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Enhancing Stormwater Management in Érd, Hungary, through Nature-Based Solutions for Sustainability and Resilience

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Traditionally, stormwater management strategies were designed to evacuate water swiftly and efficiently to mitigate flood risks. However, water conservation has become a crucial concern with growing environmental awareness, raising damage costs due to climate change and sustainability goals. Urban stormwater capture and utilization are essential for maintaining soil moisture levels, irrigating green spaces, reducing urban heat islands, supporting diverse wildlife, fostering ecological balance, and improving living conditions. This study focuses on a dynamically growing Hungarian city, Érd, with rapidly changing land use and utilizes the numerical Storm Water Management Model to simulate various water resources management scenarios. The simulations revealed multiple vulnerabilities in the channel network, leading to a comprehensive reevaluation and redesign. This redesign integrates nature-based solutions, enhancing the system's effectiveness and climate resilience with limited territorial possibilities. By comparing various design approaches, this research demonstrates that incorporating nature-based infrastructure at residential and subwatershed levels substantially improves flood mitigation and increases precipitation retention capabilities, making traditional infrastructure developments unnecessary. The findings underscore the need for innovative, adaptive infrastructure solutions. Implementing nature-based solutions mitigates flooding and contributes to resilient, sustainable urban water management systems that are better prepared to handle the challenges of a changing climate. This study underscores the critical importance of innovative infrastructure solutions and the positive benefits of nature-based solutions in fostering resilient and climate-adaptive urban water management systems in cities with small open spaces, rapid population growth, and scarce financial resources.

1. Introduction

As urban areas expand, traditional stormwater management strategies are reconsidered, considering the pressing need for sustainability and environmental conservation. These systems are now being adapted to conserve water—a critical element in today's environmentally conscious landscape (Hörnschemeyer et al., 2023). Traditional urban stormwater management has primarily relied on grey infrastructure, which includes expanding drainage networks and enlarging drainage pipes to transport water quickly away from urban areas. Such measures (Cembrano et al.,2004) are designed to manage water flow and mitigate flooding, but with the negative impacts of climate change, they often lead to increased stormwater generation and significant loss of urban water resources (Kong et al., 2017) and their impacts (Ahiablame et al., 2012). As a result, there is a need to explore and develop alternative stormwater management methods that address flooding and preserve urban water resources (Kálmán and Bene, 2023).

Nature-based solution (NbS) has become a new approach that employs green infrastructure, multilayer development, and decentralized micro-scale control to replicate natural hydrologic functions post-development (Jiang et al., 2022). This method has widespread application in the USA, Australia, China, and various European countries (Pyke et al., 2011). The effectiveness of NbS in reducing surface runoff and peak flow, minimizing soil erosion, and enhancing water quality has been well-documented (Bai et al., 2019). Common NbS practices include bio-retention cells, green roofs, permeable pavements, rain gardens, vegetative swales, and rain barrels. These practices mimic natural hydrological landscapes, enhancing water storage and allowing infiltration or

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controlled release into nearby streams (Avellaneda and Jefferson, 2020). Bio-retention cells, rain gardens, and rain barrels are particularly prevalent in residential settings such as small-sized NbS (Daniels et al., 2024).

This study explores innovative stormwater management solutions in Érd, Hungary, using the Storm Water Management Model 5.2 (SWMM) to simulate various scenarios and evaluate the effectiveness of different strategies. The analysis revealed significant vulnerabilities in the existing channel network, leading to a redesign integrating flood protection measures and nature-based solutions. This approach enhances the system's capacity for flood mitigation and increases precipitation retention at residential and sub-watershed levels, helping alleviate drought during dry summer months.

This research investigates the impact of alternative Nature-based Solutions (NbS) techniques in a rapidly growing suburban catchment that faces land constraints, addressing a gap in the existing literature. The findings offer valuable insights for urban planners as they grapple with the need for significant development and infrastructure expansion, which presents environmental, social, and economic challenges for municipalities. NbS solutions can help mitigate these challenges by reducing reliance on traditional infrastructure (economic benefits), even in areas with limited land and high development pressures (social considerations), while promoting sustainable water resource management (environmental benefits).

The resulting systems address flood risks more effectively and contribute to creating more resilient, cost-effective, and sustainable urban environments that can handle the impacts of climate change. This paper aims to contribute to the broader conversation on urban water management, highlighting the importance of adopting innovative, climate-adaptive infrastructure that prioritizes both flood prevention and environmental sustainability.

2. Site description

The modeled settlement is Érd, located in Central Hungary. Érd is a suburb of Budapest's capital and one of the most dynamically growing cities. Its population has increased by 68.4 % in the last three decades, reaching 72,962 in 2023, becoming the 11th largest settlement in Hungary. A growing population constantly challenges the municipality regarding the natural and built environment, economy, infrastructure, and public services, resulting in the restriction of condominium construction in the municipality due to infrastructure challenges. The region has a humid continental climate with approximately 2,000 h of sunshine annually. Frequent stormy weather in spring and summer sometimes causes significant damage to the natural and built environment. The average annual rainfall ranges between 550 and 600 mm. However, there are sometimes significant extremes, such as extended periods without rainfall or sudden downpours.

Located in the easter section of Érd, it is defined by the Sulák stream and its tributaries, including the Bara stream and the Tepecs ditch, along with the Érd-Diósdi branch. This area encompasses two natural watercourses, the Sulák and Bara streams, which flow through the Old Town and past the Outer Roman Road before reaching the Danube near Beliczay Island. On the western side, Érd's territory includes a portion of the Benta stream's catchment area, primarily flowing through Tárnok, the neighboring municipality. The Benta stream's catchment area is expansive, covering 410 km², although the portion within the municipality of Érd is considerably smaller at 17.7 km². The catchment areas of these streams are illustrated in Figure 1.

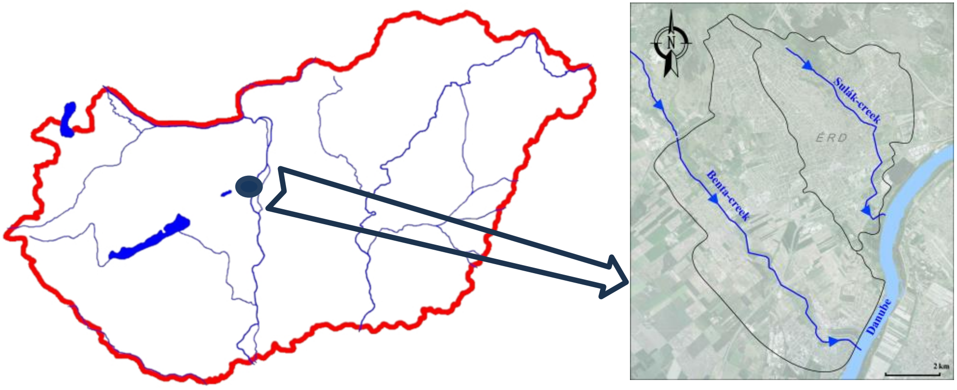
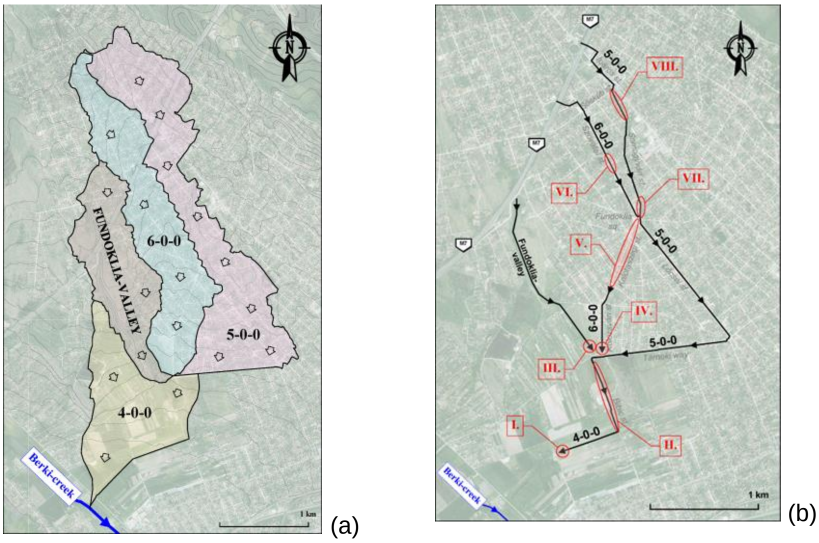


Figure 1: Map of the study area and the digital elevation model with major tributaries to the Danube

The western part of the city, where the watershed is located, was divided into four sub-watersheds based on the partially built storm sewer systems, as shown in Figure 2 (a). The total area of the watershed is 4.28 km^2. Land use is dominantly meadows and agricultural land, except 6-0-0, a suburban area characterized by single-family houses. Presently, the stormwater drainage network is partially built, with several problems, such as no receiving body at the drainage system outflow, flooding problems, and interconnection within and between the major sewer line collectors, which are missing at some locations. An interconnected storm sewer system was recently designed, but construction of the new design was not finished. Figure 2 (b) shows the delineated watersheds and summarizes the drainage system problems and locations.



(a) (b)

Figure 2: Érd, four major sub-watersheds (a), and problem summary (b)

Figure 2b highlights the following issues: I. The 4-0-0 main collector ends abruptly in the middle of agricultural land, discharging water directly onto the land. II. Only a portion of the 4-0-0 collector has been constructed. The temporary ditch has limited capacity to handle the flow, leading to multiple overflow points, with the most critical being at the upper section. III. There is no receiving structure for the flow from Fundoklia Valley.IV. The 6-0-0 main catchment also lacks a receiving body. V. The middle section of the 6-0-0 main collector has not been constructed. VI. The upstream section of the 6-0-0 collector experiences flooding issues. VII. The lower section of the 5-0-0 main collector is prone to flooding due to inadequate design. VIII. Rerouting is required because of recent housing constructions in the area, which are needed to accommodate the growing population.

3. Methodology

Four different model versions were evaluated to examine and improve the stormwater management options in the rapidly built-up area of Érd. The existing condition (V1) was used to test the current system's operation and detect problems. The (V2) model evaluates the current system by adding sections designed but never constructed. The proposed system (V3) was modeled with a detention/infiltration pond design to solve flooding problems. Several LID controls in the system (V4) were added to model V3. This scenario included a potential NbS implementation of rain barrels in the newly built lots in the suburban 6-0-0 watershed. It was applied to impervious areas that do not directly route stormwater runoff to stormwater pipes..

3.1 SWMM model structure

The EPA (U.S. Environmental Protection Agency) Stormwater Management Model (SWMM, Version 5.2, EPA) was used to simulate the hydrological response to the study area's infrastructure improvements and NbS controls. The watershed was divided into sub-catchments, and the storm drainage infrastructure system was divided into conduits, junctions, and outlets. SWMM requires many input parameters for system modeling. Most parameters used to define the ground surface and the stormwater drainage network characteristics were determined based on GIS data and available design drawings (Table 1). The remaining parameters were determined based on the land use map and literature data (Rossman, 2015), which included depression storage for pervious and impervious surfaces, Manning's n value for overland flow for pervious and impervious surfaces, and conduits, and the Green-Ampt soil infiltration parameters. Runoff from impervious and pervious areas flows directly to the storm system inlet. Imperviousness was determined based on land use maps for Fundoklia Valley. For sub-watershed 4-0-0, it was 1 %, while the rest of the area value was 5 %. For conduit flow, the dynamic wave equation was used.

Table 1: Input parameters for the SWMM model

Parameter	Type		Value
Manning's n	Overland flow	Impervious	0.015 (-)
		Pervious	0.35 (-)
	Conduit		0.012 (-)
	Open channel		0.03 (-)
Depression storage		Impervious	1.5 (mm)
		Pervious	6.0 (mm)
Soil infiltration	G-A	Hydraulic conductivity	4.33 (mm/h)
		Suction head	0.43 (mm)
		Initial deficit	0.368 (-)

3.2 Rainfall distribution

Storm events with return periods of 2 and 10 ys were simulated to investigate the hydrological impacts of various urban development scenarios and NbS controls. The Hungarian national standard was used to determine the rainfall intensity values. Manual and model-based simulations were used to calculate the time of concentration of the current system, which was also the duration of the rainfall used in the simulations. The rainfall intensities for the two-y and ten-y events were 25.7 mm/h and 51.4 mm/h. The model utilized a triangular rainfall distribution, with a base time of 55 min and the peak intensity occurring at 18 min.

3.3 Pond design and NbS controls

A detention pond and an infiltration pond were integrated into the model to enhance the flood peak reduction and the infiltration capacity of the existing system's performance. During the simulations, the model accounted for pond evaporation and infiltration losses. Hargreaves' method was utilized for daily evaporation estimates to calculate evaporation, and daily temperature data were incorporated. For modeling infiltration, the Green-Ampt model was applied. In this configuration, the hydraulic conductivity is 0.5 mm/h for the detention pond and 1.44 mm/h for the infiltration pond. As part of the LID strategies, rain barrels, and a rain garden were implemented in watershed 6-0-0. The specific parameters applied to these NbS controls are detailed in Table 2.

Table 2: NbS parameters for the SWMM model

System improvements				
Rain garden	Surface	Berm height 150 mm	Vegetation volume fraction 0.1 (-)	Surface slope 0 (-)
	Soil	Thickness 500 mm	Porosity 0.5 (-)	Conductivity 500 mm/h
Rain barrel		Storage height 1,000 mm	No drain	

The NbS designs were applied to impervious and pervious watershed areas. For rain gardens, 20 % was impervious, while 10 % pervious area was treated. Each LID unit was 400 m^2, and only one unit was applied in each sub-watershed; it was assumed that rain gardens were installed in a park, playground, or a larger lot in each sub-watershed. The flow from the rain garden goes to the same outlet as the LID unit's sub-catchment. In addition to rain gardens, 30 rain barrels – draining 100 m^2 each – were used in each sub-watershed. In the sub-watersheds, 20 % of the impervious and no pervious area was treated.

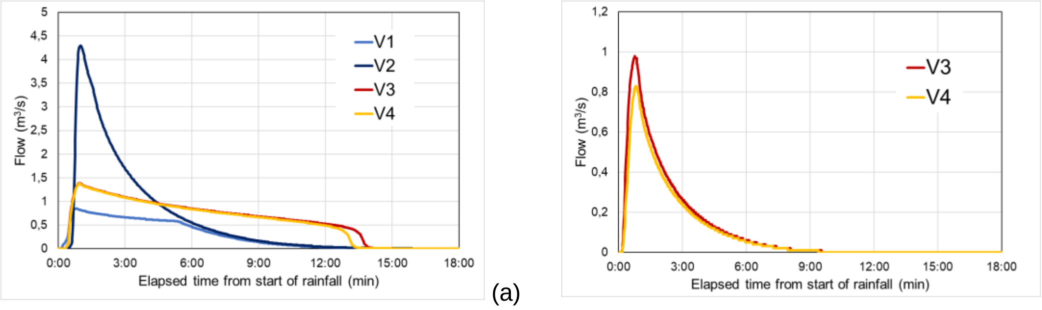
4. Results

In the first model version (V1), the goal of the model was to determine whether the problems in the system, as described in section 3.1, are evident and whether other issues would be detected. During the run, the model identified all the previously summarized problems. In addition, flooding problems were found in the sub-catchment 6-0-0. In V2, the main objective was to examine whether the problems identified for version V1 would disappear when implementing planned developments or some would persist. Some issues were solved, and flooding was reduced, but problems I, VI, VII, and VIII remained. The proposed design (V3), with the detention and infiltration pond design, addresses all the system's technical problems. Finally, based on the V3 version, in the V4 version, the impact of LID controls was evaluated that were applied in the 6-0-0 sub-watershed. The results are shown in Table 3.

Table 3: Variation of summary characteristic for 2 and 10 y return periods

Scenarios	2 y				10 y			
	Infiltration (mm)	Runoff Volume (mm)	Peak flow (m^3/s)	System loss (m^3)	Infiltration (mm)	Runoff Volume (mm)	Peak flow (m^3/s)	System loss (m^3)
V1	16.493	5.804	0.848	17,383				
V2	16.460	5.840	4.298	1,062	19.397	14.397	5.152	17,472
V3	16.460	5.840	1.384	-	19.731	14.501	3.371	6,523
V4	16.498	5.554	1.372	-	20.022	13.885	3.169	5,112

The first two columns show infiltration and runoff volume from the watershed into the storm sewer system. The peak of the outflow hydrographs is shown in the third column, and then the last column for the two-y return period rainfall is the storm system loss due to flooding. The smallest infiltration was from V2 and V3. The infiltration increased somewhat in the V4 version but not significantly. Runoff volume was reduced by 5 % when the LID method was applied in V4. Peak flow increased significantly at V2 since most flooding problems were solved, and the system delivered the total runoff volume. The installation of the two ponds (V3) reduced the peak flow by 68 % and solved the system's flooding problems. Applying the NbS (V4) did not reduce the peak further; a slight decrease in infiltration and runoff volume was observed. The impact of 10-y return period rainfall on the runoff characteristics was evaluated for V2, V3, and V4. Infiltration increased from V2 to V4. The detention pond decreased peak flow by 35 % (V3), and an additional 6 % reduction of peak flow occurred due to LID application. The system was flooded for all cases but significantly less for V3 and V4. The outflow hydrograph peak and distribution are shown in Figure 3.



(a) (b)

Figure 3: Comparison (a) of the modeled versions at the outflow and (b) two model versions at the 6-0-0 collector outflow

The effectiveness of a fully developed drainage system is demonstrated in Figure 3(a). In V2, peak flow rates significantly exceed those observed in V1, leading to system overflows and flooding at several locations. Additionally, the disconnected nature of the system causes the stormwater outflow to drain into an open field. In contrast, V3 shows a dramatic reduction in peak flow due to the implementation of detention and infiltration ponds. During the 2-y storm event, the differences between V3 and V4, where the impact of LID controls was examined, were minimal. The primary effect of LID on the hydrograph was a reduction in the base time, with little change in peak flow. Further analysis, shown in Figure 3(b), compares the outflow from the 6-0-0 system for V3 and V4 to evaluate the impact of NbS. The NbS controls contribute to a 20 % reduction in peak flow, consistent with previous research by Samouei and Özger (2020), highlighting the effectiveness of NbS in improving stormwater management at the sub-catchment level. However, NbS should not replace traditional grey infrastructure but rather be integrated with it, particularly with detention and retention pond systems—to ensure comprehensive stormwater management, as Wand et al. (2019) noted. These results underscore that a combination of strategically placed and well-designed detention/retention ponds and NbS techniques can enhance the efficiency of storm sewer systems, providing a more resilient and adaptable solution for urban stormwater management.

5. Conclusion

Hydrological performances of four urban development scenarios were analyzed under two storm events (2- and 10-y return periods) using the SWMM model in Érd, Hungary. The study evaluated hydrological responses to infrastructural changes. It assessed the effects of two NbS applications, comparing these methods with an original baseline scenario in a city with dynamic population growth and limited expansion area. The results indicate that traditional urban development, as seen in scenarios V1 and V2, could exacerbate flooding issues, highlighting the inadequacy of conventional stormwater management strategies in dealing with these challenges. Detention ponds significantly reduced flooding and peak flow (68 %) and system flooding, while NbS structures reduced runoff volume by 20 % for both rainfall frequencies. The shift from scenario V2 to V3, which includes the introduction of detention and infiltration ponds, reduces peak flow rates during storm events and alleviates the overflow and flooding issues prevalent in earlier scenarios. The further application of NbS measures in scenario V4, while subtler, helps reduce the hydrograph's base time, facilitating a quicker return to normal flow conditions. The results underscore the advantages of integrating strategic infrastructural enhancements in stormwater systems. For cities that frequently experience intense rainfall, adopting a hybrid approach that combines well-designed retention or detention systems with NbS strategies is essential. Such a comprehensive approach improves the resilience of urban infrastructures – that experience rapid land use change and increase runoff (decreasing infiltration) – and promotes more sustainable stormwater management practices. This strategy ensures that urban developments are better equipped to handle the increasing variability and intensity of storm events expected under changing climate conditions and promote balanced, sustainable development. Several studies investigating NbS have shown their usefulness in stormwater management and flood peak reduction capabilities, which aligns with the findings of this research. However, in cities with limited areas to expand but with rapid population growth, the dynamic construction is accompanied by increased flooding problems and, thus, potential material damage. This study demonstrates that the application of NbS can reduce these costs (economic benefits), increase the well-being of the population (social benefits), and improve local water resources (environmental benefits).

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