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STORMWATER MANAGEMENT IN URBAN ENVIRONMENTS: AN ANALYSIS OF ALTERNATIVES USING PHYSICAL MODELS

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A B S T R A C T

Uncontrolled urban growth has intensified soil impermeabilization due to the expansion of infrastructure such as roads, buildings, and parking lots, reducing the infiltration capacity of rainwater. This leads to an increase in surface runoff, accelerating the accumulation of flows in rivers and urban drainage systems, thereby increasing the frequency and intensity of floods. To alleviate the burden on drainage systems, stormwater management alternatives can be implemented, which, when integrated into the urban environment, help reduce surface runoff by enhancing infiltration. In this study, a physical rain-runoff model was used to evaluate the performance of three stormwater management alternatives under design storms with various return periods. The results showed that the efficiency of each alternative varied between a 40% and 100% reduction in the peak flow of the flood hydrograph, with a decrease in runoff time ranging from 10% to 60%. Finally, it was observed that the efficiency of the alternatives declined as storm duration increased.

1. INTRODUCTION

Stormwater management is generally defined by its role in controlling excess water generated by precipitation, primarily runoff from impermeable surfaces such as rooftops, streets, and parking lots (EPA, 2025). Rapid, unplanned urbanization, population growth, poor watershed management, and climate change continue to be key drivers of extreme runoff, which conventional stormwater management systems are often unable to handle (Pumo et al., 2017; Palermo et al., 2020).

Land use changes and spatial distribution have a major influence on the natural processes of a watershed (Mera-Parra et al., 2021). The urbanization of rural areas involves significant land use changes that affect infiltration. The construction of infrastructure such as roads, homes, and other buildings creates impermeable surfaces that drastically reduce infiltration (Oñate-Valdivieso et al., 2021). As a result, rainwater cannot penetrate the soil and instead becomes runoff, which can lead to rapid and extensive flooding in nearby streams. Implementing green infrastructure solutions, such as permeable pavements, green roofs, and sustainable drainage systems, can help mitigate these effects by allowing a greater proportion of water to infiltrate the (Oñate-Valdivieso et al., 2022).

Conventional drainage systems are designed to direct stormwater away from urban areas, but their limited capacity and flexibility to cope with increased runoff and the effects of climate change pose a significant challenge (Chocat et al., 2017; Mailhot & Duchesne, 2010).

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Stormwater management is a modern approach to addressing urban drainage problems. It focuses on minimizing runoff, promoting water retention, managing pollution locally, and preserving the natural drainage network. This strategy involves the use of small-scale structures that facilitate infiltration or mitigate flooding effects.

One stormwater management alternative is rainwater storage, which aims to delay the discharge of rainwater into drainage networks or receiving channels, thereby reducing peak flow rates without necessarily altering the total runoff volume (Oñate-Valdivieso et al., 2022) Another approach is rainwater infiltration, which decreases both peak flows and total runoff volumes. Additionally, infiltration helps reduce pollutant loads reaching surface water bodies, as contaminants are retained in the soil, effectively filtered by the percolation of a significant portion of surface runoff (Oñate-Valdivieso et al., 2022).

On the other hand, the purpose of a model is to represent a specific process or situation. Ideally, this representation should provide advantages over the direct execution of the event, such as reduced costs, shorter timeframes, a broader perspective, and improved information quality. Models serve as tools for analyzing a potential event through a surrogate system and are based on the concept of similarity (Oñate-Valdivieso et al., 2022b)

In this study, three stormwater management alternatives are analyzed using a physical model that simulates the natural behavior of the rainfall-runoff process on a small scale. Different configurations of management alternatives and varying storm durations were tested to assess their actual performance.

2. MATERIALS AND METHODS

2.1 Stormwater Management Alternatives

Cellular pavements are a specialized type of paving stone in which the rolling surface consists of blocks with openings, while the sub-base allows for the temporary accumulation of infiltrated water before gradually percolating into the ground. Once the water filters through the rolling surface, there are two possible disposal methods: (1) continued percolation into the ground beneath the pavement (local diffuse disposal) or (2) collection through drainage systems for discharge elsewhere (external concentrated disposal).

Infiltration trenches are longitudinal structures, typically 1 to 3 meters deep, designed to intercept surface runoff along their entire length and facilitate water infiltration into the subsoil. Stormwater enters the trench from the surface and is temporarily stored before gradually infiltrating into the ground.

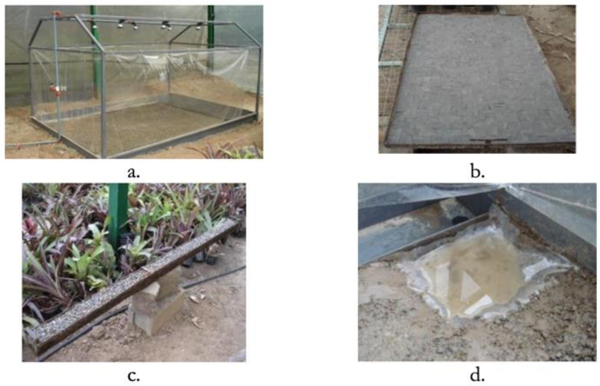

Figure 1. Elements used to validate the performance of the proposed alternatives: (a) Physical model of the watershed, (b) Porous pavement, (c) Infiltration trench, (d) Retention Pond.

Retention ponds maintain a permanently occupied water volume, which is fully or partially replaced during storm events. An additional volume is provided above the permanent water level to absorb excess runoff and mitigate flooding (Oñate-Valdivieso & Bosque Sendra, 2007). These ponds are designed to capture and retain a specific volume of water from frequent storms.

2.2 Physical Model

For the comparative analysis of the performance of cellular pavements, infiltration trenches, and retention ponds, a physical model with a surface area of 6 m² and a 0.5% slope was used. The model was equipped with sprinklers to simulate precipitation events, a channel at the lower end to collect surface runoff, and a volumetric device to measure flow rate.

The stormwater management alternatives were initially designed at full scale according to established criteria and then adapted to the model's scale, maintaining the proportional relationship between the real contributing surfaces and the model's contributing surface. In the case of cellular pavements, concrete elements resembling paving stones were constructed at a 1:25 scale relative to commercially available ones, ensuring that the total covered surface maintained the same scale. For the infiltration trench, granular material was placed within a metal cell shaped to the desired form, which was then embedded in an excavation within the model's floor, in this case. For the retention pond, a plastic sheet was placed over an excavated depression within the model basin.

The physical model and the elements used in the study are shown in Figure 1. In situ tests determined an average soil infiltration rate of 25 mm/h. Throughout all experiments, rainfall intensity was maintained at a constant 10 mm, while soil moisture conditions were kept uniform. Surface runoff under natural conditions was individually compared to runoff observed after implementing each stormwater management alternative.

3. ANALYSIS OF RESULTS

Table 1 presents the observed flood flows for storms lasting 5, 10, and 15 minutes at two locations: the center and the outlet of the basin, for the three stormwater management alternatives studied.

Table 1. Observed Peak Flows.

Element	Scenario	Storm duration (s)	Peak flows (cm3/s)	Variation (%)
Porous Pavement	Natural terrain	5	30.0	
	PP (Center)		11.8	60.7
	PP (Outlet)		0.0	100.0
	Natural terrain	10	34.4	
	PP (Center)		11.6	66.3
	PP (Outlet)		0.0	100.0
	Natural terrain	15	34.6	
	PP (Center)		12.4	64.2
	PP (Outlet)		18.0	48.0
Retention Pond	Natural terrain	5	30.0	
	RP (Center)		19.2	36.0
	RP (Outlet)		9.2	69.3
	Natural terrain	10	34.4	
	RP (Center)		25.6	25.6
	RP (Outlet)		17.8	48.3
	Natural terrain	15	34.6	
	RP (Center)		29.4	15.0
	RP (Outlet)		18.2	47.4
Infiltration Trench	Natural terrain	5	30.0	
	IT (Centro)		19.8	34.0
	IT (Outlet)		0.0	100.0
	Natural terrain	10	34.4	
	IT (Centro)		18.2	47.1
	IT (Outlet)		0.0	100.0
	Natural terrain	15	34.6	
	IT (Centro)		20.0	42.2
	IT (Outlet)		17.8	48.6

In all cases, a significant reduction in peak flood flow was observed, with reduction percentages ranging from 25% to 100% compared to the same storms under natural conditions. This reduction is attributed to increased surface retention and infiltration, which attenuate flood peaks and consequently reduce the load on the storm sewer system. Notably, for short-duration storms, runoff is entirely absent.

Table 2 presents the time elapsed from the onset of the storm to the occurrence of peak flow. The peak time increases significantly, ranging from 5% to 95% compared to natural conditions. By delaying peak flow, the storm drainage system gains additional time to evacuate stormwater more efficiently.

Table 3 presents the total runoff duration. It can be observed that porous pavement reduces the total duration of the flood event regardless of its location within the basin.

Table 2. Observed Peak Time.

Element	Scenario	Storm duration (s)	Peak time (S)	Variation (%)
Porous Pavement	Natural terrain	5	280.0	
	PP (Center)		500.0	78.6
	PP (Outlet)			
	Natural terrain	10	360.0	
	PP (Center)		440.0	22.2
	PP (Outlet)			
	Natural terrain	15	400.0	
	PP (Center)		440.0	10.0
	PP (Outlet)		700.0	75.0
Retention Pond	Natural terrain	5	280.0	
	RP (Center)		440.0	57.1
	RP (Outlet)		400.0	42.9
	Natural terrain	10	360.0	
	RP (Center)		400.0	11.1
	RP (Outlet)		480.0	33.3
	Natural terrain	15	400.0	
	RP (Center)		420.0	5.0
	RP (Outlet)		470.0	17.5
Infiltration Trench	Natural terrain	5	280.0	
	IT (Centro)		290.0	3.6
	IT (Outlet)			
	Natural terrain	10	360.0	
	IT (Centro)		420.0	16.7
	IT (Outlet)			
	Natural terrain	15	400.0	
	IT (Centro)		410.0	2.5
	IT (Outlet)		780.0	95.0

Table 3. Observed Runoff Time.

Element	Scenario	Storm duration (s)	Runoff time (s)	Variation (%)
Porous Pavement	Natural terrain	5	460.0	
	PP (Center)		400.0	-13.0
	PP (Outlet)		0.0	-100.0
	Natural terrain	10	790.0	
	PP (Center)		530.0	-32.9
	PP (Outlet)		0.0	
	Natural terrain	15	1140.0	
	PP (Center)		610.0	-46.5
	PP (Outlet)		380.0	-66.7
Retention Pond	Natural terrain	5	460.0	
	RP (Center)		480.0	4.3
	RP (Outlet)		370.0	-19.6
	Natural terrain	10	790.0	
	RP (Center)		850.0	7.6
	RP (Outlet)		530.0	-32.9
	Natural terrain	15	1140.0	
	RP (Center)		1100.0	-80.3
	RP (Outlet)		970.0	-14.9
Infiltration Trench	Natural terrain	5	460.0	
	IT (Centro)		490.0	6.5
	IT (Outlet)		0.0	-100.0
	Natural terrain	10	790.0	
	IT (Centro)		800.0	1.3
	IT (Outlet)		0.0	-100.0
	Natural terrain	15	1140.0	
	IT (Centro)		760.0	-30.9
	IT (Outlet)		500.0	-56.1

A similar effect is observed with the retention pond and infiltration trench when placed at the basin outlet, where their position enhances the basin's infiltration capacity. However, when the retention pond and infiltration trench are in the center of the basin, the reduction in total runoff duration is minimal, with some cases even showing slight increases.

4. CONCLUSIONS

Stormwater management reduces surface runoff to urban drainage systems, providing a relatively cost-effective alternative to mitigating the impacts of extreme precipitation events.

The three alternatives analyzed effectively reduce peak flow, delay the occurrence of maximum flow, and shorten the duration of flood events, consequently decreasing the total volume of direct runoff. These effects are even more pronounced when the management alternatives are implemented at the basin outlet.

The retention pond demonstrated the highest efficiency in reducing flood flow, with its performance largely dependent on its storage capacity. Cellular pavements and infiltration trenches also showed significant efficiency, primarily influenced by their infiltration surface. However, their practical effectiveness depends on the feasibility of implementation, as well as construction and maintenance costs.

Integrating multiple stormwater management alternatives within urban environments can provide a promising solution for urban drainage challenges, particularly when they are harmoniously incorporated into the landscape.

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