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Original Research Article

HYDROLOGICAL MODELING-BASED ASSESSMENT OF THE IMPACT OF URBANIZATION ON RUNOFF FROM WATERCOURSE CATCHMENTS

Hubert JAMRY[*] , Marcin WDOWIKOWSKI, Katarzyna WARTALSKA
Faculty of Environmental Engineering, Department of Water and Wastewater Management and Waste Technology, Wrocław University of Science and Technology, Wrocław, Poland

Abstract

Urban expansion significantly alters natural hydrological regimes and increases the risk of flooding, particularly in suburban catchments undergoing rapid land-use transformation. The replacement of permeable surfaces with impervious infrastructure reduces infiltration and increases pressure on existing drainage systems. This study evaluates the hydraulic performance of a suburban catchment in southwestern Poland (18.78 km²) using an integrated modelling approach combining SWMM hydrodynamic simulations with high-resolution (1 m) terrain analysis in SCALGO Live Poland. Results show that an imperviousness level of approximately 18% is sufficient to exceed the hydraulic capacity of the drainage system during design rainfall events. The introduction of two retention reservoirs (total capacity 180 000 m³) reduced peak flows by 32% and eliminated 93% of high-risk flood zones. The study highlights the importance of integrated hydrological modelling for planning effective stormwater retention strategies in rapidly urbanizing catchments.

Keywords: hydrological modelling, stormwater management, urbanized catchment, SCALGO live, SWMM

1. INTRODUCTION

Rapid urban growth and intensive urbanization observed in recent decades pose significant challenges for stormwater management, increasing the risk of local inundations [1,2]. The replacement of permeable land with sealed surfaces, such as roads, parking lots and rooftops, accelerates surface runoff and reduces the retention capacity of urban catchments [3,4]. These processes significantly modify the natural hydrological response of catchments, particularly in peri-urban environments undergoing active land-use transformation.

The problem is further intensified by climate change, with the IPCC predicting an increase in the frequency and intensity of extreme rainfall events in Central Europe, including Poland [5]. Such changes significantly increase the likelihood of urban flooding and flash flood phenomena. Under these evolving climatic and spatial conditions, traditional stormwater management approaches based mainly on

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[*] Corresponding author: Faculty of Environmental Engineering, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, hubert.jmary@pwr.edu.pl

drainage conveyance are often insufficient, making the use of modern forecasting and analytical tools essential [2].

In response to these challenges, hydrological modeling has become a fundamental tool in water resource management and urban infrastructure planning. It enables the simulation of stormwater flows, flood risk assessment, and optimization of drainage systems under various meteorological and land-use scenarios [6-8]. By integrating meteorological, topographical and hydrological data, such models support the evaluation of both existing and planned infrastructure solutions, including retention systems and green infrastructure [2,3,9]. Studies conducted for Polish catchments indicate that hydrological models are increasingly applied in climate change impact assessments, spatial planning, and flood analysis in ungauged basins [9-12].

Among the most widely applied modeling tools are SWMM (Storm Water Management Model), SWAT (Soil and Water Assessment Tool), MIKE and HEC-based models, as shown in Fig. 1. SWMM is one of the most commonly used tools for modeling urban drainage systems, enabling detailed simulation of rainfall–runoff processes, channel flows and retention mechanisms [13-16]. SWAT is primarily applied in agricultural catchments to assess the influence of land-use changes on water balance and quality [7,16,17], while MIKE and HEC-RAS are widely used in river hydrodynamics and flood risk assessment, allowing simulation of complex hydraulic conditions [7,12,19].

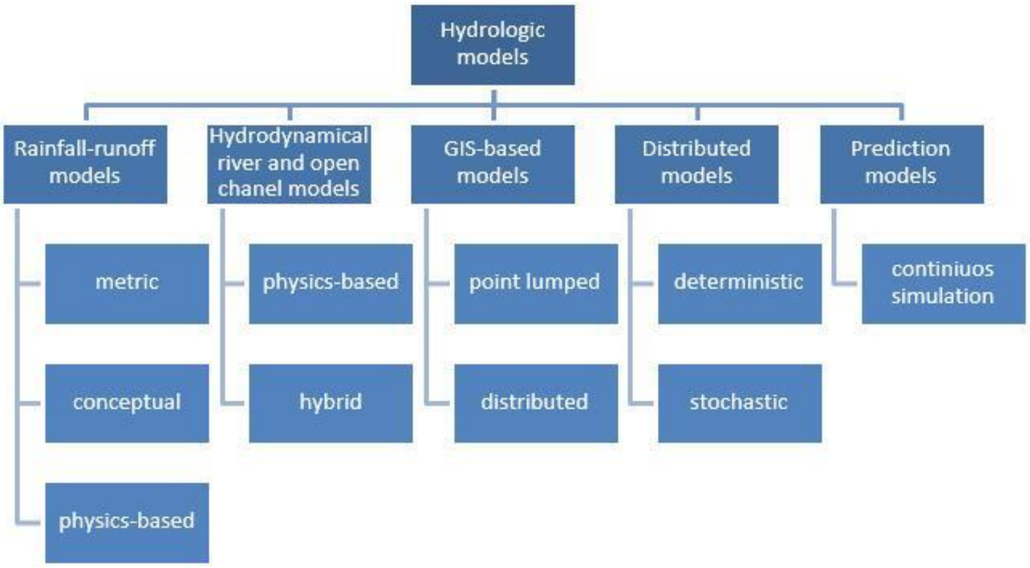

Fig. 1. Classification of hydrological models [own elaboration]

Despite the widespread use of these tools, a significant research gap remains in the integration of high-resolution spatial data with dynamic hydrodynamic simulations in small, rapidly urbanizing suburban catchments. Traditional modeling approaches often rely on simplified conceptual representations or terrain data of limited spatial resolution, which fail to capture micro-topographic variability that dictates actual flow paths in peri-urban landscapes.

The novelty of this research lies in the synergistic integration of a high-resolution Digital Terrain Model (DTM) with a 1-meter spatial resolution and dynamic flow simulations based on the full Saint-Venant equations. Unlike existing studies, this approach combines the advanced surface flow analysis capabilities of the SCALGO Live platform with the hydrodynamic precision of the SWMM engine. This methodology allows for a more rigorous identification of hydraulic bottlenecks and flood-prone zones that are often 'smoothed out' in lower-resolution models. Consequently, this study provides a new framework for assessing the effectiveness of localized retention measures in heterogeneous, rapidly developing Central European catchments, filling the gap between large-scale hydrological assessment and site-specific engineering design. Therefore, the main objective of this study is to verify the functioning of the stormwater drainage system within the catchment of the Wieściszów Tributary Stream and the Graniczny Canal River. The verification is performed through the assessment of surface runoff magnitude and the analysis of hydraulic capacity of existing infrastructure under current rainfall conditions. The study also aims to identify critical hydraulic sections and flood-prone areas and to evaluate the effectiveness of selected retention measures designed to reduce peak discharges and improve the hydrological safety of the region. By integrating high-resolution terrain analysis with dynamic hydrodynamic modeling, the research provides a comprehensive framework for assessing drainage system performance in suburban areas exposed to increasing impervious surfaces and climate-driven precipitation extremes.

2. STUDY AREA

The study area includes the catchment of two watercourses: the Wieściszów Tributary Stream and the Graniczny Canal River, located in the Lower Silesian Voivodeship, Wrocław County, within the municipalities of Czernica and Długołęka. The area of the analyzed catchment is 18.78 km². The catchment includes the Wieściszów Tributary Stream and the Graniczny Canal River located in the Lower Silesian Voivodeship (southwestern Poland). The Graniczny Canal, with a length of 19.43 km, originates in the Czernica municipality and flows west, serving as the border between the Czernica and Długołęka municipalities until it joins the Mrówka River [20]. Fig. 2 shows a topographical map with the location of the analyzed catchment.

The catchment is characterized by a varied topography. In the northern part, near Nadolice Wielkie, there are small hills with a height of up to 132 m above sea level. The terrain slopes downwards to the south, transitioning into a plain [21]. Geologically, the catchment is primarily composed of Quaternary sediments, such as morainic clays and fluvioglacial sands, as well as river sediments.

The climate in this area is temperate warm with a predominance of oceanic influences, with an annual rainfall of about 550 mm [20]. These areas are mainly agricultural, covering about 78% of the surface, while forests cover about 3.5% of the catchment. Built-up areas constitute about 13.4% of the surface, which is related to the dynamic urban development around Nadolice Wielkie and Wieściszów [21]. Due to their proximity to Wrocław, these areas are becoming increasingly attractive for settlement. The expansion of new housing estates and the increased intensity of land use create a number of challenges related to water management, including an increased risk of flooding and inundation, and difficulties in obtaining water permits.

Fig. 2. Topographic map of the areas with the location of the catchment area [own elaboration]

3. MATERIALS AND METHODS

While HEC-RAS is a standard for river hydraulics and MIKE offers robust urban drainage modules, SWMM was selected for this study due to its specialized capabilities for integrated suburban-agricultural drainage systems. Furthermore, the choice of SWMM was dictated by the fact that the sections of the rivers under analysis were heavily channelled, running partly through farmland and then through densely built-up urban areas; in addition, the geometric parameters of the regulated channels were similar and consistent almost along their entire length (see Table 1 for detailed characteristics). Key factors included its seamless compatibility with SCALGO Live Poland data exports and its ability to simultaneously model overland flow, channel hydraulics, and retention structures within a single, unified computational environment. This integration is critical for capturing the complex interaction between surface runoff and drainage infrastructure in rapidly urbanizing catchments.

To test the capacity of the catchment, an integrated hydrological and hydraulic modelling framework was developed using the SWMM program and the SCALGO Live Poland platform. The workflow of the study is presented in Fig. 3 and includes terrain preprocessing, catchment delineation, hydrodynamic modelling, calibration, flood risk assessment and retention scenario analysis. SWMM was used to simulate runoff and hydraulic conditions under different rainfall scenarios, while SCALGO Live Poland provided high-resolution terrain and hydrographic data for spatial analyses.

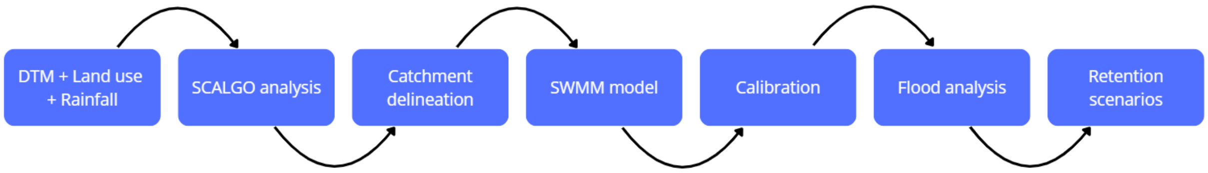

Fig. 3. Methodological workflow of the integrated SWMM–SCALGO modelling approach [own elaboration]

3.1. Catchment Geometry and Spatial Analysis in SCALGO

The SCALGO platform enables the creation of a DTM, which serves as the basis for hydrological analysis and design. By using this model, it was possible to accurately identify the main watercourse based on GIS data analysis, allowing for the determination of its location and channel course. In the next step, the main watercourse was automatically divided into sections and nodes, which significantly simplified the detailed mapping of the catchment's hydrography, allowing for a more precise analysis of its properties.

Thanks to the SCALGO platform, detailed data such as geographical coordinates, terrain elevation, and channel bed depth were obtained for each node and section of the watercourse, enabling an accurate representation of the actual hydrological conditions. Based on the terrain elevations, the boundaries of the catchment and its sub-catchments were determined, which allowed for the calculation of the area of each, the determination of the terrain slope, and the type of land use. Furthermore, SCALGO enabled the identification of surface runoff areas, including tributaries to the main watercourse, as well as non-standard flow zones, such as drainage channels.

3.2. Hydrodynamic Model Development in SWMM

The data obtained from the SCALGO platform formed the basis for a precise simulation of the rainfall-runoff phenomenon within the SWMM environment. The model developed in the program took into account a number of key parameters related to the catchment, watercourse, and rainfall load, which allowed for an accurate simulation of flows in the catchment.

The hydrodynamic model of the catchment was developed for an area of 18.78 km², which included 67 sections of the watercourse, divided into three parts with different characteristics. Part 1 covered agricultural, undeveloped areas; Part 2 covered rural areas and areas planned for future development; and Part 3 covered the river's border canal, which had different hydrodynamic parameters (Fig. 4). Figure 4 also presents the boundaries of the stormwater catchment included in the hydrodynamic analysis. Each of these sections was modeled as an open channel with a trapezoidal cross-section, which accounted for varying bottom widths and channel bank slopes, adapted to local topographical conditions. The drainage network incorporated in the SWMM model was derived from two sources: (1) geometric and topographic data extracted from the SCALGO Live Poland platform, which provided node coordinates, terrain elevations, and channel bed depths at 1 m resolution; and (2) field inspections conducted in 2023, aimed at assessing the actual condition of the watercourse, including verification of the river channel geometry, vegetation conditions, and the overall physical state of the stream. No existing GIS drainage cadastre was available for the catchment; therefore, the network was constructed within SWMM based on the above data. Each channel section was modelled as an open trapezoidal channel with parameters specified in Table 1. This approach allowed for a detailed representation of the actual flow conditions in the catchment.

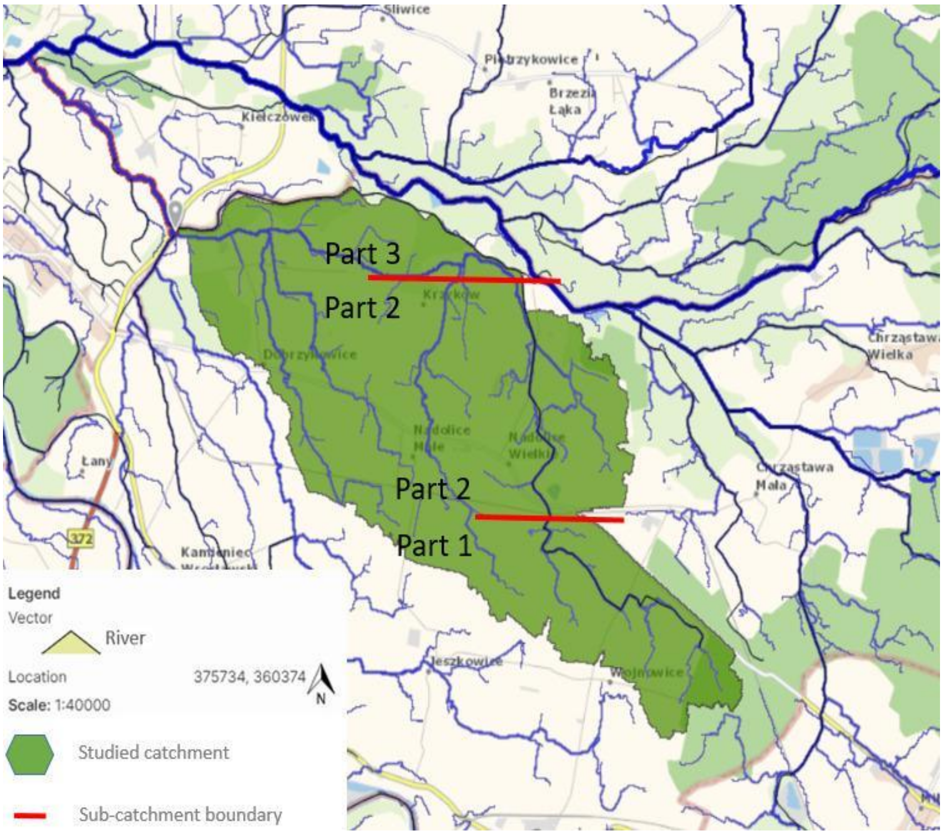

Fig. 4. Map of the watercourse division and stormwater catchment boundaries

For the model developed in this way, characteristic parameters of the catchment and the watercourse were defined, which have a crucial impact on the accuracy of the simulation results. Manning's roughness coefficients were adopted in accordance with the guidelines of Sawicki [22]. These coefficients significantly influence the representation of flow dynamics in each of the three diverse areas of the catchment, considering different terrain features such as land cover or soil type.

To describe the phenomenon of stormwater infiltration into the soil, the Horton model was used. This model accounts for the temporal variability of soil infiltration capacity during a rainfall event, reflecting key physical processes occurring in the unsaturated zone. In particular, it considers the initial high infiltration rate resulting from dry or partially saturated soil conditions, followed by a progressive reduction caused by pore filling and increasing soil moisture content. The model also incorporates the long-term stabilization of infiltration at a minimum value, which represents the limiting hydraulic conductivity of fully saturated soil. The rate at which infiltration decreases depends on soil characteristics such as texture, permeability, and compaction, which are represented through a decay parameter controlling the speed of saturation [23,24]. The values for the infiltration parameters were adopted based on [23]. Table 1 presents all the coefficients used.

Table 1. Parameters and coefficients adopted to develop the hydrological model

Parameter	Part 1	Part 2	Part 3	Remarks
The width of the channel bottom [m]	0.5	0.75	0.75	Trapezoidal section with angle of inclination 45°
Catchment area $[km^2]$	18.78			Total catchment area
Share of permeable surface [%]	92	82	82	Vegetation area, crops, forests
Share of impermeable surface [%]	8	18	18	Buildings, roads, squares
Channel roughness coefficient (n) [-]	0.04	0.04	0.04	Poor hydrological conditions (uneven cross-section, aquatic vegetation, stones)
Runoff coefficient (Cs) [-]	0.25	0.25	0.25	For planes and plateaus
Retention rate (v) [-]	0.8	0.8	0.8	Rich vegetation, moderately permeable soil
Surface retention height [mm]				
Permeable surfaces	2.5	2.5	2.5	
Impermeable surfaces	5	5	5	
Soil infiltration (according to Horton's model)				
Initial infiltration rate (maximum) [mm/h]	152	152	152	Sandy-clay soils with vegetation
Minimum infiltration rate [mm/h]	7.5	7.5	7.5	Soils with moderate infiltration capacity
Decay coefficient (k) $[h^{-1}]$	4	4	4	
Drying time of the soil [days]	7	7	7	
Catchment surface roughness coefficient $[s/m^{1/3}]$				
Permeable surfaces	0.2	0.2	0.2	
Impermeable surfaces	0.02	0.02	0.02	
Soil characteristics				
Soil type	Sandy-clay soils			
Soil source	River sediments, boulder clays			

3.3. Rainfall Scenario and Simulation Setup

To carry out the simulation, the catchment was subjected to a model Euler Type II rainfall event, whose pattern corresponds to conditions prevalent in the city of Wrocław (verified, for example, in the study) [25]. According to the assumptions of this model, the maximum instantaneous rainfall intensity occurs towards the end of the first third of its duration. The Euler Type II rainfall model is considered suitable for modeling drainage systems in Poland [26-29].

Based on IMGW (Institute of Meteorology and Water Management) data for Wrocław, a probabilistic model of maximum rainfall depths was developed (generalized exponential distribution, duration t ϵ [5; 4320] minutes, exceedance probability p ϵ [1;0.01]). The design rainfall for the Euler Type II scenario was determined using this model. To verify the occurrence of backflows in the stormwater channels included in the study, the catchment was subjected to a rainfall event with a frequency of C = 3 years – the currently recommended frequency for verifying backflows in residential areas and a duration of t = 90 minutes. For this rainfall scenario, the maximum instantaneous intensity appears between the 25th and 30th minute and amounts to 100.44 mm/h.

The SWMM model allowed for the simulation of surface runoff and flows in the watercourse channel, as well as the definition of retention capacity, infiltration, and flow in retention reservoirs. This was aimed at better representing the actual hydrological processes. For the calculation of average annual flows, Iszkowski's formulas were used, which allowed for the preparation of realistic simulations of hydrological conditions in the catchment [30]. Iszkowski's formulas make it possible to determine the initial distributions of velocity and water depth in the watercourse channels.

They are based on the relationship between flow velocity, water depth, and the geometry of the channel cross-section, allowing for a precise estimation of initial flow conditions based on data about channel geometry and hydraulic characteristics [30]. The calculations were performed using the following formulas (3.1) and (3.2).

Average annual discharge:

$$Q_S = 0{,}03171 \cdot C_S \cdot P \cdot A \tag{3.1}$$

where:

Q_s – annual average discharge, $m^3 \cdot s^{-1}$,
C_s – runoff coefficient (ratio of runoff to precipitation), unitless,
P – normal (average) annual precipitation, m,
A – catchment area, km^2.

The lowest annual discharge:

$$Q_0 = 0{,}2 \cdot C_S \cdot v \tag{3.2}$$

where:

Q_0 – the lowest annual discharge, $m^3 \cdot s^{-1}$,
v – retention coefficient depending on vegetation, permeability of the terrain and size of the river basin, unitless.

In the process of model calibration and verification, the initial conditions, related to the distribution of water depth and flow velocity in the individual sections of the modeled network, played a crucial role. These conditions were established based on local hydrometric measurements collected during the Spring field observations in 2023, which was key to obtaining realistic results in the simulations. During the field inspection, an assessment was carried out to verify the compliance of engineering structures, such as weirs, culverts and bridges, with the available digital spatial data, DTM and BDOT (topographic object database). In order to ensure the best possible alignment of digital data with actual conditions and to verify the actual flow capacity of channels, which become heavily overgrown with vegetation during the growing season, the geometric parameters of riverbeds and channels were measured in selected sections. It was found that whilst the consistency of engineering structures was almost 100% (it was found that one bridge was undergoing renovation and had not been updated in the Wrocław County databases), a correction of the DTM was required regarding the alignment of the channels in rural sections and the capacity of channels and rivers in urbanized sections by approximately 30% (the identified differences in accuracy between the DTM and field results were 70.7%). The changes were incorporated into the DTM in SCALGO, and the corrected data were then used in the SWMM model. Field measurements of water velocity confirmed the calculations, showing a 95% correlation for typical flows; under normal conditions, i.e. during dry periods, the water level lies between the low and average long-term levels. Additionally, the model was calibrated using design rainfall events generated by the Euler Type II method, allowing for adjustment of key hydrodynamic parameters to reflect the observed runoff behavior during extreme precipitation scenarios. Precisely selected hydrodynamic parameters and initial conditions allowed for the creation of a realistic model of flows in the catchment and the acquisition of accurate and reliable simulation results. For the calculation of flood conditions, a maximum rainfall of 100 mm was assumed, which, under the terrain conditions analyzed, corresponds to a flood with a probability of exceedance of p = 0.02% (a return period of 500 years).These results formed the basis for further hydrological analysis and water management planning within the catchment, including flood risk assessment.

3.4. Flood Risk and Retention Analysis Using SCALGO

The SCALGO platform utilizes a high-resolution DTM with a 1-meter resolution, allowing for a very precise representation of the topography of a given area. Based on this model, a number of advanced analyses were carried out, including a flow simulation that took into account the Saint-Venant equations. This enabled a realistic representation of dynamic flows in both open channels and pipes, including phenomena such as flood waves, which allowed for accurate modeling of crisis situations related to floodwaters [21]. The SCALGO platform also enables the accurate visualization of an analyzed catchment channel profile and the water surface level, allowing for a precise representation of the channel's shape and flow dynamics. This type of visualization is also helpful in analyzing areas at risk of flooding, making it possible to identify places that require special protection [21]. Additionally, the SCALGO platform offers the ability to model and simulate retention reservoirs, which allows for analyses regarding the impact of these facilities on the reduction of peak flows. Through these simulations, it was possible to evaluate the effectiveness of retention reservoirs in preventing inundation and managing surface water during heavy rainfall [21,31].

4. RESULTS

4.1. Hydraulic performance of the catchment (SWMM)

The hydrodynamic modeling carried out using the SWMM program and the analysis in SCALGO Live Poland allowed for a detailed determination of the limitations of the drainage infrastructure in the analyzed catchment. The results indicate insufficient hydraulic capacity of the drainage system. These problems become particularly evident in the case of intense model rainfall.

Simulations were performed for a model Euler Type II rainfall event with a duration of $t = 90$ minutes and an exceedance frequency of $C = 3$ years. The analysis of the results indicates that the maximum load on the network occurred in the 76th minute of rainfall, when a full or nearly full filling of the channel was observed along most of the watercourse's length, which generates a high risk of overflow. The initial state of the simulation (at 16 minutes) is shown in Figure 5, while the maximum channel filling is illustrated in Figure 6, which shows a fragment of the collector (the second part of the watercourse). Figure 7 presents the profile of the final section of Part 3 of the watercourse during the maximum loading conditions.

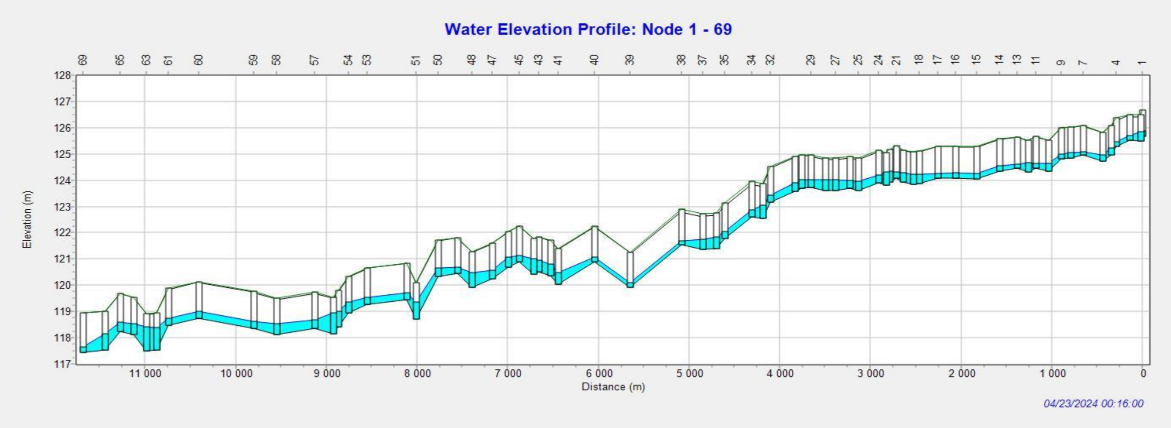

Fig. 5. Stream profile in the entire catchment area at the 16th minute of simulation (SWMM plot)

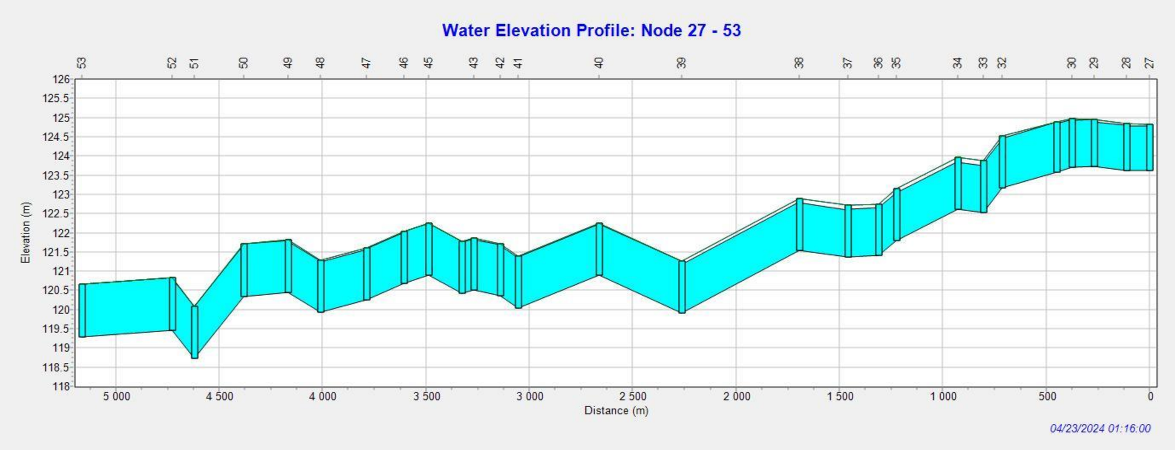

Fig. 6. Profile of the second part of the stream in the 76th minute of the model rainfall duration for C = 3 years and t = 90 min (SWMM plot)

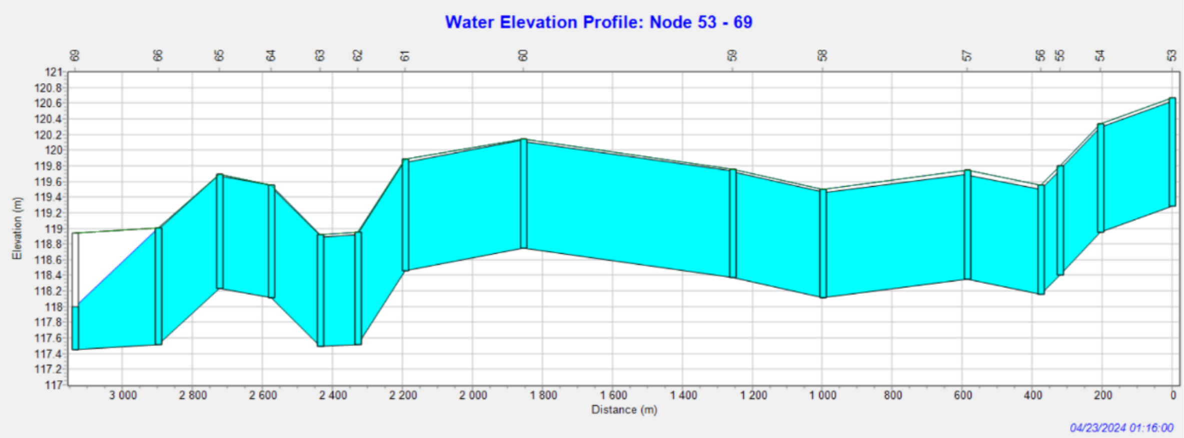

Fig. 7. Profile of the third part of the stream in the 76th minute of the model rainfall duration for C = 3 years and t = 90 min (SWMM plot)

In the first part of the catchment, the maximum volumetric flow was 0.669 m^3 $\mathbf{s^{-1}}$, and the maximum flow velocity reached 1.24 m $\mathbf{s^{-1}}$. The results are presented in the hydrograph in Figure 8. It was found that the channel capacity was insufficient along the entire length of the analyzed section. In the second part of the catchment, a maximum flow of 1.057 m^3 $\mathbf{s^{-1}}$was identified, with a flow velocity reaching 1.56 m $\mathbf{s^{-1}}$. The full filling of the channel along the entire length of the section poses a particular threat to residential areas in this part of the catchment. The results are presented in the hydrograph in Figure 9. In the third part of the catchment, the maximum flow reached 1.146 m^3 $\mathbf{s^{-1}}$, and the maximum flow velocity was 1.12 m $\mathbf{s^{-1}}$. The greatest risk of overflow was noted in the lower parts of this section, close to the river catchment's mouth, although the threat decreased towards the end of the analyzed area. The results, presented in the hydrograph in Figure 10, unequivocally indicates the limited capacity of the system throughout the entire catchment, which requires corrective actions.

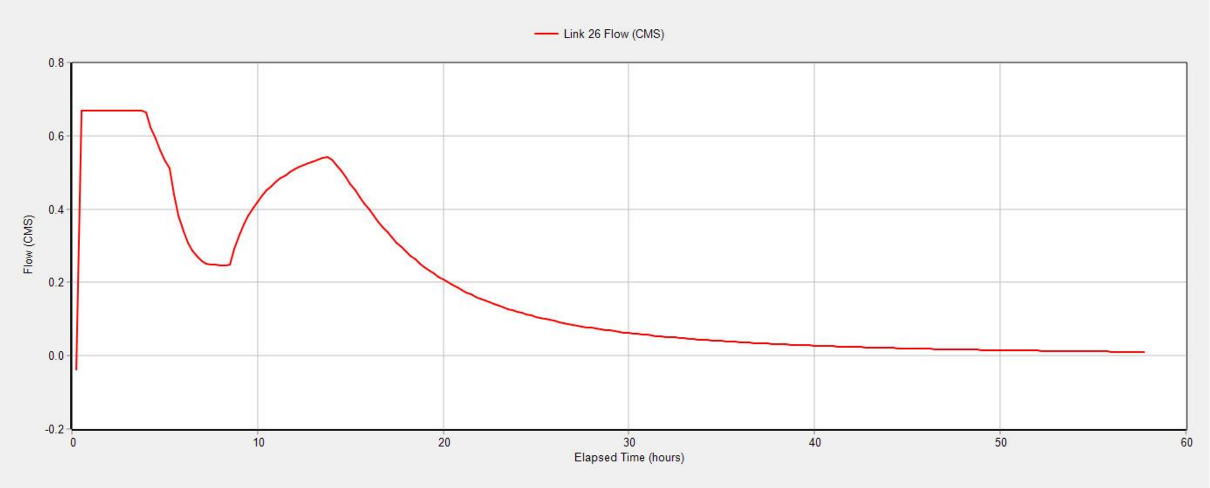

Fig. 8. Flow hydrograph in the last section of the first part of the stream for C = 3 years and t = 90 min (SWMM plot)

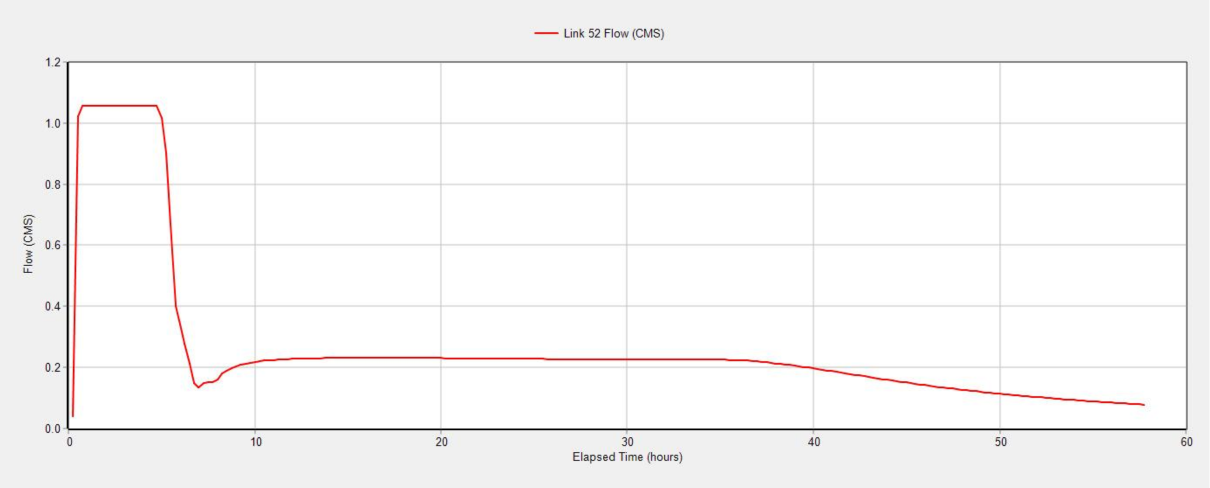

Fig. 9. Flow hydrograph in the last section of the second part of the stream for C = 3 years and t = 90 min (SWMM plot)

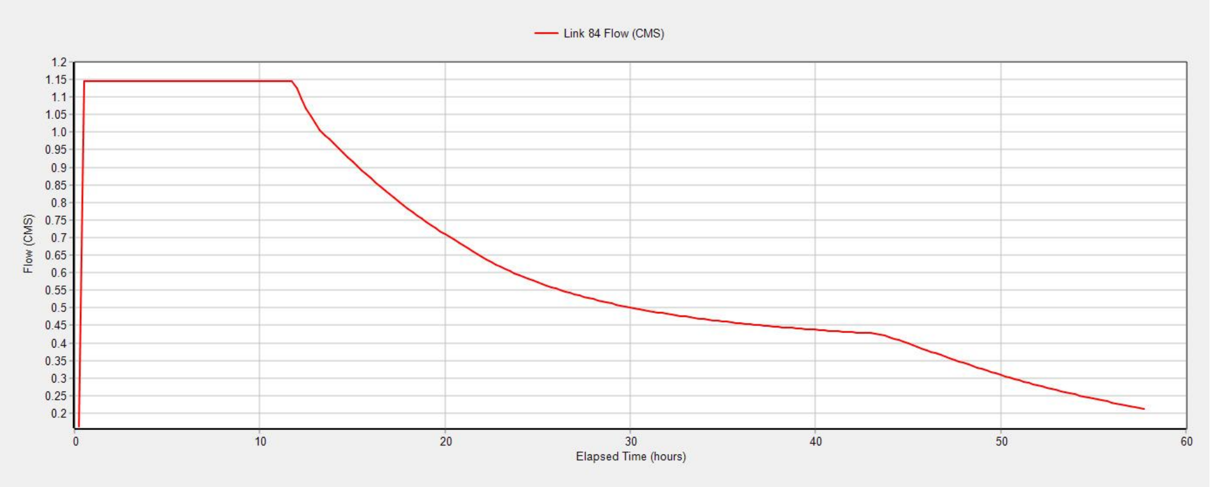

Fig. 10. Flow hydrograph in the last section of the third part of the stream for C = 3 years and t = 90 min (SWMM plot)

Table 2 presents selected simulation results from the SWMM program for the nodes and sections within the analyzed catchment. These data reveal that the channel reached full capacity along the entire length of the studied catchment. This situation poses a real threat of overflows and flooding in these areas.

Table 2. Flow and outflow values from the studied areas

Catchment area	**Flow on a section, m^3·s^{-1}**	**Maximum outflow, m^3·s^{-1}**
I part	0.669	7.912
II part	1.057	18.204
III part	1.146	21.615

4.2. Spatial flood risk assessment (SCALGO live)

The SCALGO analysis made it possible to identify areas particularly vulnerable to flooding under extreme rainfall conditions with an intensity of 100 mm. Two scenarios were studied: one without considering surface runoff and one that included infiltration and runoff.

Scenario 1 - without surface runoff. In the first part of the catchment, three water accumulation areas were identified, two of which were classified as high-risk flood zones. These areas primarily concerned agricultural land, indicating the limited water retention capacity of the soil (Fig. 11).

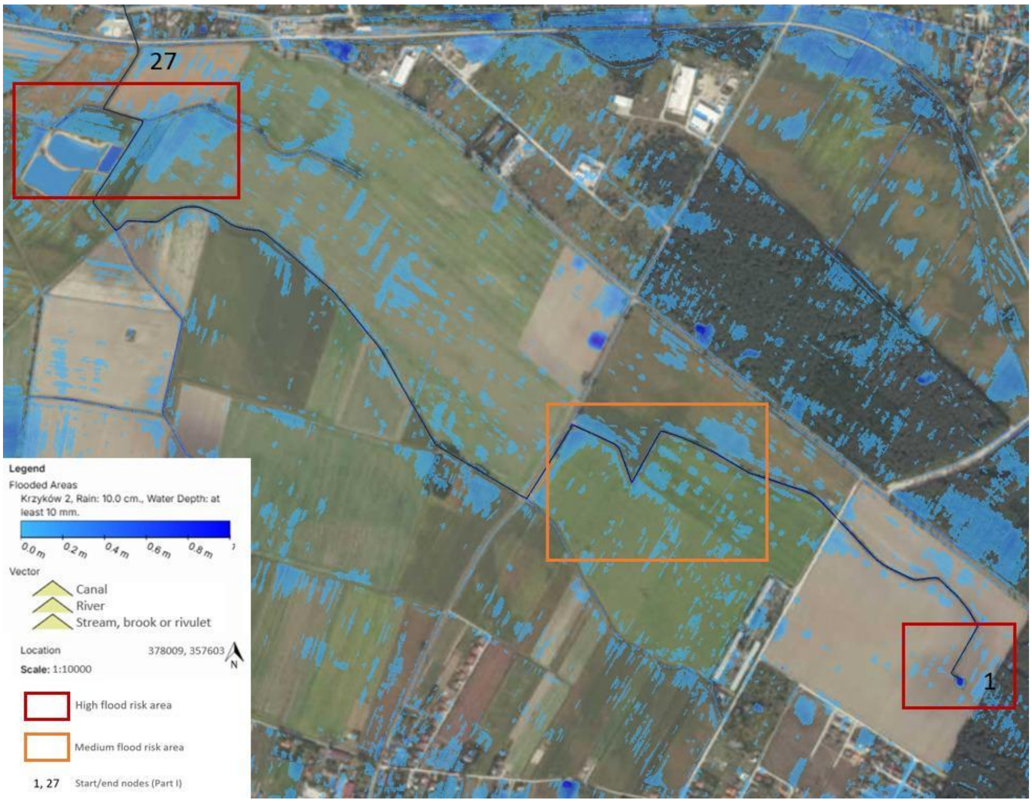

Fig. 11. Part I of the catchment area exposed to 100 mm of rainfall (SCALGO plot)

In the second part of the catchment area, three areas with a high risk of flooding were noted, including residential areas, which highlights the need for protective measures in this region (Fig. 12).

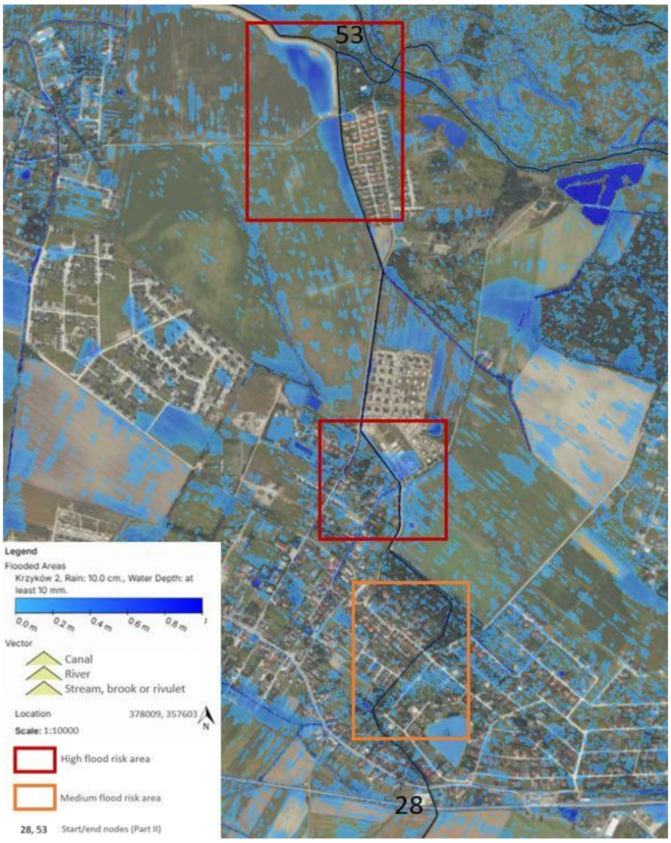

Fig. 12. Part II of the catchment area exposed to 100 mm of rainfall (SCALGO plot)

In the third part of the catchment area, one large area of water accumulation was observed, covering more than half of the length of the stream, which makes this part particularly vulnerable to flooding (Fig. 13).

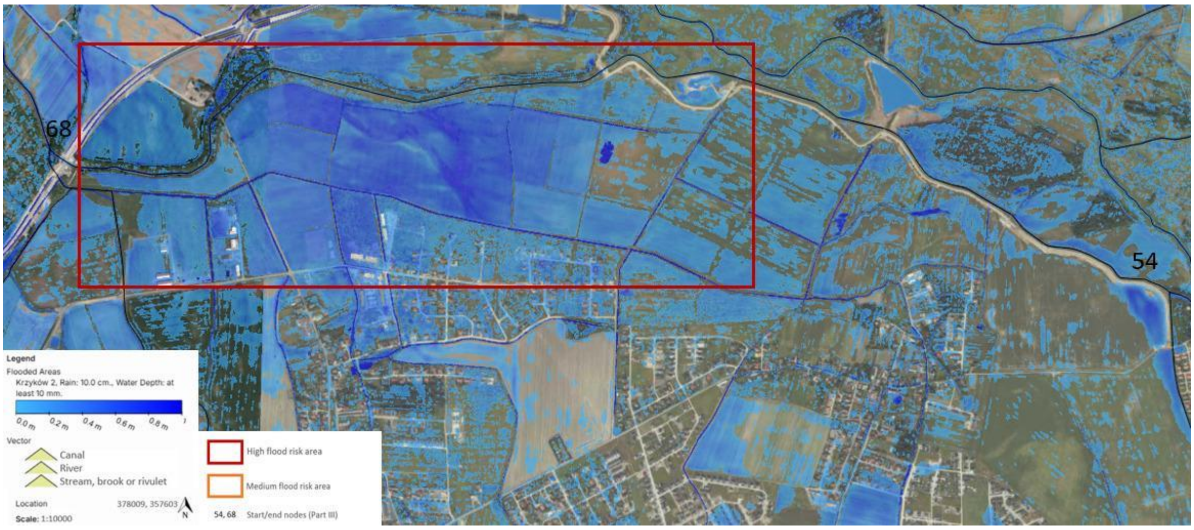

Fig. 13. Part III of the catchment area exposed to 100 mm of rainfall (SCALGO plot)

Scenario 2 - with surface runoff. In the first part of the catchment, the risk of flooding decreased, being limited to three locations classified as medium-risk. In the second part of the catchment, one location remained in the high-risk category, indicating the need for special urban planning supervision (Fig. 14).

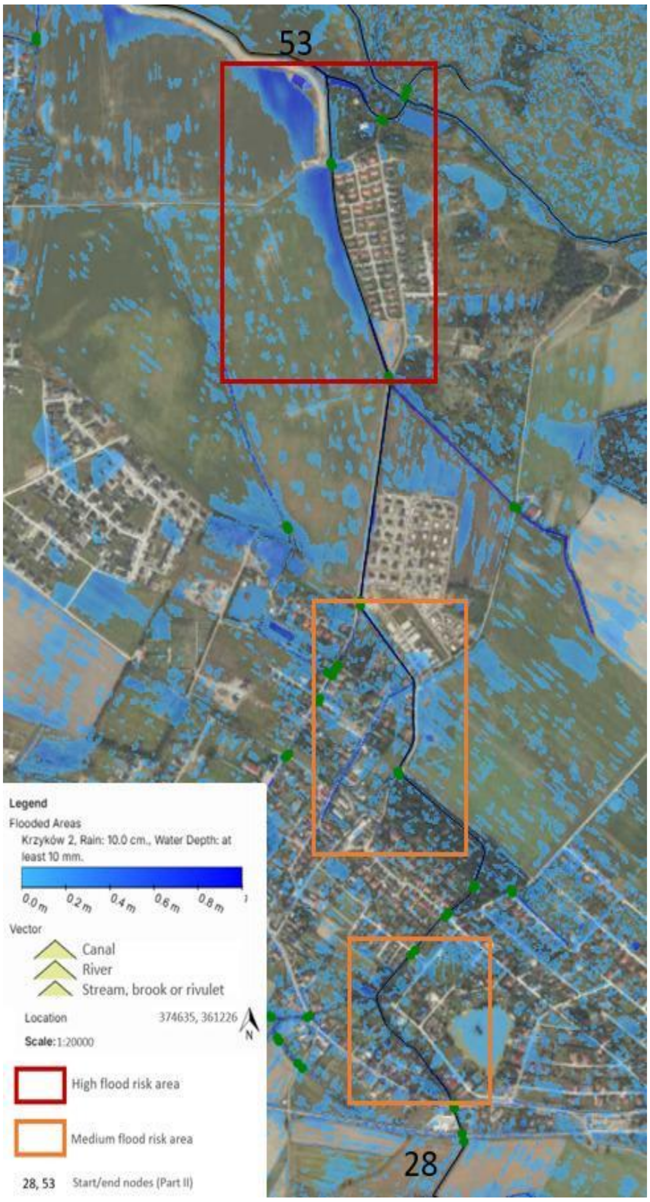

Fig. 14. Part II of the catchment area exposed to 100 mm of rainfall, taking into account the runoff coefficients (SCALGO plot)

In the third part of the catchment area the water level has decreased, but the risk of flooding remains high in the lower parts of the section (Fig. 15).

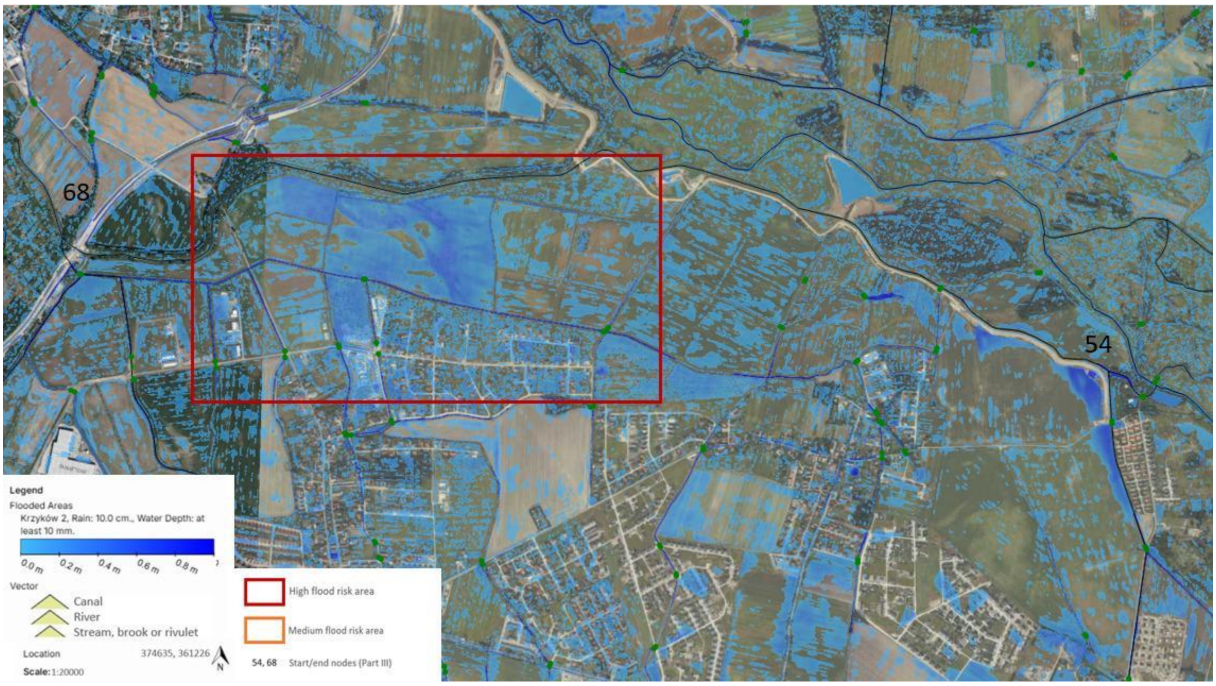

Fig. 15. Part III of the catchment area exposed to 100 mm of rainfall, taking into account the runoff coefficients (SCALGO plot)

The analyses conducted clearly indicate the limited effectiveness of the current drainage system under intense rainfall conditions. Both the results of the hydrodynamic modeling and the analysis in SCALGO Live Poland confirm the need for corrective actions, such as the construction of retention reservoirs, the modernization of drainage infrastructure, or the implementation of solutions that increase local retention.

4.3. Performance of retention reservoirs

Based on the conducted analyses, which included hydrodynamic modeling and spatial analysis using the SCALGO platform for both simulation scenarios (without considering surface runoff and including runoff coefficients), potential locations for the construction of retention reservoirs were identified within the catchment. The selection of these locations was primarily based on areas characterized by the highest flood risk observed in both analysis scenarios. In addition, the technical feasibility of constructing retention reservoirs in these areas was considered, including land availability, soil conditions and existing infrastructural constraints. In such locations, retention reservoirs could effectively collect stormwater and reduce the risk of flooding. To improve the functioning of the stormwater drainage system, the impact of introducing two retention reservoirs was analyzed. Reservoir 1 is a flow-through retention basin located in the upstream part of the catchment. It has a total storage volume of 108 600 m^3 (active storage 81 450 m^3) and a surface area of 3.62 ha. The basin is designed with 45° side slopes and a maximum depth of 3.5 m, enabling temporary stormwater retention and controlled discharge to the receiving channel.

Reservoir 2 is a flow-through retention basin located in the downstream part of the catchment. It has a total storage volume of 74 100 m^3 (active storage 55 575 m^3) and a surface area of 2.47 ha. The basin is characterized by 45° side slopes and a maximum depth of 4.5 m, ensuring effective attenuation of peak flows before discharge to the receiving watercourse. The reservoirs were located at key points within the catchment.

The results of introducing retention reservoirs into the catchment area, obtained from hydrodynamic modeling performed in the SWMM environment, indicate a significant reduction in peak flows and flow velocities within the analyzed drainage system.

In the first part of the catchment, the maximum flow decreased by 37% (from 0.669 m^3/s to 0.422 m^3/s), and the flow velocity dropped to 0.89 m/s, which reduces the risk of erosion and overflow. In the second part of the catchment, the maximum flow was reduced by 31.7% (from 1.057 m^3/s to 0.721 m^3/s), and the flow velocity decreased to 1.15 m/s, which significantly lowers the risk of flooding in residential areas. The channel profile in the second part is shown in Figure 16. The hydrograph of the flow after the reservoir is provided in Figure 17.

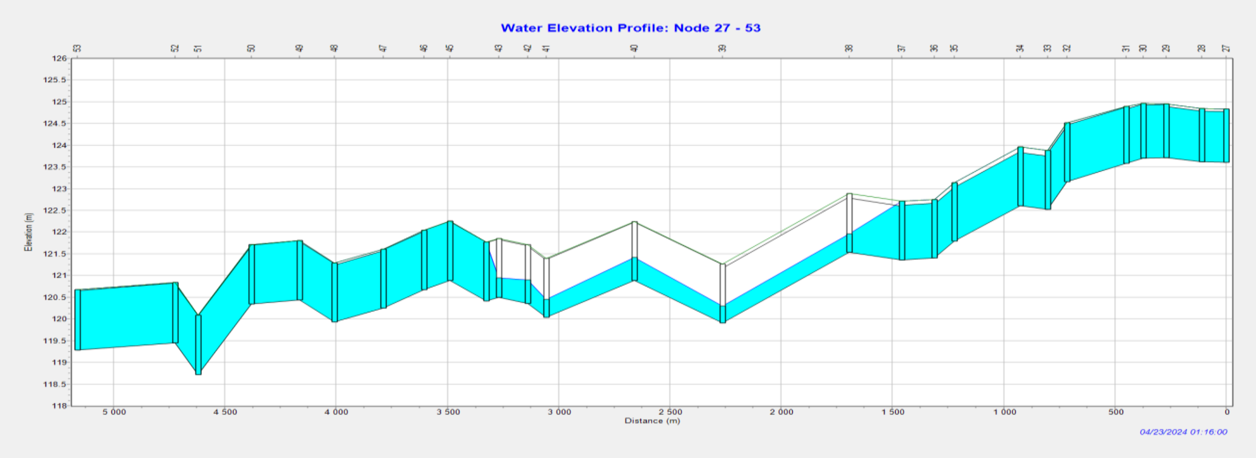

Fig. 16. Profile of the second part of the stream with the Z1 reservoir in operation in the 76th minute of the model rainfall duration for C = 3 years and t = 90 min (SWMM plot)

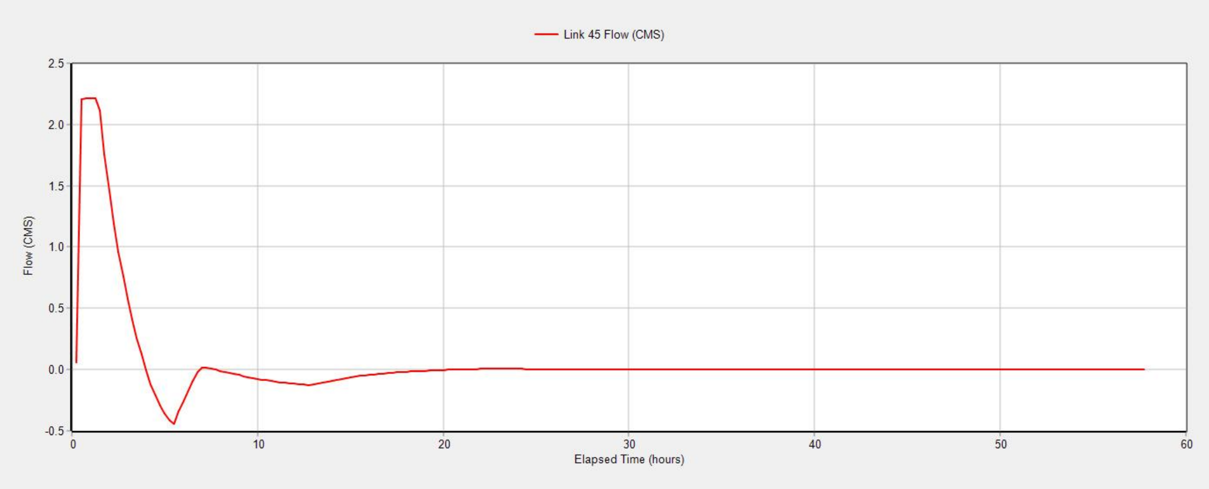

Fig. 17. Flow hydrograph in the section behind the operation zone of reservoir Z1 for model rainfall C = 3 years and t = 90 min (SWMM plot)

In the third part of the catchment, the maximum discharge decreased by 29.2% (from 1.146 m³/s to 0.812 m³/s), and the flow velocity was 0.97 m/s, which significantly reduced flooding areas. The stream profile in the third part is shown in Figure 18. The flow hydrograph downstream of the reservoir is shown in Figure 19.

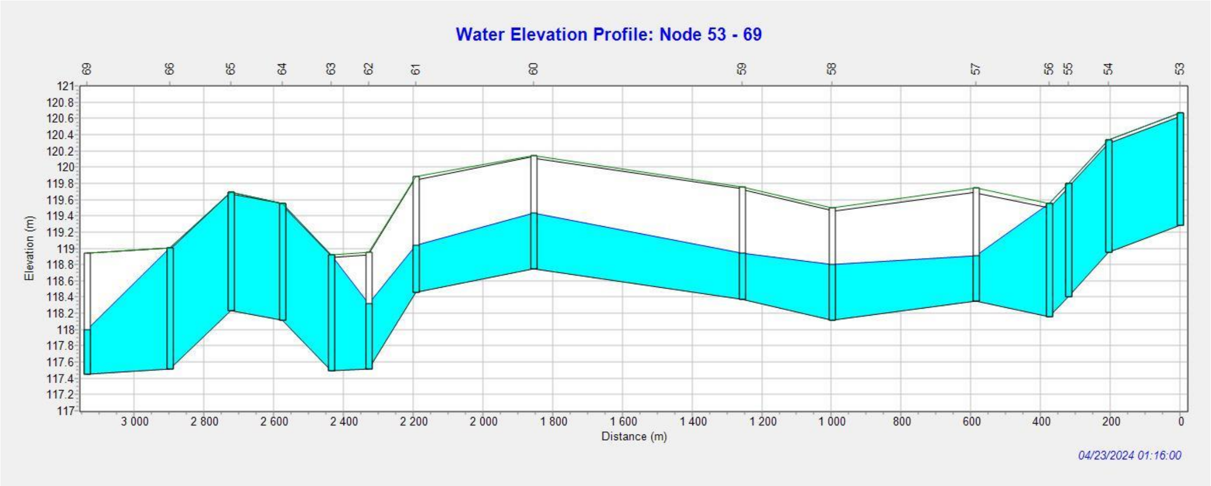

Fig. 18. Stream profile with the Z2 reservoir in operation in the 76th minute of the model rainfall for C = 3 years and t = 90 min (SWMM plot)

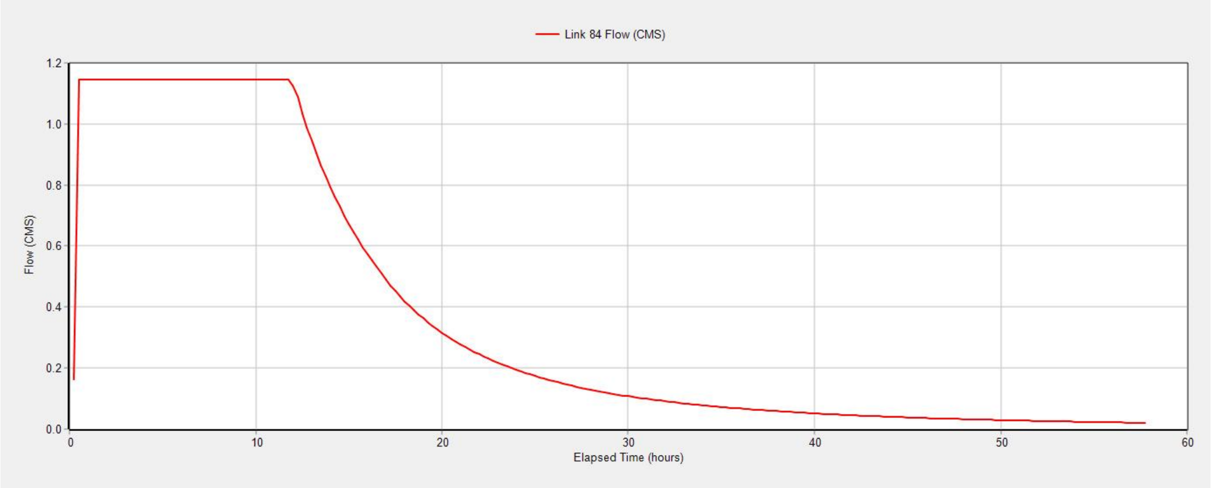

Fig. 19. Flow hydrograph in the last section of the stream for C = 3 years and t = 90 min (SWMM plot)

The spatial analysis performed using the SCALGO platform confirmed the positive impact of the proposed retention reservoirs on reducing flood risk within the catchment. In the first part of the catchment, high-risk areas were completely eliminated, and medium-risk areas were reduced by 78%. In the second part of the catchment, the risk of flooding in residential areas was reduced by 85%. In the third part of the catchment, the floodplain decreased by 62%, leaving only marginal risks. The locations of the reservoirs are shown in Figure 20.

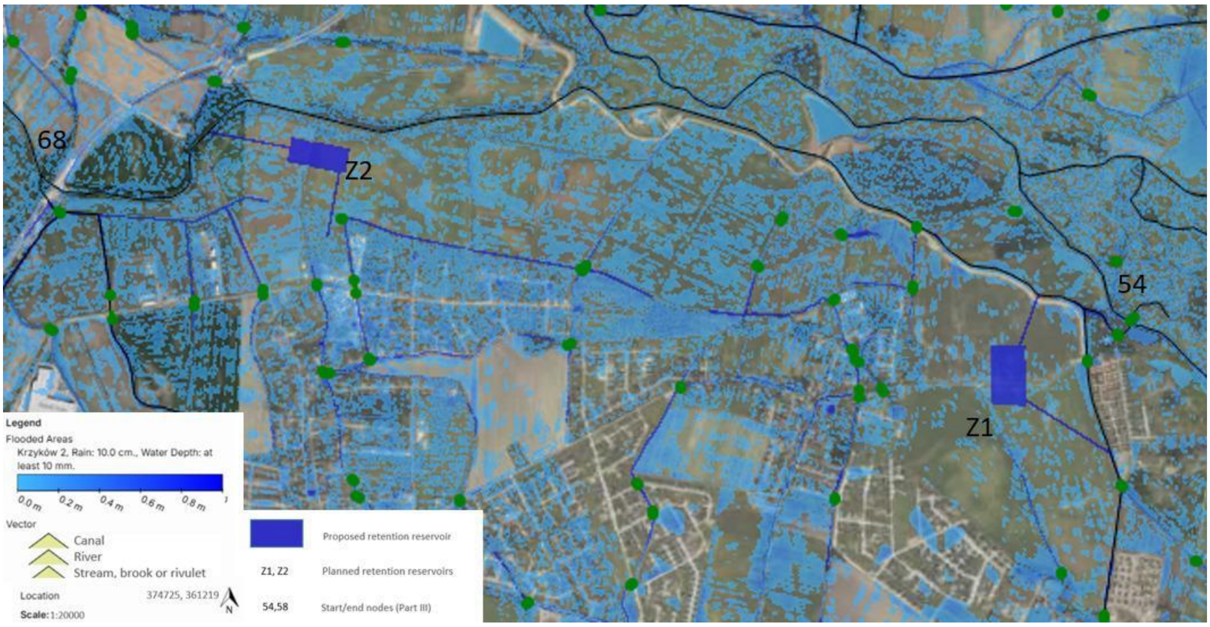

Fig. 20. Location of tanks in the SCALGO platform (SCALGO plot)

The impact assessment of the proposed retention reservoirs indicates that their implementation significantly improves the capacity of the drainage system. The simulations showed that maximum flows were reduced by an average of 32%, while the risk of flooding was eliminated in approximately 93% of the previously identified high-risk areas. The results confirm the need for further corrective actions, such as: modernizing drainage infrastructure, increasing local retention and spatial planning that accounts for variable hydrological conditions. These actions are essential for improving the hydrological situation in the context of intensifying extreme events caused by climate change. Tables 3 and 4 compare the results of the analysis with the inclusion of retention reservoirs in both SCALGO and SWMM.

Table 3. Outflow results from the area before and after the tanks used in the SCALGO platform

Area	**Flow accumulation**	
	Runoff, m^3	**infiltrated or drained, m^3**
Retention tank 1		
Before	23 647.26	284 224.78
Below	4643.74	58 039.56
Retention tank 2		
Before	20306.89	219267.32
Below	0.00	325 316.61

Table 4. Outflow results from the area before and after the reservoirs used in the SWMM program

Area/section	**Flow on a section, $m^3 \cdot s^{-1}$**	**Maximum outflow, $m^3 \cdot s^{-1}$**
Before retention tank 1	1.027	10.684
Below retention tank 1	0.232	7.781
Before retention tank 2	1.277	19.545
Below retention tank 2	0.831	12.547

5. DISCUSSION

5.1. Performance of retention reservoirs

The hydrodynamic simulations indicate that the existing stormwater drainage system within the catchment of the Wieściszów Tributary Stream and the Graniczny Canal River is hydraulically insufficient under current precipitation conditions. The analyses revealed that an impervious surface share of approximately 18% already constitutes a critical threshold at which the hydraulic capacity of the system is exceeded during design rainfall events with a return period of C = 3 years. Similar relationships between increasing imperviousness and accelerated runoff generation have been widely reported in previous studies [2,3], confirming that even limited urbanization can significantly alter catchment hydrological response. The rapid filling of the drainage network, occurring after only 76 minutes, indicates a short runoff concentration time characteristic of peri-urban catchments undergoing intensive land-use transformation.

The conducted analyses demonstrate a strong relationship between land-use structure and hydrological response. Although agricultural areas constitute the dominant land-use category, covering approximately 78.2% of the basin, their retention capacity is increasingly reduced by expanding residential development, which currently occupies about 13.4% of the area. In areas dominated by sandy–loamy soils and dense vegetation cover, infiltration processes modelled using the Horton equation effectively reduce surface runoff volumes. However, within sealed surfaces such as roads, parking areas and rooftops, precipitation is rapidly transformed into surface runoff, resulting in peak discharges reaching 1.057–1.146 m^3/s in downstream sections of the watercourses. These observations are consistent with previous studies emphasizing the dominant influence of land-use change on runoff generation in peri-urban catchments.

The reliability of the obtained results was supported by the use of high-resolution topographic data. The SCALGO Live platform enabled detailed mapping of natural runoff paths and closed depressions, which were subsequently incorporated into the hydrodynamic simulations in SWMM [35]. The integration of high-resolution terrain data with dynamic flow equations based on the Saint-Venant formulation improved the spatial representation of runoff processes and increased the consistency of model results with observed field conditions [33,34].

5.2. Effectiveness of retention measures

The simulations demonstrated the high effectiveness of retention-based mitigation measures. The introduction of reservoirs Z1 and Z2 resulted in an average reduction of peak flows by 32%, with the greatest reduction of 37% recorded in the most hydraulically stressed upstream section, and led to the elimination of approximately 93% of the high flood-risk zones identified in the baseline scenario. These results highlight the considerable potential of retention structures to mitigate flood risk in peri-urban drainage systems, which is consistent with previous studies investigating the role of distributed retention and blue–green infrastructure in suburban stormwater management. From a spatial perspective, the SCALGO analysis confirmed that high-risk areas in the first part of the catchment were completely eliminated, flooding risk in residential areas of the second part was reduced by 85%, and the floodplain in the third part decreased by 62%.

5.3. Practical implications

The combined use of SWMM with terrain-based surface flow analysis platforms like SCALGO provides a comprehensive framework for evaluating infrastructure performance and identifying critical hydraulic locations, and may serve as an effective decision-support tool for local authorities responsible for spatial planning and water management. The results suggest that the implementation of distributed retention measures should become an integral component of development strategies in rapidly expanding peri-urban municipalities such as Czernica and Długołęka. The study confirms that the integration of high-resolution spatial data with dynamic hydrodynamic modeling significantly improves the ability to identify flood-prone areas and evaluate the effectiveness of mitigation measures in peri-urban catchments undergoing active land-use transformation. Such approaches are increasingly important in the context of sustainable stormwater management and climate adaptation strategies.

6. CONCLUSION

This study demonstrates that the integration of hydrodynamic modeling with high-resolution spatial analyses provides an effective framework for assessing the performance of stormwater drainage systems in rapidly urbanizing catchments.

The combined application of the SWMM model and spatial analyses performed using the SCALGO Live Poland platform enabled a detailed assessment of runoff processes and the hydraulic capacity of the drainage infrastructure within the studied catchment (18.78 km^2). The results revealed that the existing drainage system becomes hydraulically overloaded during intense precipitation events, with critical sections reaching full capacity during the simulated design rainfall.

The analyses confirmed the strong influence of land use on the hydrological response of the catchment. An impervious surface share of approximately 18% was identified as a critical threshold at which the hydraulic capacity of the drainage network becomes exceeded during rainfall events with a return period of C = 3 years.

Simulation scenarios also demonstrated that the introduction of retention solutions can significantly improve the performance of the drainage system. The implementation of two retention reservoirs with a combined capacity of 180,000 m^3 reduced peak flows by approximately 32% and eliminated up to 93% of high-risk flood areas identified in the initial model.

The results highlight the importance of integrating advanced hydrological modeling with high-resolution terrain data in the planning and management of stormwater infrastructure. Such an approach enables the identification of critical hydraulic bottlenecks and supports the implementation of effective adaptation measures aimed at increasing the resilience of urban and suburban areas to intensifying precipitation events and ongoing urbanization processes.

7. LIMITATIONS OF THE STUDY

This study provides valuable insights into the hydraulic functioning of the analyzed suburban catchment; however, several limitations should be noted. First, the hydrodynamic simulations were performed using a single design rainfall scenario based on the Euler Type II model. While this model is widely accepted for drainage system verification in Poland and is appropriate for the stated objectives, it does not fully capture the variability of real rainfall events. Future research should incorporate long-term observed rainfall series and multiple return-period scenarios to better characterize hydrological variability and improve the generalizability of results.

Second, the calibration and verification of the SWMM model were constrained by the limited availability of detailed hydrometric data within the catchment. Although local measurements were used to define initial conditions, additional long-term monitoring data would improve the reliability of model calibration and reduce uncertainties in predicted flow dynamics.

Third, the proposed retention reservoirs were evaluated based on hydraulic performance criteria, without a detailed assessment of economic feasibility, land-use constraints, or environmental impacts. In practice, the implementation of such infrastructure requires comprehensive planning analyses, including cost–benefit evaluation and stakeholder considerations.

Finally, the study focuses on a single suburban catchment located in southwestern Poland. Although the methodological framework is transferable, the specific hydrological responses and effectiveness of retention measures may vary depending on local climatic, geological, and land-use conditions. Further studies conducted in different catchment types would help verify the broader applicability of the proposed approach.

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