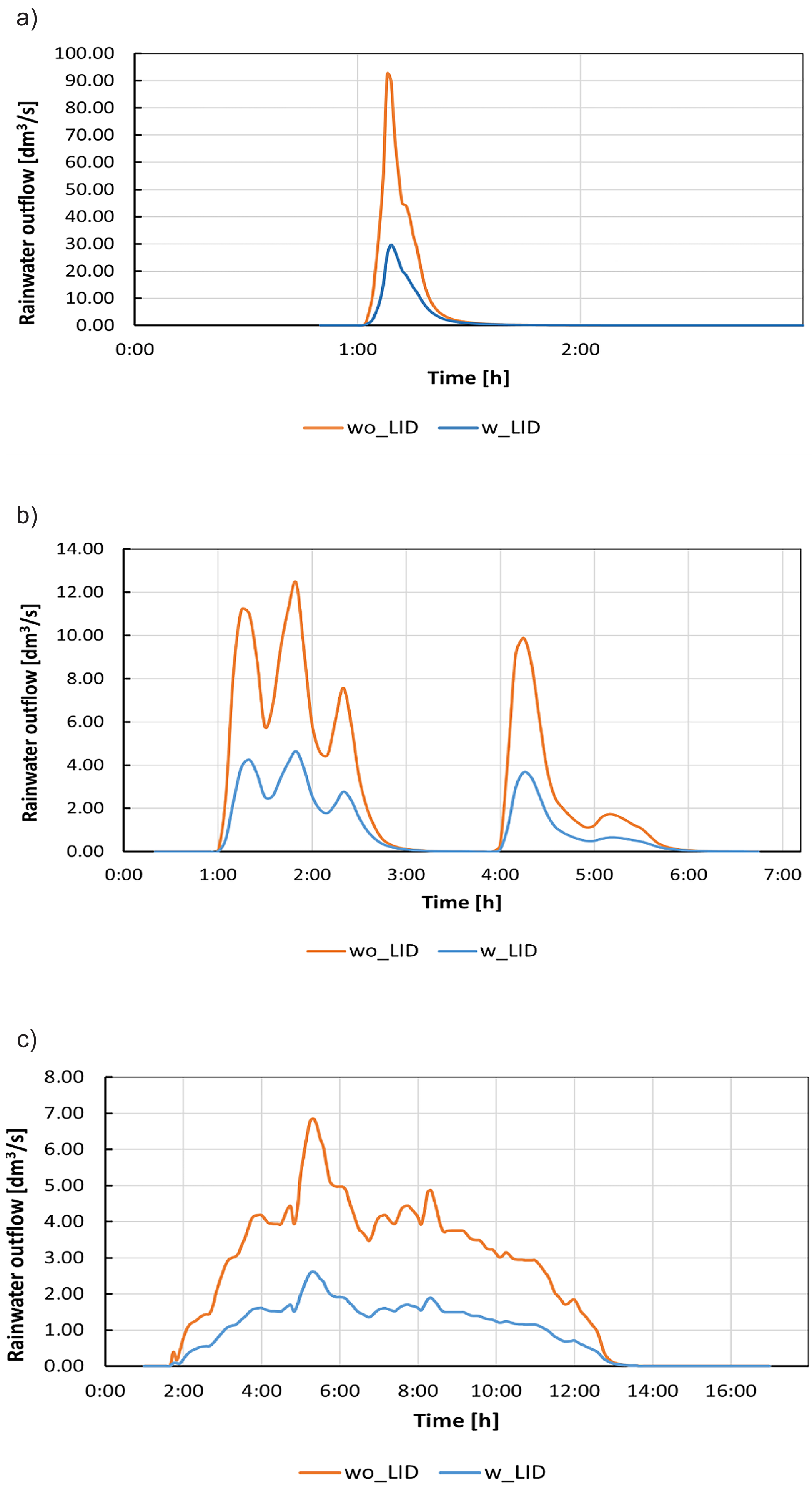

Figure 4. Rainwater outflow hydrographs for three simulated rain events: a) 24.10.2023, b) 27.10.2023, c) 31.10.2023

Table 4. The hydraulic and water retention properties of permeable pavement LID controls feature in SWMM

Pavement layer	
Thickness	100 mm
Void ratio	0.15
Permeability	45.44 mm/h
Clogging factor	0
Soil	
Thickness	60 mm
Porosity	0.437 m^3/m^3
Field capacity	0.062 m^3/m^3
Wilting point	0.024 m^3/m^3
Conductivity	120.4 mm/h
Conductivity slope	40
Suction head	35.3 mm
Storage	
Thickness	10 mm
Void ratio	0.75
Seepage rate	8.57 mm/h

of multiple LID solutions and RWH systems is to establish a hydrologically sustainable catchment with a consistent water retention performance in response to varying precipitation conditions. In this research, all of the proposed green infrastructure systems were applied simultaneously, therefore it is challenging to establish the hydrologic impact of each individual solution. There is an abundance, however, of research exploring the water retention effectiveness of installing green roofs, raingardens, permeable paving and rainwater harvesting systems exclusively. An overview of previous research on retention capacity of extensive green roofs conducted by Manso et al. (2021) emerged with an 57% average reduction of stormwater runoff across different climates and extensive green roof solutions. The water retention performance of intensive green roofs and substrates was greater than for the extensive types and averaged at 79%, however this type of green infrastructure is only applicable in large-scale projects (Paithankar and Taji, 2020). In studies performed by Baryła et al. (2018) the calculated retention rate ranged from 47.02 to 51.14% for extensive roof substrates. Similarly, according to Wałęga et al. (2018), the installation of bioretention cells reduces stormwater outflow volume by over 54%. Based on previous research, the sole application of extensive green roofs or raingardens was less efficient in retaining rainwater than in this study, in which in addition to increasing the amount of bioactive surfaces, the study object was also supplemented with other green infrastructure measures. There are comparatively few studies available on various combinations of multiple green infrastructure solutions being applied simultaneously. Lin et al. (2021) assessed the water retention performance of permeable pavements for three sites in Taipei, Taiwan, which resulted in rainwater retention rates ranging from 9.1 to 61.0%. The highest water conservation rate was observed at BeiTou site, which was provided with additional storage for retained stormwater by a raingarden. The exclusive application of permeable pavement leads to less satisfying outcomes, for example, in a study conducted by Zhu et al. (2019) the surface runoff reduction rate averaged at around 50%. Campisano and Modica (2016) calculated the reduction of peak runoff after installing a RWH system to range from 30 to 68%, but only in an event of rainfall characterized by a maximum intensity of 15–23 mm/h. According to the findings of Palla et al. (2017) on the topic of RWH installations, the reduction in runoff peak and volume was estimated at 33 and 26%, respectively. In order to obtain better results, the additional application of multiple LID measures would be optimal. Ekmekcioğlu et al. (2021) conducted a research with multiple LID applications (green roofs, permeable pavements and bioretention cells) on an auto-calibrated model in SWMM. Out of the three proposed LID controls, only green roofs and permeable pavements were concluded to be effective in reducing peak runoffs and rainwater outflow volume. Their research proves that adapting multiple LID solutions allows for a greater reduction in rainwater runoff than individual LID applications. The best peak

Table 5. The rainfall data selected for numerical runoff modelling

Rain event date	Depth [mm]	Intensity [mm/min]	Duration [min]	Unit Runoff [$dm^3/(s{\cdot}ha)$]
24.10.2023	15.93	1.06	15.00	177.00
27.10.2023	30.00	0.05	665.00	7.52
31.10.2023	11.00	0.04	265.20	6.91

Table 6. Statistic description of calculated outflow hydrographs determined for three simulated rainfall events

Rain event date	Variant	Mean flow [dm³/s]	Peak flow [dm³/s]	Median [dm³/s]	SD [dm³/s]	Peak flow reduction [%]
24.10.2023	wo_LID	7.18	92.43	0.12	18.21	67.99
	w_LID	2.72	29.59	0.09	6.41	
27.10.2023	wo_LID	3.08	6.85	3.47	1.63	61.90
	w_LID	1.19	2.61	1.35	0.63	
31.10.2023	wo_LID	2.93	12.43	1.20	3.69	62.59
	w_LID	1.14	4.65	0.53	1.37	

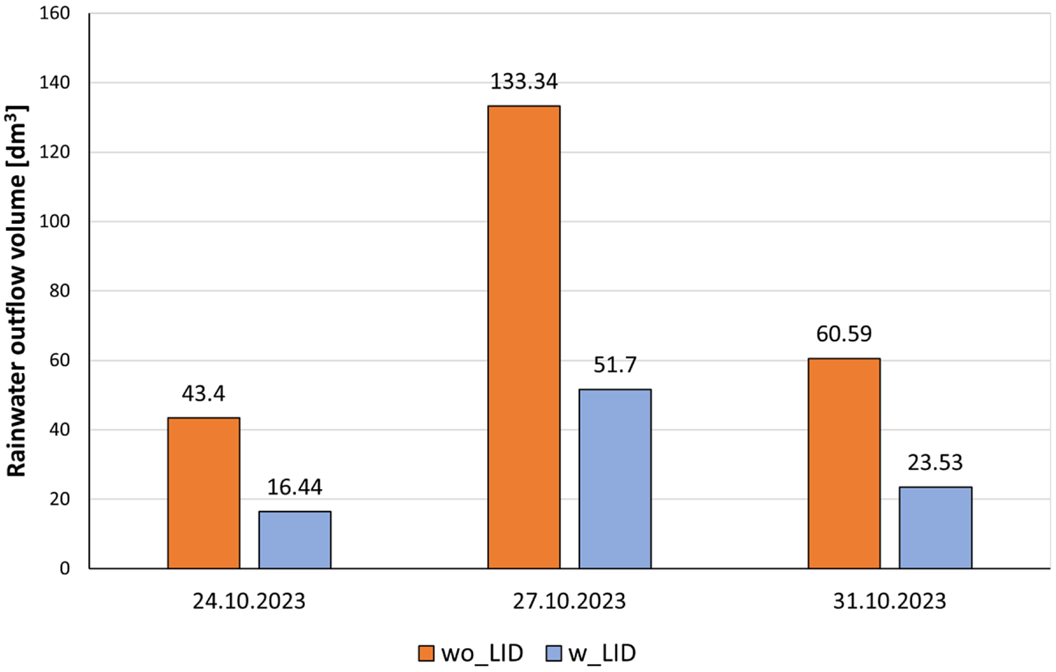

Figure 5. Rainwater outflow volumes for three simulated rain events

runoff (56.02%) and rainwater volume (58.79%) reduction performance was calculated for a 10 year return period. With the inability to calibrate the surface runoff model developed for the purpose of this research, the results ought to be addressed as preliminary to possible further studies on sustainable water management concentrating on suburban areas, which remain understudied.

The presented in this paper popular manners of sustainable rainwater management were reported as successfully implemented to the existing suburban or even rural developments, in various combinations and under different local climatic conditions, to reduce volume and peak flows of rainwater runoff (Petrucci et al., 2012; Sauri and Garcia, 2020; Gui and Zhang, 2020; Putri et al., 2023). However, according to several literature reports, taking into account the significant investment as well as operation and maintenance costs of green roofs, rainwater harvesting and permeable pavements the economic sustainability of LIDs application may be doubtful. The possible low profitability of small-sale sustainable rainwater management, directly affecting its social acceptance and willingness-to-pay of the future investors and users, was reported not only for the current economic conditions in Poland (Musz-Pomorska et al., 2020; Godyń, 2022; Iwanek and Suchorab, 2023; Musz-Pomorska et al., 2024) but also for the different regions of various countries (Farreny et al., 2011; Kim et al., 2016; Notaro et al., 2016, Severis et al., 2019). Thus, assuring the social acceptance, which may be obtained by state, local governments or outside co-founding (Kim et al., 2016; Jin et al. 2023), seems to be the main challenge in increasing popularity of the sustainable rainwater management.

CONCLUSIONS

The numerical calculations performed in this study resulted in important findings in the field of sustainable stormwater management in peri-urban areas. Key conclusions from the conducted analysis are as follows:

- Introducing green infrastructure solutions in a low density housing estate catchment resulted in a significant decrease in peak stormwater outflow and rainwater outflow volume.
- A simultaneous utilisation of multiple LID controls and RWH system allowed for a 61.90–67.99% decrease in peak stormwater outflow.
- Applying several green infrastructure measures resulted in limiting the volume of rainwater directed into stormwater drainage system after a rainfall event, with the calculated reduction rate of 61.17–62.12%.
- The diversification of applied LID solutions allowed the establishment of a catchment which was less susceptible to fluctuating precipitation conditions, with its water retention ability remaining consistent irrespective to the intensity and duration of simulated rain events.
- The object of this study was only developed as a conceptual project, therefore the results generated for its numerical model ought to be addressed as preliminary, since runoff modelling requires calibration for more reliable calculations.

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