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Research Paper

Optimization of Parking Lot Stormwater Management: a Case Study

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Abstract. As urbanization accelerates, parking lots lead to stormwater runoff and localized flooding due to impervious layers and inefficient drainage. This case study evaluates stormwater management strategies across four parking lots in Debrecen, Hungary, to propose effective retrofitting solutions. The methodology combines visual site assessments with a comparative analysis of global best practices identified in the literature. Findings suggest integrating Green Infrastructure (GI) and Low Impact Development (LID) principles into parking lot design can enhance infiltration and significantly reduce surface runoff. Key recommendations include utilizing nearby vegetated depressions and replacing conventional concrete slabs with permeable surfaces. Beyond the flood avoidance, these strategies aim to reduce pressure on the local sewer system and minimize puddle formation.

Keywords: Stormwater Management, Green Infrastructure, Low Impact Development, Sustainable Drainage Systems, Permeable Surfaces, Surface Runoff, Vegetated Depressions, Parking Lots

Introduction

Urban populations are expected to grow in all countries over the coming decades at different rates. By 2050, it is estimated that seven out of every ten people worldwide will reside in urban areas [1]. Along with exacerbating climate change, this trend in urbanization can significantly impact the allocation of natural resources within cities, including stormwater flow. Stormwater runoff is a mixture of urban wastewater and surface water formed from heavy rains or snowmelt. It is becoming a significant problem because of impervious surfaces, including roads, parking lots, rooftops, sidewalks, and heavily compacted soils.

This study mainly focuses on parking lots, typically constructed using impervious layers. There is a lack of comparative studies on various stormwater management techniques in parking lots. This research analyzes four different parking lots in Hungary as case studies. Existing drainage systems are evaluated for their effectiveness in managing stormwater runoff. Moreover, the study identifies key challenges related to stormwater management in parking lots and explores potential improvements using sustainable drainage systems (SuDS). The primary objectives of this research are:

- To compare the stormwater management performance of different parking lots in the city of Debrecen in Hungary.

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- To assess the feasibility of implementing green infrastructure solutions under various environmental and design constraints.
- To propose strategies for improving stormwater management based on observed case studies and best practices.

As urbanization accelerates, effective stormwater management in parking lots is essential for reducing flood risks, enhancing water quality, and promoting sustainable urban development. This study contributes to the ongoing discourse on urban resilience by offering practical recommendations for integrating sustainable drainage solutions into parking lot design.

1. Literature review

1.1. Urban Stormwater Management: An Overview

Sewer systems emerged with early urbanization, marked by drainage tracks dating back to 3500 BCE in the Indus Valley and 2500 BCE in Mesopotamia [2]. Advanced systems in Mohenjo-Daro (3500–3000 BCE) demonstrate early engineering prowess [3]. The Greeks and Romans subsequently refined drainage networks.

After Hamburg's devastating fire in 1842, William Lindley designed a combined sewer and drinking water system in the city's reconstruction plan [4]. This transition from fragmented to coordinated infrastructure impacted the future of urban drainage. The 19th century became known as the "golden age" of urban sewers, driven by public health reforms and the proliferation of standardized designs across Europe and North America.

Early sewers combined wastewater and stormwater without treatment, leading to pollution. Wastewater treatment plants were later introduced, but combined systems risked exceeding capacity, while separate systems could discharge untreated stormwater along the shortest route [5]. By the 20th century, engineers designed sewer pipes based on standardized rainfall events, adapting to urban expansion. Older, oversized systems addressed initial demand, but rapid urbanization and soil sealing resulted in costly, large-scale networks, sometimes requiring multi-meter-diameter tunnels. From the 1960s to the 1990s, stormwater management evolved from fast drainage to controlled detention and localized infiltration [5].

Concepts such as Best Management Practices (BMPs), Low-Impact Development (LID), and Sustainable Drainage Systems (SUDS) incorporated green infrastructure elements like detention basins, swales, permeable pavements, and green roofs. These innovations aimed to alleviate sewer system overload and promote sustainability. Today, stormwater runoff is recognized as a valuable resource for secondary uses.

1.2. Parking lots and their impact on stormwater runoff

The impervious layers common in cities significantly affect the hydrological cycle, increasing runoff by up to 55%. The deep infiltration rate is five times smaller than in forested areas because the asphalt-like layers act as a barrier, preventing water from infiltrating the ground [6].

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Accelerated runoff due to high impervious surfaces can lead to flooding in urban areas with inadequate drainage systems. It can carry harmful pollutants such as trash, oil, heavy metals, and dirt into streams, lakes, and groundwater. Originating from construction sites, lawns, improperly stored hazardous waste, and illegal dumping, these pollutants degrade water quality, harm aquatic ecosystems, and potentially impact human health. Hence, effective stormwater management techniques are needed to mitigate the risks of water degradation and flash floods.

Unoccupied parking spaces represent a significant opportunity to mitigate the negative impacts of impervious surfaces on stormwater management worldwide. Systematically reallocating redundant car parking spaces can significantly improve urban sustainability [7]. For example, replacing up to 24 hectares of asphalt with biodiverse green spaces could expand tree canopy cover by 31–59 hectares in central Melbourne. This alone could mitigate the urban heat island effect and improve stormwater infiltration and runoff management.

1.3. Concepts and techniques of stormwater management

Traditional grey infrastructure struggles to cope with heavy rainfall, leading to urban flooding. A Yale School of Forestry & Environmental Studies report on the Philippines concluded that green infrastructure is more cost-effective in most urban flood management scenarios [8]. Similar to how riparian buffers in Fiji proved to be the most cost-effective flood mitigation strategy, incorporating green infrastructure (rain gardens or tree canopies) into parking lot design can significantly enhance stormwater management. This section analyzes concepts from countries that adopted green and grey infrastructure.

China’s Sponge City initiative, launched in 2014, is one of the most ambitious national-level green infrastructure programs [9]. As the term implies, these cities are designed to function like a large sponge, capable of absorbing, storing, and purifying rainwater. This process involves naturally filtering rainwater through the soil, channeling it to urban aquifers, and releasing it for reuse when necessary. Unlike traditional urban stormwater management, sponge cities use natural solutions to enhance the resilience of stormwater systems. A key technique in this approach is integrating green and grey infrastructure.

Low Impact Development (LID) is a comprehensive land-use planning and engineering approach designed to preserve or enhance the natural hydrology of developing watersheds. LID systems use practices that mimic natural processes, such as infiltration and evapotranspiration. For example, parking groves offer a sustainable stormwater management solution and pollution control in new and retrofitted commercial or institutional parking lots [10]. They employ permeable surfaces, trees, and water storage beneath the paving to promote infiltration and reduce runoff. Positioning storm sewer inlets within landscaped areas enhances water treatment before runoff enters the drainage system. While snow removal and proper design for bearing capacity are needed, parking groves are an effective way to improve the environment and the appearance of parking areas.

Traditional stormwater infrastructure relies on extensive underground pipes and concrete channels to convey runoff. In contrast, the LID employs a variety of landscape practices and designed systems that preserve natural drainage features. This approach can be applied to new developments,

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redevelopments, and retrofits of existing areas and is adaptable to a range of land uses from high-density urban to low-density rural areas.

LID focuses on managing stormwater at the source using small-scale solutions like bioretention systems and green roofs. However, SUDS covers a broader range of techniques to replicate natural drainage, often using a series of treatment stages [11]. Both approaches share the goal of sustainable stormwater management but differ in scale and implementation.

1.4. Comparative analysis of different drainage systems

A cost-benefit (B/C) analysis of rainstorm control in the Caohejing drainage system in Shanghai, China, found that rain barrels (RB) had the highest B/C ratio of 0.8129, followed by bioretention (BR) at 0.7724, and infiltration trenches (IT) at 0.6195. In contrast, permeable pavement (PP) had the lowest B/C ratio of 0.3183, indicating that it may be less cost-effective when used alone [12]. Implementing LID measures can restore ecosystem functions and increase biodiversity in urban areas. Additionally, these solutions can be integrated into the urban landscape with minimal disruption and lower maintenance costs.

Another quantitative analysis confirms that flood risks and maximum floodwater volumes are significantly reduced under drainage systems incorporating sponge infrastructure compared to traditional drainage methods [13]. The proposed renovation project for the Shuixianghuayuan old residential area in China highlights the critical role of nature-based solutions in mitigating urban flooding and improving water quality. The study also confirms that combining green infrastructures (GI) is more effective than a single GI. Despite these advantages, this new Chinese approach requires further governmental support and policy modification as it is in its early stages.

Another research evaluating the performance of LID practices highlights that RB was the cheapest and most cost-effective option, but it did not significantly reduce runoff [14]. In contrast, PP had the highest cost and lowest cost-effectiveness due to high LCC (life cycle cost) and low runoff removal rate. The combined LID scenario (IT + PP + RB) had the best technical performance but was not cost-effective due to high engineering expenses. LID selection should be based on technical performance and economic cost. The results indicate that RB should be prioritized as a cost-effective measure in areas with budget constraints. However, despite higher costs, combinations like IT + PP + RB should still be considered in areas requiring maximum runoff reduction. These insights can be practical for other countries depending on local needs and financial resources.

Moreover, the effectiveness of LID in mitigating runoff was demonstrated through BR cell and PP installation in a highly impervious commercial parking lot in Reynoldsburg, Ohio. The BR cell significantly reduced runoff depths and peak flow rates by 83% and 86%, respectively, showcasing its effectiveness in stormwater management [15]. However, the PP did not show significant hydrology improvements, as the median surface infiltration rate decreased by 96%. It indicates surface clogging due to sediment loading and lack of routine maintenance. Despite this, the combined effects of the BR cell and PP led to a 47% reduction in runoff depths and a 56% reduction in peak flow rates, proving that LID can effectively mitigate runoff in highly impervious and connected commercial catchments if appropriately sized and maintained [15].

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A comparative field study in Oviedo, Spain, analyzed the effectiveness of a swale and a filter drain compared to a conventional concrete ditch drainage system. The study monitored water quality parameters over 25 months and found that both SUDS significantly reduced pollutant concentrations in stormwater runoff [16]. The filter drain system was particularly effective, demonstrating lower concentrations of Total Suspended Solids (TSS), Dissolved Oxygen (DO), and pH than the swale. Geotextile layers in both SUDS further enhanced pollutant removal, especially for TSS reduction.

These findings confirm that SUDS are not only viable but also highly effective for stormwater treatment, much like LID strategies. Given the success of SUDS in Spain, its adoption in other urban areas could significantly improve stormwater management and water quality.

1.5. Stormwater management solutions in urban parking lots

Several sustainable stormwater strategies have been studied in parking lots, which contribute heavily to runoff due to their impervious surfaces. One example is Noushin Zadehesmaeil's 2019 thesis on green infrastructure for parking lots in Kitchener and Waterloo. The research shows how GI in parking lots can reduce runoff, increase infiltration, and improve water quality. According to the design, GI could cut annual discharge by 25.7% and runoff by 3–26% [17]. This would help to mitigate floods, recharge groundwater, and improve environmental quality. Also, cost savings of $368,650 show that to fullGI is financially viable and can reduce dependence on traditional systems. The study also notes public benefits of LID, including less air pollution, carbon sequestration, and greater urban resilience. A primary barrier is the lack of a structured market for ecosystem services, which undervalues GI's financial return. This extends payback periods and discourages private investment. To fully realize the potential of green stormwater solutions, policy adjustments and economic incentives are needed to integrate environmental and infrastructure development into a cohesive urban planning strategy.

The IMAX parking lot retrofit is another example of sustainable stormwater management. This study shows that systems, like PP and BR cells, effectively control runoff and improve water quality. The project shows that permeable surfaces can capture precipitation, reduce sewer overload, and enhance infiltration. Permeable pavement with granular "O" and ¾" clear stone captured 83% of annual precipitation, with no outflow during extreme rainfall (43–66 mm/hr) [18]. This proves that well-designed permeable lots reduce runoff and prevent sewer overloading. Lag times of up to 6 hours show how permeable surfaces slow runoff and reduce flood risks. Infiltration tests confirmed that ¾" clear stone provides a higher infiltration rate (4840 mm/hr) compared to granular "O" (4190 mm/hr). That is why selecting the right aggregate material based on its effectiveness is crucial. After the retrofit, the TSS concentrations reached 97% of reduction, exceeding the target of 80%. This confirms the key role of permeable pavement in filtering pollutants and improving water quality.

Moreover, Heifer International's parking lot in Arkansas and the Bloedel Donovan Park retrofit in Washington are strong examples of how GI can enhance stormwater management. Heifer's lot uses permeable pavement and bioswales to manage stormwater by directing it to a detention pond and wetland. At Bloedel Donovan Park, a bioretention system with native plants reduced impervious surfaces and achieved significant cost savings (75-80%) over traditional stormwater management methods.

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Incorporating trees into urban environments significantly reduces surface runoff through interception, transpiration, and enhanced infiltration. A study in Manchester, UK, demonstrated that tree pits in urban areas could reduce runoff by 62% compared to asphalt surfaces, highlighting the crucial role of root systems in facilitating water infiltration [19]. Similarly, research has shown that trees can effectively complement GI elements such as bioswales and structural soils. Trees planted over asphalt exhibit 30% higher transpiration rates than those over turfgrass [20]. Given their ability to fit within constrained urban spaces while offering ecological and aesthetic benefits, trees should be prioritized in future stormwater management strategies.

2. Methodology

The methods used for this study include a short literature review and a case study conducted in the centre of Debrecen, a city in Hungary (Figure 1). Four parking lots were selected for analysis. The first parking lot consists of three separate sections (1A, 1B, and 1C), each located on different streets with a similar layout. Each section has a central green area resembling a pond, surrounded by parking spaces. The second parking lot is located near section 1B and is adjacent to apartment buildings and private garages. The third and fourth parking lots are located closer to the city centre and are surrounded by residential and commercial buildings.

The analysis was carried out through two visual investigations. The first visit focused on capturing general photographs of each site. The second visit took place on a sunny day immediately after a rainfall to observe the impact of precipitation on the parking lots. The number of available parking spaces was counted on-site during the visits. For consistency, photographs of sections 1A, 1B, and 1C were taken from similar angles to allow a comparative visual analysis. The slope direction at each site was visually assessed by analyzing water flow patterns and elevation differences within the lots. Differences in water retention and drainage were noted in various sections. Based on these observations, the effectiveness of the existing layouts was evaluated, and possible improvements were considered. Proposed solutions were developed by identifying problem areas (e.g., poor drainage, inefficient layout) and matching them with best practices in the literature review. Suggestions include minor structural modifications and landscape changes to enhance water runoff and increase space efficiency.

2.1. Estimation of Surface Runoff Rate

The surface runoff rate can be calculated from a given precipitation characterized by its intensity with the following equation:

$$\boldsymbol{Q = \frac{1}{36} * C * i * A}$$

where Q - runoff rate, [l/s]

C - runoff coefficient, [-]

i - rainfall intensity, [mm/h]

A - size of the drainage area, [m^2].

DOI: 10.21791/IJEMS.2025.11.

Although a full runoff rate calculation was beyond the scope of this study, the runoff coefficient (C value) was evaluated based on different land cover types.

The runoff coefficient (C) is a dimensionless coefficient that shows the relationship between the amount of runoff and the amount of precipitation received. This value is high for areas with low infiltration and high runoff (pavement, steep gradient) and small for permeable, well-vegetated areas (forest, flat land) [21].

The size of the drainage area cannot be measured using the map because the line between the paved road and the green surfaces is not represented. Surveying measurements can be carried out in further studies.

The occurrence and runoff volume depend on precipitation characteristics such as intensity, duration, and distribution, as well as specific physical aspects of watersheds, including soil type, vegetation, slope, contribution area, and permeability [22]. Permeability describes the watershed's ability to absorb water. Therefore, with often permeable surfaces, the chance of water infiltration increases, and the volume of drained rainfall reduces. Runoff coefficient of roads and pavements is between 0,7 and 0,95 [22].

Concrete grid pavers or turf blocks are constructed by interlocking concrete or plastic cells filled with soil and planted with turfgrass or a low-maintenance ground cover. They allow water to pass through their structure into a crushed aggregate base layer, from which it infiltrates into the subgrade. They are designed to absorb direct rainfall rather than stormwater runoff. Turf blocks are produced in various shapes, sizes, textures, and colours. They are typically used in locations with minimal traffic and low usage frequency, such as residential driveways, terraces, patios, sidewalks, overflow parking, street shoulders, and emergency access lanes. Their runoff coefficient ranges from 0.15 to 0.6, like that of grassed surfaces [23].

3. Case Study Analysis of Parking Lots in Debrecen, Hungary

3.1. Overview of Site Parameters

The selected sites were analyzed based on defined parameters to evaluate their relationship with green infrastructure principles (Table 1).

- Pavement Type: to evaluate the materials used in construction, determining their permeability and impact on water infiltration.
- Slope: to assess whether the surface is designed to direct runoff efficiently toward drainage or infiltration areas.
- On-Site Retention: to check for the presence of infrastructure (e.g., retention basins, permeable surfaces) that capture and temporarily hold stormwater.
- Surface Runoff vs. Infiltration: to identify whether runoff is dominant or if the design facilitates infiltration, which influences flood risk and groundwater recharge.
- Tree Canopy (%): to evaluate the extent of tree coverage in mitigating the urban heat island effect and intercepting rainfall/snowfall.

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Additionally, statistical data such as total surface area and number of parking spaces were recorded. To better understand the lot's contribution to green infrastructure, its surrounding environment, including proximity to public transport, and nearby buildings, was also considered.

Site Parameters	Parking Lot 1	Parking lot 2	Parking lot 3	Parking lot 4
Address	1A - Gáborjáni Szabó Kálmán utca 1B - Mata János utca 1C - Dienes János utca	Ótemető utca	Kossuth utca	Monti Ezredes utca
Surface area (m^2)	1A - 600 1B - 560 1C - 560	685	1221	580
Number of parking spaces	1A - 49 1B - 46 1C - 46	37	65+	31
Pavement type	Permeable paving grid & Impervious concrete layer	Impervious concrete slab	Permeable paving grid & Impervious concrete slab	Impervious concrete slab
Slope	Slightly/moderately sloped toward catch basins	Slightly sloped toward catch basins	Slightly sloped	Slightly sloped
On-site retention	Partially, yes	-	Partially, yes	-
Surface runoff/infiltration	Surface runoff towards catch basins Small infiltration	Surface runoff towards catch basins	Surface runoff towards catch basins Small infiltration	Surface runoff towards catch basins
Tree canopy	50%	10%	25%	45%
Proximity to public transport	120-250 m	300-500 m	50 m	150 m
Nearby buildings	Residential	Garages and residential buildings	Residential & economic	Residential & economic
Shared parking concept	No, only for residents	No, only for residents	Yes, shared among residents and office workers	Yes, shared among residents and office workers
Presence of EV charging stations	-	-	-	-

Table 1. Site Characteristics for Debrecen Parking Lots according to the chosen parameters

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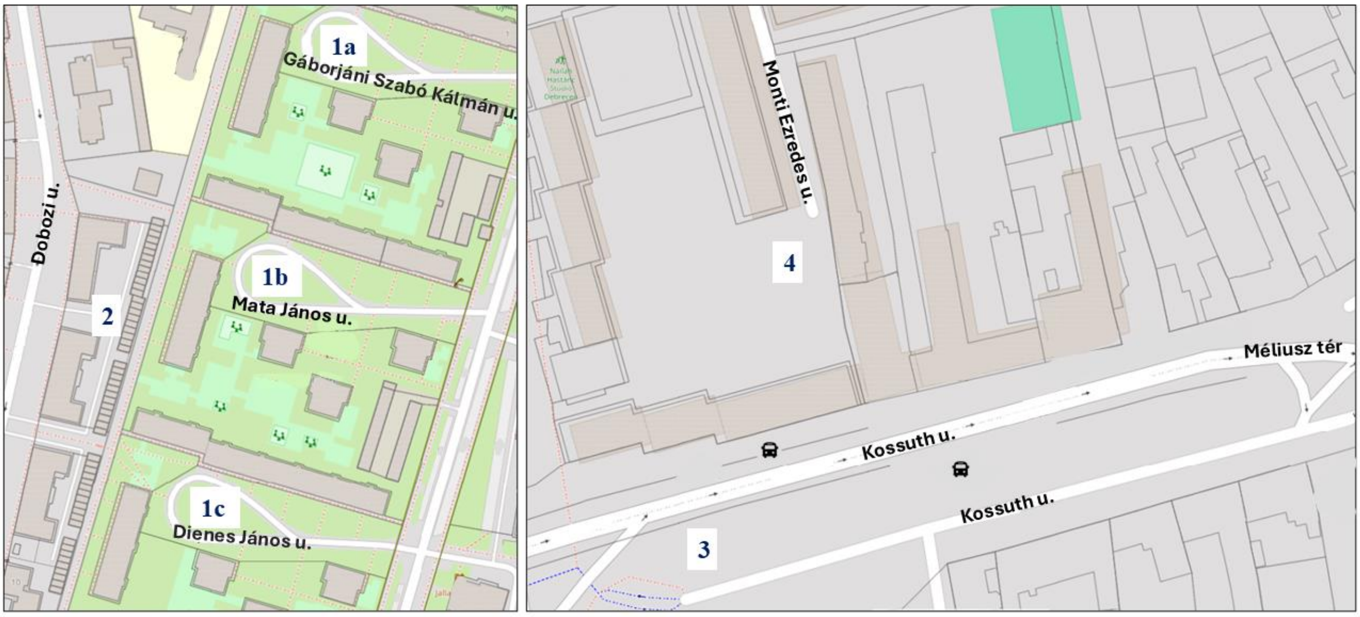

Figure 1. The selected parking lots on the map

Parking Lot 1

The first investigation site consists of three adjacent parking lots with similar layouts (Figure 2).

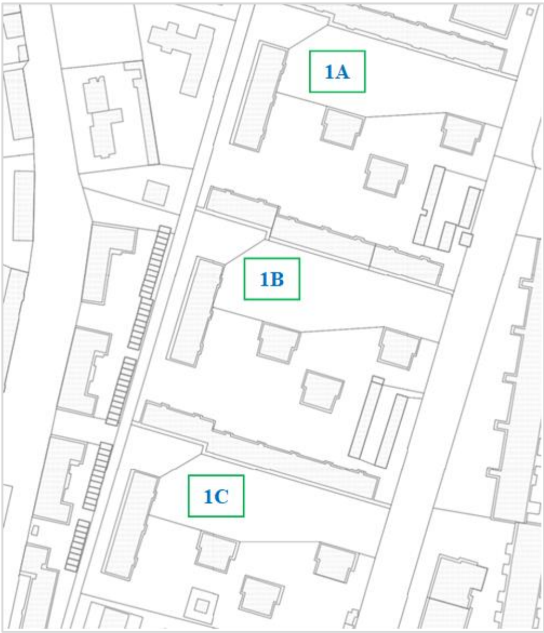

Figure 2. The layout of parking lots 1«A», 1«B», and 1«C»

As a reference, Parking Lot 1«A» is taken and shown in detail (Figure 3). The surface composition includes two primary materials: pervious concrete grids and an impervious concrete layer (Figure 4). Visual inspection indicates that the blue-marked area consists of concrete grids over the soil, allowing for partial stormwater infiltration. However, due to the limited retention capacity of these grids, excess stormwater flows onto the adjacent impervious concrete path rather than being fully absorbed (Figure 5).

DOI: 10.21791/IJEMS.2025.11.

A depressed area resembling a drop is located within the lot, encircled by the permeable grids. This area contains three main drainage components (Figure 5):

- Two linear catch basins are positioned along the same axis.
- A wide radial manhole grate at the lowest point of the depression.

Figure 3. Parking lot 1«A» layout

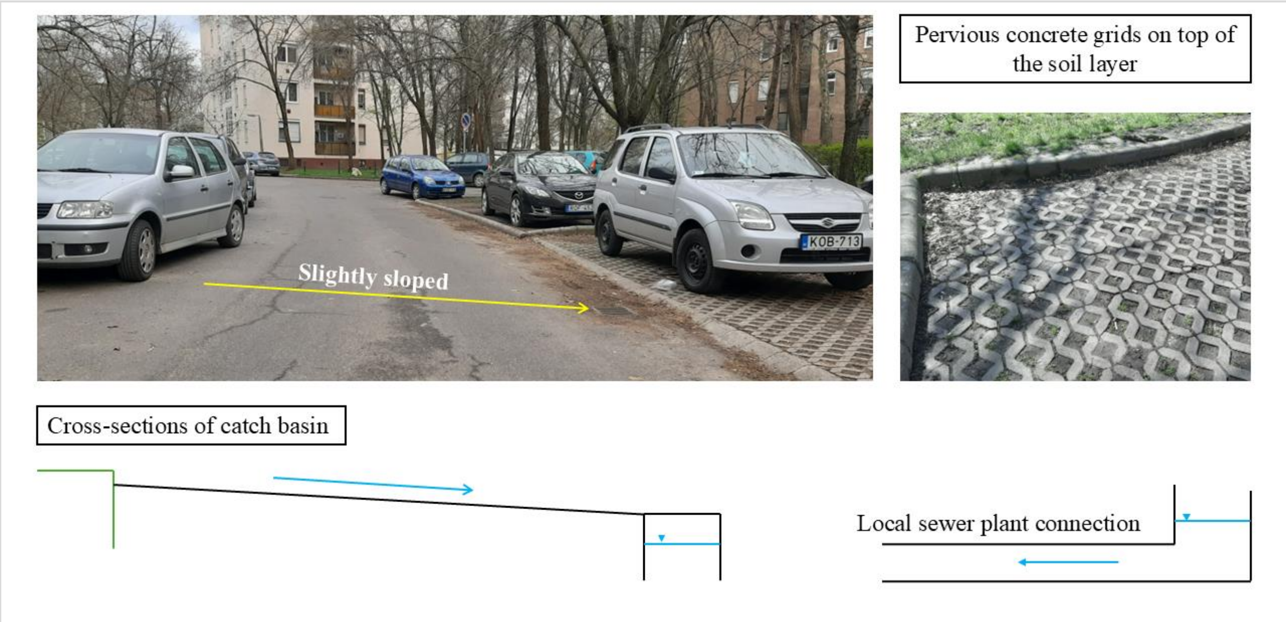

Figure 4. The surface composition of parking lot 1«A»

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Sediment accumulation around catch basins indicates limited retention capacity and prolonged runoff time during heavy rainfall. Additionally, excess water from the saturated pervious layer may contribute to overflow.

Figure 5. Catch basins near the permeable layer

The parking lot is sloped towards the drainage inlets, facilitating water flow (Figure 4). Among the three lots, Parking Lot 1B exhibited the most effective slope, as no significant water pooling was observed after rainfall, and its catch basins functioned efficiently.

The tree canopy coverage is highest in Parking Lot 1«A», while 1«B» and 1«C» have similar, but lower canopy densities (Figure 6).

Figure 6. The tree canopy in parking lot 1

3.2. Parking Lot 2

The parking lot has a concrete slab next to a residential building and a row of private garages (Figure 7). There are six basins in the area, two small and four large.

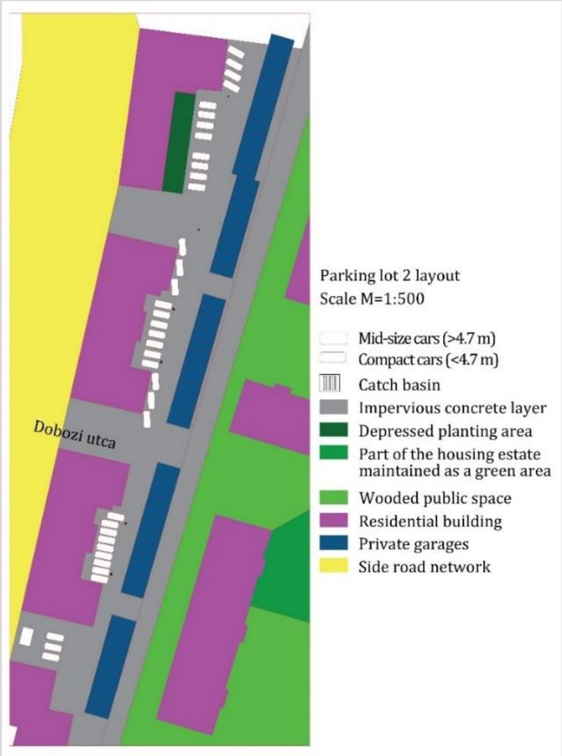

Figure 7. Parking lot 2 layout

The adjacent garages have roof drainage pipes that discharge directly onto the asphalt surface. As a result, this leads to puddle formation near parked cars during rainfall (Figure 8).

Figure 8. Puddle formation due to roof drainage discharge onto the asphalt surface

The parking lot surface is generally sloped toward the catch basins. However, due to some deteriorated sections of the concrete layer, water and sediments accumulate after rainfall (Figure 9).

Figure 9. Water accumulation due to deteriorated concrete sections

3.3. Parking Lot 3

The third parking lot is located on Kossuth Street and is illuminated by nine streetlight columns (Figure 10). It is located near public transport and commercial buildings, making it a shared space for both workers and residents.

The lot consists of three distinct sections. The first zone, covering 150 square meters, consists of a curb with permeable, smooth, rectangular pavers. These were installed a few years ago and remain the newest section (Figure 11).

Figure 10. Parking lot 3 layout

Figure 11. Permeable smooth pavers

Next is a concrete slab that slopes toward the catch basins, followed by interlocking pavers placed directly on the soil, which enhances water infiltration (Figure 12). These latter two sections are aligned

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in a single row and adjacent to a green area, which presents significant potential for stormwater management.

Figure 12. Section of the parking lot with a) sloped concrete and b) interlocking pavers

One day after the rainfall, puddles were observed in specific areas, marked with blue ellipses on the map (Figure 10). The most significant accumulation occurs near the residential buildings on the opposite side of the parking lot. Water collects in this area due to improper grading, mainly where the fronts of parked cars are located (Figure 13). Additionally, the elevated square with a tree requires improved drainage and functionality.

Figure 13. Water accumulation after rainfall along parking lot 3

3.4. Parking Lot 4

The fourth parking lot is located near a playground and is surrounded by residential buildings. The surface is made of a concrete slab and accommodates approximately 31 parking spaces. Four catch basins are positioned at the lot's beginning and end (Figure 14).

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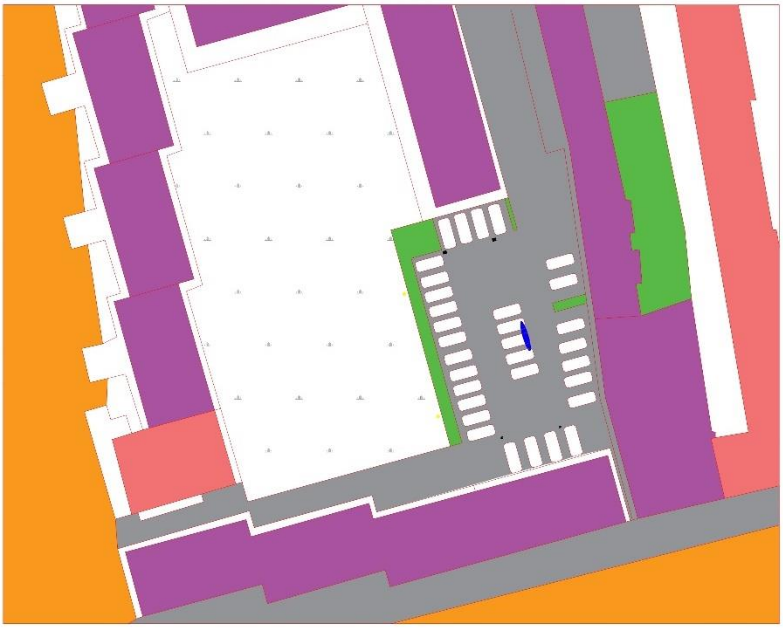

Figure 14. Parking lot 4 layout

The parking lot surface exhibits a concave profile, which slopes from both sides toward the centre. A combination of concrete slab settlement and the deterioration of surface sections over time contributes to water pooling in the central area during rainfall (Figure 15).

Figure 15. Water Accumulation and Deteriorated Concrete in Parking Lot 4

4. Recommendations

Although runoff from impervious surfaces poses significant challenges for urban waterways, its negative impacts can be mitigated by disconnecting these surfaces and redirecting flow toward decentralized green infrastructure. In a related study, Jarden et al. (2015) used a before–after–control–impact (BACI) design, where streets served as subcatchments to evaluate the hydrologic performance of street-scale green infrastructure elements, including bioretention cells and rain gardens. The results showed a reduction in peak discharge up to 33% and a decrease in total stormwater runoff volume up to 40% [24].

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Therefore, it is recommended to utilize depressed areas in parking lots 1«A», 1«B», and 1«C» for improving the stormwater management capacity. This would increase the stormwater retention and infiltration. The proposed plan includes:

- Deepening the depressed area to 15–30 cm to increase storage capacity.
- Creating perforations in the concrete curb to redirect runoff into the vegetated depression.
- Replacing compacted soil with a bio-retention soil mix (e.g., 50% sand, 25% compost, 25% topsoil) to improve infiltration.

With these modifications, the depressed area will function as a rain garden (Figure 16). Since trees are already present, this retrofit will reduce pressure on the local sewer system, mitigate flooding, and enhance groundwater recharge. Also, evaluating catch basin efficiency and monitoring potential sediment accumulation will help maintain long-term performance.

Figure 16. Curb cuts applied to channel runoff into a rain garden

The figure below illustrates real-life curb cut solutions implemented in existing parking lots.

Figure 17. Curb cut drainage solutions

Applying a similar approach, the nearby depressed area in parking lot 2 can also improve runoff management and retention (Figure 18). The presence of existing vegetation, such as trees, would significantly reduce the load on the sewer system. If the budget allows, replacing the current concrete slab with a permeable surface would enhance stormwater infiltration. However, since the catch basins function effectively, repairing the worn-out concrete sections may be a more cost-effective solution.

DOI: 10.21791/IJEMS.2025.11.

Figure 18. Proposed stormwater infiltration zone as a rain garden

Regarding parking lot 3, most parking spaces are located along the vegetation. This green space with existing trees could be utilized as a bioswale to improve runoff control (Figure 19). All recommendations for sustainable retrofitting should be considered. This way, puddle formation would be minimized.

Figure 19. Potential bioswale site for enhanced runoff infiltration

Mueller et al. developed and evaluated a simple method for estimating the reduction in stormwater runoff resulting from redirecting runoff from an impervious surface (e.g., rooftop) onto a pervious surface (e.g., lawn). Their findings demonstrate the usefulness of urban lawns as a stormwater

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mitigation measure and can be integrated into urban runoff models that include indirectly connected impervious areas [25].

Therefore, for parking lot 4, the parking surface slope can be reversed by redirecting stormwater runoff toward the playground side, which will be a significant cost due to reconstruction. The adjacent planted area could then function as a bioswale and help to manage stormwater more sustainably (Figure 20). Also, the degraded concrete sections could be replaced with a new concrete slab layer.

Figure 20. Redirection of Runoff Toward Playground for Bioswale Integration

5. Conclusions

Overall, the study found that the selected parking areas in Debrecen demonstrate varying degrees of integration of the principles of green infrastructure. Two of them are partially covered with permeable materials and use adjacent green areas to improve the efficiency of stormwater management. At the same time, the other two parking spaces have exclusively concrete pavement, with a slope towards the drainage elements.

Common problems identified at all sites include wear of concrete sections and inefficient use of adjacent green spaces. All four parking lots are connected to a local storm sewer system, after which the water flows to the sewage treatment plant.

The following solutions are proposed to optimize stormwater management through the modernization of parking lots:

- modification of slopes towards green areas,
- arrangement of rain gardens,
- replacing the existing surface layer with more permeable materials.

Implementing these measures will enhance water retention and reduce surface runoff. An integrated approach considering the unique characteristics of each site is essential. These parking lots in Debrecen have significant potential to transform into more environmentally efficient and sustainable urban elements.

This paper presents a conceptual approach rather than a detailed design or construction plan. The proposed solutions are based on principles of green infrastructure to improve stormwater management.

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I propose extending the research to determine the actual runoff coefficient of each different surface type by considering rainfall of various intensities. Such research results are available, and the method can be adapted [26].

Although this is more of a task that belongs to the preparatory phase of planning, conducting accurate measurements to calculate the runoff area is also suggested. In the next implementation phases, more detailed technical development, including necessary calculations, should be provided.

Moreover, geodetic and geotechnical fieldwork should be conducted in the planning phase to evaluate soil permeability, groundwater level, and identify any risks of contamination or infiltration into undesired layers.

Conflicts of Interests

The authors declare no conflict of interest.

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