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Urban Stormwater Management with Rain Gardens – A Case Study of Kecskemét, Hungary

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Abstract
This research explores the potential benefits of rain gardens, a form of nature-based solutions (NbS) for urban stormwater management in Kecskemét, Hungary. An experimental rain garden was established using plants with varying drought tolerances to capture rainwater from a single-family house roof. This garden was monitored for a year to assess its rainwater retention capacity and observe plant development and survival. Concurrently, we identified areas within Kecskemét prone to flash floods from heavy rainfall, demarcating promising locations for rain garden conversion. Our primary goal was to identify applicable plant species and quantify how much rainfall could be retained in rain gardens. Our results show that drought-tolerant plants (e.g. *Festuca amethystina, Festuca pallens glauca*) perform better in the dry conditions typical of Kecskemét. Based on our calculation, the possible rainwater retention is about 1,500 m³, with 60 planned rain gardens. These findings suggest that the widespread urban application of rain gardens, as a nature-based solution, can significantly contribute to mitigating flash floods and enhancing urban resilience to extreme weather events.

Keywords: rain garden; stormwater; water retention; extreme precipitation; Hungary

Introduction
Urban areas worldwide face mounting pressure on water resources as climate change intensifies (Löscher et al., 2017). The spread of impermeable surfaces due to urbanization disrupts the natural water cycle, curtailing infiltration and evaporation crucial for maintaining stable urban microclimates (Osheen & Singh, 2019). This disruption triggers several issues: excessive runoff reduces water available for evapotranspiration, leading to soil desiccation and stressed green spaces (Osheen & Singh, 2019), while heavy rainfall events increasingly cause flash floods on sealed surfaces, washing pollutants into water systems. These

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challenges underscore the need for sustainable solutions that emulate natural water management processes.

The "sponge city" concept (Zevenbergen et al., 2018) is one of the possible solutions, which integrates green spaces, rain gardens, storage facilities, and green roofs into urban landscapes (Jiang et al., 2018; Nguyen et al., 2019). Blue-green infrastructure builds on sponge city principles, tackling water retention and drainage by merging ecological and engineering approaches (Wang et al., 2022; Zareba et al., 2022; Zhang et al., 2022). This involves surface elements for permanent or temporary water retention and subsurface storage to manage stormwater sustainably (Rosenberger et al., 2021; Tokarczyk et al., 2017). Across Europe, escalating rainfall intensity strains traditional drainage systems, often designed for outdated historical rainfall patterns (Ashley et al., 2005; De Toffol et al., 2009). In response, European urban planning increasingly incorporates the principles of nature-based solutions (NbS) through the implementation of blue-green infrastructure to manage excess rainfall, mitigate floods, and improve urban livability (Liu et al., 2019). The NbS concept refers to strategies that use natural features and processes to address societal challenges – such as climate change, food and water security, and natural disasters – while preserving biodiversity and promoting sustainable development (O'Hogain & McCarton, 2018). Specific examples of such green infrastructure, like rain gardens and constructed wetlands, are critical NbS applications that support broader climate adaptation efforts in Hungary by reducing runoff volume into sewers (Ge et al., 2023; Liao et al., 2017; Siwiec et al., 2018).

A rain garden is a landscaped depression designed to collect, treat, soak, filter, and retain rainwater from roofs, driveways, or streets, using modified soil and specific plants (Boguniewicz-Zablocka & Capodaglio, 2020; Kelly et al., 2020). As urbanization continues, innovative and cost-effective solutions are vital to combat rising flash flood risks, which occur when intense, short-duration rainfall overwhelms the ground's infiltration capacity, especially in sealed urban environments. While traditional sewer systems are costly to build and maintain, rain gardens offer a more economical alternative, though their effectiveness depends on local soil and watershed characteristics (Boguniewicz-Zablocka & Capodaglio, 2020; Ishimatsu et al., 2017; O'Donnell et al., 2017).

Climate change impacts are particularly pronounced in Hungary's "Homokhátság" region (Danube-Tisza Interfluve), including the city of Kecskemét. Rising temperatures and extreme weather have led to decades of desiccation. In Kecskemét, a city without natural surface watercourses, these extremes manifest as flash floods during heavy rains, especially in low-lying areas with extensive paving or impermeable saline soils (Luo et al., 2018; Papagiannaki et al., 2017). Kecskemét's 2021 Climate Strategy outlines rainwater management principles focused on water retention: 1) reducing runoff coefficients by increasing green areas, 2) property-level regulations for rainwater retention, and 3) promoting rainwater utilization (infiltration, evaporation) (Kecskemét Megyei Jogú Város, 2021).

Rain gardens align perfectly with these goals. The increasing frequency of flash floods (e.g., 2011, 2015, 2018, 2020, 2021, 2024) disrupts traffic, causes public dissatisfaction, and inflicts financial damage, particularly on city-center retail. Rapid water drainage post-flood further worsens drought conditions. Thus, in the water-scarce Homokhátság, retaining water and reducing water use are important goals.

Research on rain gardens in semi-arid regions like Homokhátság is limited, though examples from the US and Mediterranean exist (Herrera et al., 2017; Jiang et al., 2015). This study's novelty lies in its specific Central Eastern European context, demonstrating that even plants not typically listed for rain gardens can be viable. It highlights the potential of incorporating local native vegetation, regardless of initial drought or moisture tolerance assessments. In drier climates, selecting species with lower water needs yet resilient to occasional flooding is particularly beneficial.

Therefore, this research aims to answer:

1. What insights can an experimental rain garden offer regarding suitable plant species and water retention capacity?
2. Which green areas in a flood-exposed sample area of Kecskemét are suitable for rain garden development?
3. How much water could potentially be retained by rain gardens in this study area?

Data and Methods

Study Area

Kecskemét (population 108,120 in 2022) is situated in the Homokhátság region (Figure 1), an area highly vulnerable to climate change and exposed to aridification. The city's economy, once dominated by agriculture, is increasingly industrial, highlighted by a large automotive plant established in the early 2010s, now occupying 450 hectares.

The selected study area, encompassing approximately 2 hectares, is situated in the city center of Kecskemét. A key topographical feature of this site is its lower elevation relative to the adjacent urban landscape. Consequently, it functions as a natural catchment, accumulating surface runoff from the surrounding areas. This characteristic renders the area particularly susceptible to inundation by flash floods during heavy rainfall events, making it a pertinent location for studying rainwater retention strategies. The land cover is predominantly characterized by impervious surfaces, such as urban pavement, typical of a residential zone.

Figure 1. The location of Kecskemét in Hungary and the study area

The average temperature in Kecskemét rose by 3.5°C between 1991 and 2019 (KSH, 2024). The urban heat island effect is pronounced in densely built-up areas and the paved inner city, where summer night temperatures often remain above 20°C. July-August average temperatures reach 30°C, with highs up to 37°C. Climate models project extreme aridity for the region by century's end, with frequent severe droughts (Kecskemét Megyei Jogú Város, 2021).

However, climate change here doesn't necessarily mean less rainfall overall. Average annual precipitation has varied significantly in the last 15 years, from 359 mm to 881 mm (Figure 2). Rainfall distribution is uneven; while it might seem drier, especially during summer heatwaves, a substantial portion of precipitation often falls in large, intense events. In Kecskemét's multi-story residential and densely built-up areas, stormwater flows into a closed drainage network. The city's separated sewer system prevents rainwater from overwhelming the smaller-capacity sewage network during extreme events. Kecskemét has 20 water catchments: 1-16 (2,121 hectares total) drain into the Csukásér main channel, while 17-20 flow into an upper stormwater reservoir (Kecskemét Megyei Jogú Város, 2020). With typical annual rainfall of 500-550 mm, approximately 12 million m³ of rainwater and wastewater are drained from the city annually.

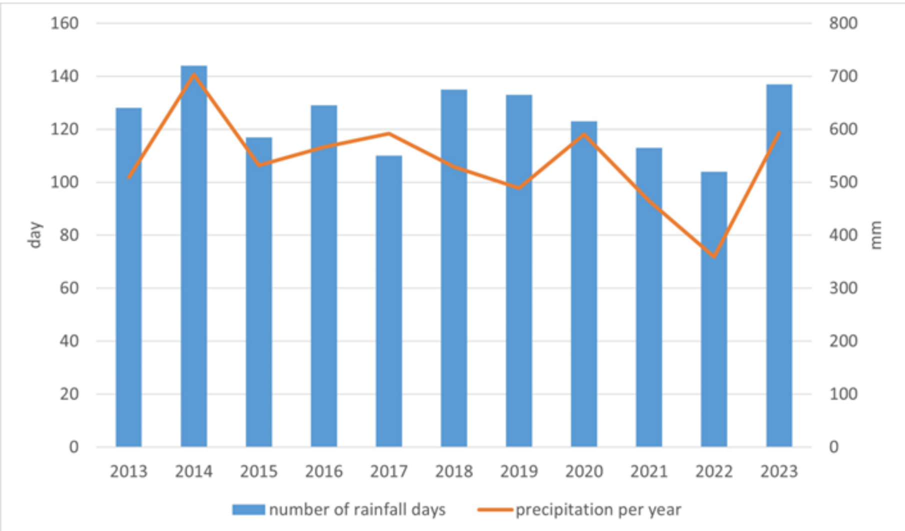

Figure 2. The average annual amount of precipitation and the number of rainfall days by year in Kecskemét (2013-2023)
Source: Central Statistical Office (KSH)

The flood issues from extreme weather are concentrated in our selected study area (Figure 1). This area acts as a catchment for surrounding higher-lying streets, frequently flooding (approx. 10 mm/h) during intense downpours (Figure 3). HungaroMet (met.hu) data indicate such events are increasingly common: over the last 50 years, daily summer precipitation amounts have risen by over 2 mm, while the number of rainy days has fallen (HungaroMet, 2024).

Figure 3. Flash floods in the study area (Vágó street) in 2020 June (left) and August (right)
Source: Levente Szekeres

Methodology

The study employs a two-pronged approach to answer the research questions. First, a small experimental rain garden was created to test plant viability. Second, we identified a nearly 140,000 m² downtown Kecskemét area exposed to flooding to assess its potential for rain garden implementation. Figure 4 outlines the research phases.

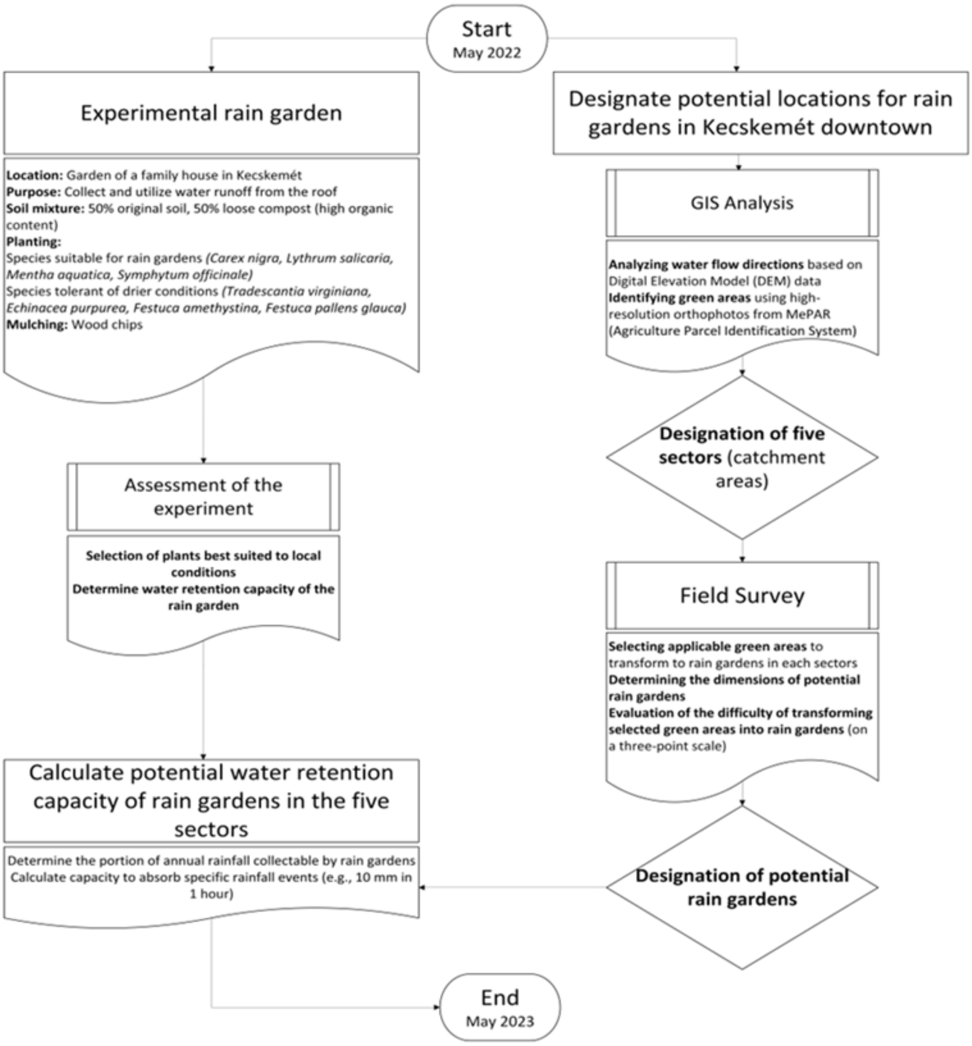

Figure 4. Flow diagram showing the connection between different research phases

Creation of a Rain Garden and Determination of Water Retention Capacity

An experimental rain garden was established in a family house garden in Kecskemét to collect roof runoff. The soil comprised a 50/50 mix of original soil and loose, high-organic-content compost from the local water utility, Bácsvíz Ltd. Selected plant species were planted, and bare soil was mulched with wood chips to conserve moisture, reduce transpiration, prevent erosion, and inhibit weeds. The experiment ran from May 2022 to May 2023. This one year was sufficient for testing the viability of the plants. However, monitoring of the vegetation in the experimental rain garden has continued since then.

Plant species selection was informed by Central and Eastern European literature and the Homokhátság's climate. We chose species commonly used in rain gardens (*Carex nigra, Lythrum salicaria, Mentha aquatica, Symphytum officinale*) and species tolerant of drier conditions (*Tradescantia virginiana, Echinacea purpurea, Festuca amethystina, Festuca pallens glauca*) (Kasprzyk et al., 2022; Bortolini & Zanin, 2018; Laukli et al., 2022; Vaculova & Stepankova, 2017). Plant viability was assessed by monitoring plant cover and health (leaf water availability, disease symptoms, growth) relative to their initial state.

Soil water retention capacity was the focus of soil testing, as permeability is key for rain gardens. The Hungarian Detailed Soil Physical and Hydrological Database (MARTHA) (Makó et al., 2010) indicates that Kecskemét's city center and the experimental site have sandy soils with high organic matter (Arenosols and Cambisols). Thus, detailed lab tests for soil type were deemed unnecessary, as practical compost ratios (40-50%) are standard. The soil properties of hypothetical urban rain gardens were assumed to match the experimental garden.

To evaluate water retention, one liter of an air-dry mixture of original sandy soil and compost was saturated with water. The amount percolating within 30 minutes was measured. Water began percolating after 29 seconds, with 0.3 liters dripping through by the end. Since 1.48 kg of the soil-compost mix is one liter, 1 liter of the mixture can hold 0.55 liters of water. The 3.04 m² experimental rain garden, filled with 1.51 m³ of this soil-compost mix, had a water retention capacity of approximately 833 liters. This equates to 0.28 m³ retention per square meter for a 60 cm deep rain garden. These results were extrapolated to estimate the potential capacity of urban rain gardens. Increasing rain garden depth proportionally enhances retention; our calculations represent a lower bound. The calculation was performed using the following formula (1):

$$V = \left(\frac{a+c}{2}\right) * m * l \qquad (1)$$

, where a is the width of the base of the trapezoidal depression formed for the rain garden = 50 cm,
c is the width of the top surface of the trapezoid = 80 cm,
m is the depth of the experimental rain garden = 60 cm,
l is the length of the rain garden = 380 cm.

The product of these measurements provides the volume of the depression, which we converted to cubic meters. The resulting volume was 1.48 m³. Based on these measurements, the area of the rain garden was calculated to be 3.04 m².

Designation of Potential Locations for Rain Gardens and Determination of Water Retention Capacity

In the study area, we explored creating rain gardens in existing green spaces to collect runoff from paved surfaces and roofs. Green areas were identified manually in QGIS using MePAR (Agricultural Parcel Identification System) high-resolution orthophotos. The city's Digital Elevation Model (DEM) helped determine main flow directions, allowing us to select green surfaces lower than their surroundings to act as catchments. Public utility and drainage network locations were also considered using city GIS data. Potential rain garden sites were then manually designated, followed by field surveys for finalization. The study area was divided into five main sectors (catchment areas) (Figure 5), further subdivided into 12 sub-sectors for efficient analysis. Results are presented by the main sectors.

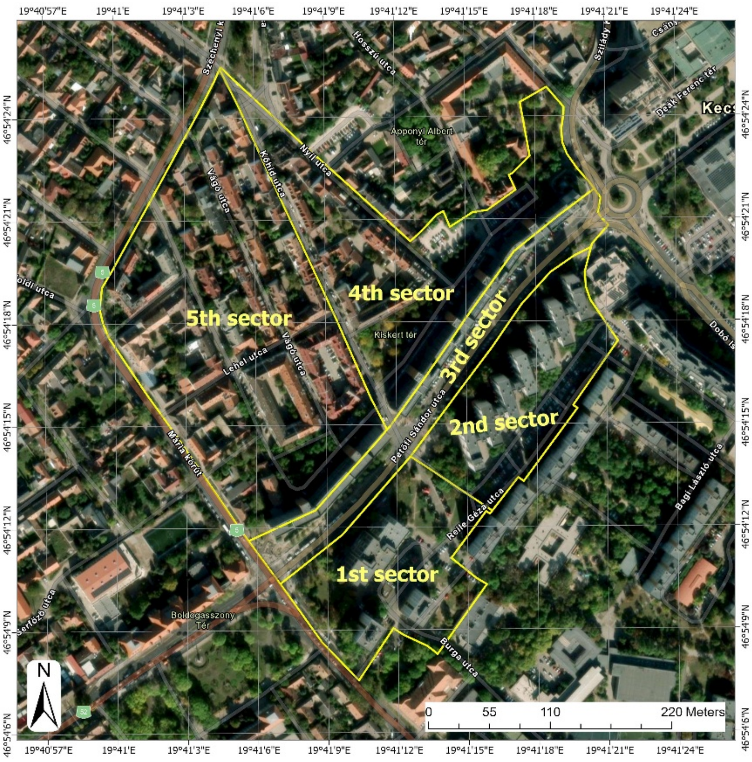

Figure 5. Five sector division of the study area

Within each sector, the estimated size of planned rain gardens was determined based on paved/unpaved surface ratios, allowing calculation of potential water retention. Comparing this with rainfall data (May 2022 – May 2023, Figure 6), we estimated the portion of annual rainfall retainable. We also calculated the capacity to absorb specific events (e.g., 10 mm rain in one hour).

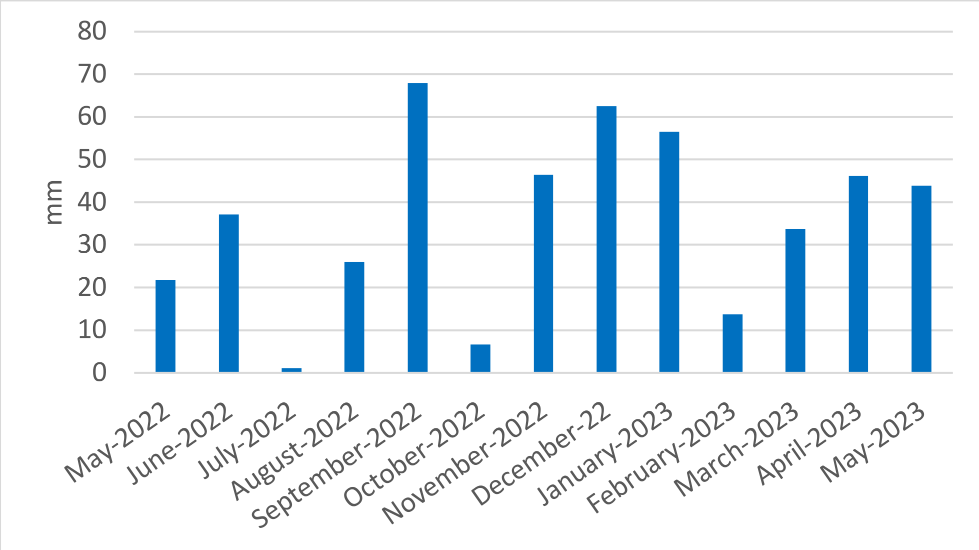

Figure 6. The average monthly rainfall in Kecskemét between May 2022 and May 2023.
Source: Central Statistical Office (https://www.ksh.hu/stadat_files/kor/hu/kor0056.html)

Extreme rainfall is increasingly frequent in Kecskemét. For instance, on August 4-5, 2020, nearly 70 mm fell in 12 hours (Netatmo weather station data), with several 30-minute periods seeing 15-20 mm (Figure 7). Such events highlight the inadequacy of existing drainage and the need for better stormwater management.

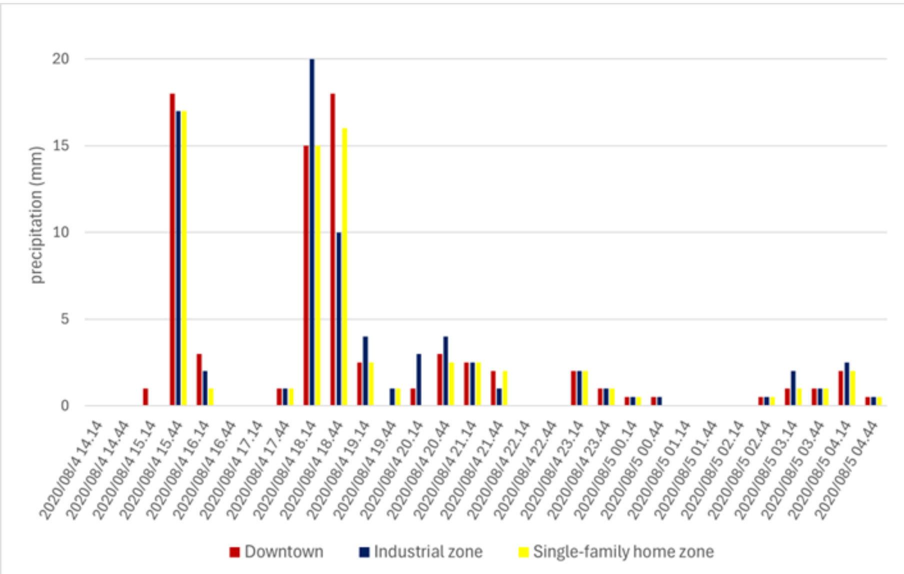

Figure 7. The amount of precipitation measured by Netatmo meteorological stations within 12 hours at various points in Kecskemét (August 4-5, 2020)

Results

Vegetation Viability in the Experimental Rain Garden

The experimental rain garden, with its two plant groups, functioned efficiently within six months. It successfully collected and retained roof runoff, even during heavy downpours and persistent rain. The permeability test showed the sandy soil-compost mix retained 0.55 liters/dm³. For our 3.04 m² garden, this meant a retention capacity of 0.83 m³ (approx. 0.28

m³/m²). This value was used to calculate the potential of urban rain gardens (assuming 60 cm depth, see Table 1). Retained water benefits not only garden plants but also nearby vegetation, promoting balanced water distribution.

Table 1. Comprehensive parameters of planned rain gardens by sector

Sector	**Area (ha)**	**Area of green surfaces (m^2)**	**Number of planned rain gardens**	**Total area of planned rain gardens (m^2)**	**Potential water retention capacity (m^3)**	**Floor area of buildings (m^2)**	**Number of buildings**	**Population (person)**
1	2.3	4,610	9	2,580	722	2,233	4	63
2	2.6	2,445	15	1,160	324	2,847	1	603
3	1.2	1,423	20	337.5	93	0	0	0
4	3.1	3,560	10	963	269	8,847	40	559
5	5.1	1,200	6	455	127	21,131	112	1,100
Total	**14.3**	**13,238**	**60**	**5,495.5**	**1,535**	**35,058**	**157**	**2,325**

Source: Compilation by own

The compost mixture provided adequate nutrients, evidenced by rapid plant recovery and growth. Soil life revived with the appearance of arthropods, and plants thrived (Figure 8). After an initial 200-liter watering at planting (absorbed by the soil mix), plants were watered only twice during the extremely dry summer (August 4 and 8, 2022). Otherwise, they relied on retained rainwater, developing primarily without additional irrigation.

Figure 8. The development of plants in the experimental rain garden (image "A" shows the plants after planting, while the image “B” shows them four months later)

Lythrum salicaria, initially questionable for survival, grew vigorously and bloomed, demonstrating its vitality (Figure 9).

Figure 9. *Lythrum salicaria* after planted (arrived almost without any leaves) (A) and its development two weeks (B) and two months later (C)

Plant species recommended by Vaculova and Stepankova (2017) and Laukli et al. (2022) showed less vigor in our setup. *Carex nigra* survival without irrigation is doubtful. *Mentha aquatica* appeared more durable. Drought-tolerant plants like *Festuca amethystine* proved more viable, all surviving without watering.

Water Retention Capacity of Planned Rain Gardens

Using GIS data for the study area, we calculated the total green surface area and determined the number and area of potential rain gardens. Assuming a 60 cm depth, the 60 planned rain gardens could retain over 1,500 m^3 of rainwater. This capacity roughly equates to simultaneously collecting 10 mm of rainfall across the area. Importantly, runoff from higher-lying areas, especially to the northeast (Figure 10), and water collected by existing stormwater drainage, must also be considered.

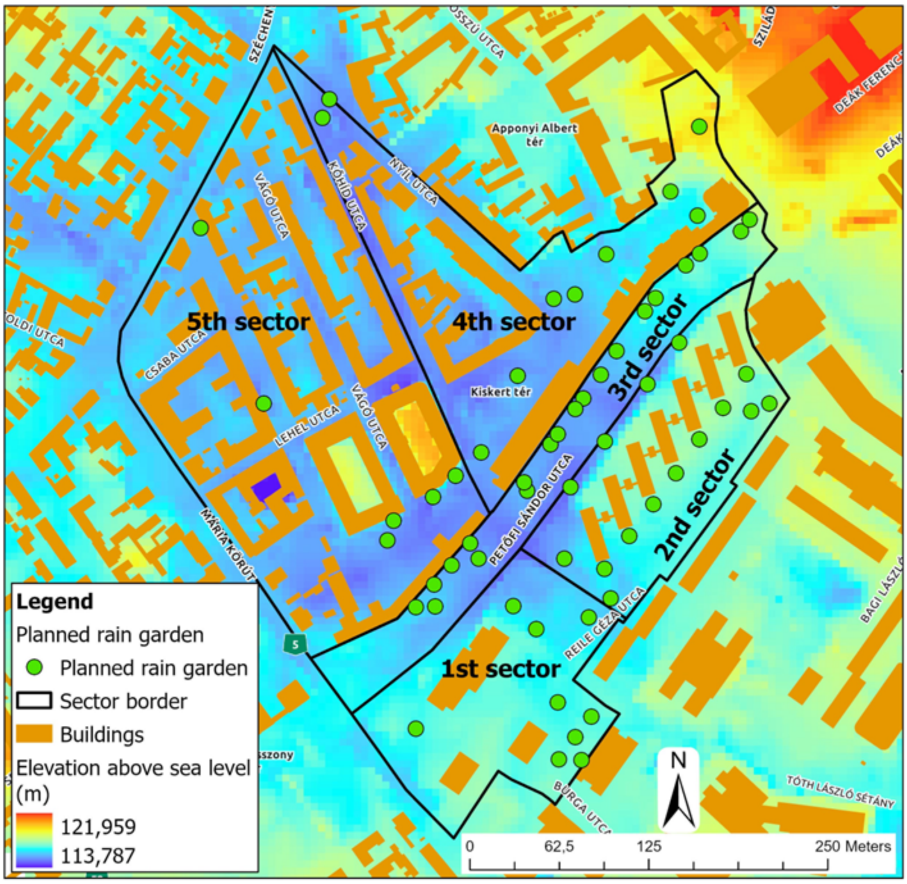

Figure 10. The location of the planned rain gardens on the DEM map (DEM data are provided by Lechner Knowledge Center)

Our measurements suggest a properly designed rain garden system in the study area could efficiently store a significant portion of rainwater from a major event (e.g., 10 mm/day). During more intense storms (e.g., 10 mm/hour), the system would reduce the load on the drainage network, allowing it to handle runoff more effectively. Table 1 details the characteristics and potential water retention per sector.

On the base of our measurements we classified the rain gardens by required implementation effort into three types (Figure 11):

- **Type 1 (40 sites):** Created on existing green surfaces with minor earthworks, no pavement disruption.
- **Type 2 (8 sites):** Smaller green areas, lower absorption capacity, but minimal land conversion.
- **Type 3 (12 sites):** Require major construction (pavement/sidewalk/curb modification), higher cost.

Of 60 potential sites, 40 (two-thirds) are Type 1, implementable without significant cost or construction (Table 2, Figure 11). Eight Type 2 sites, though offering limited space for rain gardens, also avoid major land conversion. Twelve Type 3 sites require significant modification and higher costs. Notably, 50% of Type 3 sites are in Sector 5, making it the most challenging for creating adequate retention capacity. This sector is also densely built-up with limited green space, meaning residential plots offer little contribution to water retention.

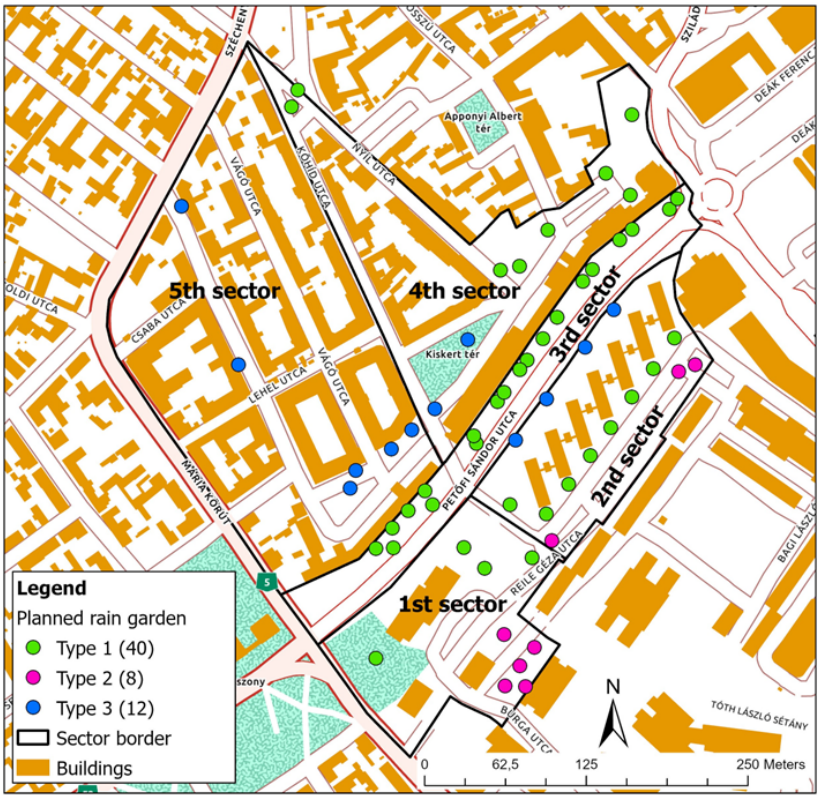

Figure 11. The location of different types of rain gardens in terms of the amount of construction required for implementation

Table 2. The suitability of different sectors for accommodating rain gardens

	Suitability for rain garden		
Sector	Type 1	Type 2	Type 3
1	4	5	
2	8	3	4
3	20		
4	8		2
5			6
Total	**40**	**8**	**12**

Source: Compilation by own

Discussion

The findings from the experimental rain garden and the Kecskemét study area indicate that this type of green infrastructure can significantly mitigate problems caused by flash floods. The potential installation of 60 rain gardens could retain approximately 1,500 m^3 of water, sufficient to prevent flash floods even from a 100 mm rainfall event. This aligns with global research: a Kyoto study showed 60% stormwater retention (Zhang et al., 2019; Zhang et al., 2020), a Xi'an study found runoff coefficients reduced to near zero (Tang et al., 2016), and Montreal examples demonstrated up to 62% retention (Autixier et al., 2014) and Chinese models also predict high retention rate (53-100%) (Hou et al., 2020). Based on the latest calculations from Taiwan (Chen et al., 2024; Chen et al., 2025), if rain gardens were created on 10% of public spaces, they could collect approximately 48,000 to 710,000 m^3 of rainwater annually. In Taiwanese climate, this amount would be sufficient to meet the annual irrigation water needs of approximately 85 km² of vegetation-covered area and reduce annual runoff by 16%. Gdansk is one of the first Polish cities where rain gardens have been widely adopted. Here, rain gardens can handle 72% of the precipitation events studied (Burszta-Adamiak et al., 2023). Thus, according to the above findings, rain gardens are part of low-impact development (LID) systems that can effectively manage flash floods caused by heavy rainfall as part of urban stormwater management (Gulshad et al., 2024).

Studies identify diverse plant species suitable for rain gardens, with considerable heterogeneity even within Central Europe. For instance, a Nitra, Slovakia study prioritized ornamental plants preferring wetter conditions (e.g., *Liatris spicata*) (Bortolini & Zanin, 2018). In contrast, tests in colder Northern European climates included species like *Hemerocallis cv.* (Laukli et al., 2022), also common in Central European gardens. At the same time, plants that are known as indoor ornamental plants in Central Europe (e.g., *Chlorophytum comosum, Dracaena reflexa, Ruellia simplex, Sansevieria trifasciata*) are also viable in rain gardens under tropical conditions. These species showed good adaptability and a healthier morphological appearance in rain gardens compared to specimens living in traditional gardens (Chaves et al., 2025).

This highlights that optimal plant choices vary regionally, necessitating local studies (Doğmuşöz, 2024; Bruner et al., 2023). Consequently, different cities might need varied technological solutions and plant selections (Greksa et al., 2023; Suleiman et al., 2020), which also impacts construction and maintenance costs and economic viability (Kasprzyk, 2022).

Rain gardens have recently appeared in Kecskemét (2021/2022), proving effective. The Gerlice Street project (18 rain gardens) and the Shostakovich Street rain garden have successfully prevented previous flooding and waterlogging. These examples support our findings and indicate that converting green areas to rain gardens is an effective tool in urban development to solve complex environmental problems. A New York City study found traditional gray infrastructure 22% more expensive to build and maintain than blue-green alternatives for stormwater management (City of New York, 2011).

Wider application of our results may be limited by local, primarily climatic conditions. Thus, local studies are vital to determine soil water retention and ideal soil-compost ratios. Plant suitability requires preliminary viability testing, as poorly performing rain gardens can reduce public acceptance. Success is more likely with active local population involvement and awareness of benefits. Thus, while rain gardens offer significant potential, adaptation to local conditions and community needs is key for long-term success.

Finally, several limitations need consideration. The experimental garden was in a single-family home setting, not fully capturing urban complexities. While soil permeability was tested, other properties like organic matter content also affect long-term performance. The one-year duration may not capture long-term performance changes or challenges like soil compaction or clogging. The study focused on water retention and flood mitigation, with limited attention to other benefits like biodiversity enhancement or carbon sequestration.

Conclusions

This research explored rain gardens as elements of blue-green infrastructure, focusing on their role in urban climate adaptation and flash flood prevention. Our experimental rain garden in Kecskemét tested two plant groups: species typically found in wetter environments and drought-tolerant species (less tested in rain gardens previously). The results show that these drought-tolerant species plants are viable and applicable in sandy soil-based rain gardens. While plants adapted to wetter conditions were less well developed though still usable. Wetter-habitat plants would likely perform better in clay-rich soils.

To investigate the possible application benefits of rain gardens, we selected a flash-flood-sensitive area in Kecskemét. Using QGIS, we analyzed topography and utility networks, supplemented by field observations, to identify potential green areas for conversion to rain gardens. We found that constructing 60 rain gardens in the 140,000 m² study area could retain at least 1,500 m³ (1.5 million liters) of rainwater from average rainfall. During heavier precipitation, this would reduce the load on local stormwater drainage, decreasing flash flood likelihood. Water stored would gradually absorb into the urban soil, cooling the environment through vegetation evapotranspiration. The sustainable use of green-blue infrastructure worldwide can enhance rainwater management efficiency, making cities more resilient.

Municipalities should embrace nature-based solutions, e.g. rain gardens over conventional methods. Development plans should prioritize them, and the local dwellers needs clear information on the benefits of rain garden compared to traditional drainage. A follow-up study will examine Kecskemet's existing rain gardens' long-term hydrological performance, soil development and ecological succession under the changing climate conditions, which will further support urban stormwater management planning.

Acknowledgments

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