MASTER IN ENVIRONMENTAL ENGINEERING 2023/2024

GREEN ROOFS - HYDROLOGICAL PERFORMANCE AND CONTRIBUTION TO URBAN RAINWATER MANAGEMENT

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Dissertation submitted for the degree of

MASTER ON ENVIRONMENTAL ENGINEERING

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October 2023

Acknowledgements

Many people have played a crucial role in my academic journey, particularly during the course of this Master's thesis. Therefore, I would like to express my sincere gratitude to all those who have contributed to my growth, development, and achievements.

First of all, I would like to express my deepest thanks to my supervisors, Cristina Santos and Cristina Monteiro. Your availability and continuous encouragement were fundamental to the success of this work. Your guidance was priceless.

My sincere thanks go to Mr. Miguel, whose help in the laboratory was indispensable to the progress of this work.

I would like to express my appreciation to Leca Portugal, S.A., and Nutrofertil for their contribution to this thesis through the provision of necessary materials, for the implementation of the GR pilot system. Without their assistance, this thesis would not have been possible. Also, I would like to express my appreciation to Eng. Rui Ramos, Commercial and Marketing Director of Leca Portugal, for all the technical support and availability right from the beginning. I would also like to extend my gratitude to my dear friend Sara and her father, Júlio Sousa, as well as the company he represents, Sistimetra. The generous loan of the flow meter played a crucial role in my research, and I am sincerely grateful for their support.

In addition, I am extremely grateful to my friends at university, who have been with me through all of the good times and the not-so-good times over the past five years. Your patience, kindness, and understanding have been the pillars of my university life, and I am grateful for the lifelong ties we have formed.

To my childhood friends, and for the long-lasting friendships that have stood the test of time, you have always brought out the best in me.

The Teixeira family holds a very special place in my heart. They have been a constant support, encouraging me to new adventures. Special thanks also go to the Garradas family. They have guided me throughout my life, from the very beginning.

Lastly, but certainly not least, I would like to show my deepest appreciation to my parents, sister, “brother” and grandparents for their boundless patience, constant support, and all the sacrifices they've made, which shaped my life. They have been crucial in making me the person I am today.

Abstract

Rapid urbanization is leading to a decline in green spaces as they are replaced by impervious surfaces. Additionally, climate change increases the frequency and intensity of extreme precipitation events. As a result, the traditional urban drainage system is unable to retain and detain the surface water generated by extreme rainfall events, therefore pressuring the city's water drainage infrastructure. Green roofs (GR) stand out as a popular Nature-based Solution (NbS) that can play a significant role in mitigating the impacts of urbanization due to their ability to retain and detain runoff.

This master's thesis aimed to evaluate the hydrological performance of an extensive pilot GR system using a commercially available system, named kit LECA® Nutrofertil GR D, which will be called from now on LECA-based GR system. Both its drainage and substrate layers contain Lightweight Expanded Clay Aggregate (LECA®), provided by Leca Portugal S.A and Nutrofertil, respectively. This system was established at the Hydraulics Laboratory of the Department of Civil Engineering at the Faculty of Engineering of the University of Porto. The methodology followed the widely recognized standard German Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) guidelines.

The evaluation was carried out through various simulations of rainfall events, with consequent analysis of performance indicators related to the system's water retention and detention capacity, as well as the runoff coefficient. These parameters will help designers to combine traditional infrastructures with GR in the design and management of urban rainwater infrastructures. Also, water quality runoff has been assessed.

The LECA-based GR system achieved an average peak attenuation of 90.8%, with a peak delay of up to 14 min and a runoff delay of 3.70-6.21 min. The runoff retention varied between 10.1%, and 39.8%, equivalent to 108.0 mm/h and 39.57 mm/h, respectively, over the whole period. The maximum runoff coefficient was 0.899. The runoff water quality met the water quality standards for urban and landscape uses and water quality for re-use in irrigation.

The implementation of a LECA-based roof stands out as a viable option for improving existing roofs performance regarding urban stormwater management due to its ability to absorb and retain rainwater, together with its capacity to withstand roof retention without standing water pressure on the roof membrane, contributing therefore to cities resilience in a climate change scenario.

Keywords: **Green Roof, Hydrological Performance, Water Detention, Water Retention, Runoff Coefficient, LECA-based Roof, Peak Reduction and Delay**

Declaração

Declara, sob compromisso de honra, que este trabalho é original e que todas as contribuições não originais foram devidamente referenciadas com identificação da fonte.

Mafalda Mendes

Porto, 19 de setembro de 2023

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Glossary

A	area	m^2
Q	design flow	L / min
I	precipitation intensity	mm / h
t	time (rainfall duration)	min
I_{RO}	maximum runoff amount	mm
I_{RF}	maximum rainfall amount	mm
TP_{RO}	time of the runoff peak	min
TP_{RF}	time of the rainfall peak	min
t_P	water passage time	min
RP	retorn period	year

List of Abbreviations

EU	European Union
NbS	Nature-based Solutions
R&I	Research and Innovation
LID	Low Impact Development
BMP	Best Management Practices
WSUD	Water-Sensitive Urban Design
SUDS	Sustainable Urban Drainage System
GI	Green Infrastructure
GR	Green Roofs
RWH	Rainwater Harvesting Systems
MBGR	Multilayer Blue-Green Roofs
C	Runoff Coefficient
IDF	Intensity/Duration/Frequency
WFD	Water Framework Directive

1 Introduction

1.1 Framework

In 2019, 50% of the world population lived in cities [1]. Given that global urbanization will continue to expand, an approximate 83.7% increase in urban citizens is predicted by 2050 [2]. This rapid urbanization leads to an increase in the displacement of green spaces (such as forests, croplands, and grasslands) by impervious surfaces (streets, buildings) in cities centres, leading to negative environmental impacts and changes in the urban water cycle [3]. The high area of impervious surfaces tend to reduce the infiltration rate of rainwater, increasing therefore the intensity of surface runoff. Thus, there is a greater risk of flooding in urban areas, especially those with high population density and also an increase in water resource degradation.

Climate change emerges as an agent that puts further pressure on cities due to more frequent and intense extreme precipitation events. Furthermore, the interconnectivity of climate change, biodiversity loss, and ecosystem degradation creates significant societal challenges that affect economic and social stability, public health, and the well-being of urban populations. The combination of rapid urban expansion and climate change amplifies current and future social and natural disasters, posing a major risk to human health and quality of life, as well as to nature conservation.

The management of stormwater in urban areas with high levels of impervious surfaces relies on the construction of traditional sewer systems, highlighting the issue of poor resilience in the design of urban drainage systems. Stormwater cannot be discharged promptly when the rainfall intensity exceeds the drainage capability of pipeline networks, leading to urban flooding. Moreover, the pumping and subsequent treatment of diluted sewage demand substantial energy inputs, contributing to the already substantial greenhouse gas emissions from water systems [4].

The challenge of effective stormwater runoff control methods (at or near the source) and management in urban planning is of significant importance since the traditional approach to managing excess stormwater in urban areas, through sewerage systems, has been seen as inefficient. Alternatives, on the other hand, need a shift away from current practices, which fail to adequately consider the impact of business on the environment. Instead, new approaches that acknowledge the value of nature and its contributions to society and the economy as the foundation for carbon-neutral, nature-friendly, and fair economic development must be adopted [5].

The Biodiversity Strategy is a core part of the Green Deal of the European Union (EU) [6]. These policies aim to reverse the loss of biodiversity and promote sustainable development by restoring habitats, expanding protected areas, and improving management, governance and funding efficiency. The European Union's Biodiversity Policy 2030 aims to improve society's ability to adapt to challenges such as climate change, forest fires, lack of food and disease public health problems (benefiting both people and the environment) and ensuring that Europe's biodiversity is restored by 2030 [7]. Based on this, Nature-based Solutions (NbS) take place has a new perspective for innovation and transformative opportunities, essential for green economic growth and sustainable development, combining engineering and scientific approaches in a cost-efficient way [8]. The EU's Research and Innovation (R&I) policy agenda for Nature-based Solutions identifies NbS as capable of promoting sustainable urbanization, restoring ecosystems, protecting biodiversity, developing climate change adaptation and mitigation (NbS as a low-maintenance and low-carbon solution to climate change mitigation) and enhancing biodiversity [8]. Moreover, by retaining rainwater within the soil through infiltration, NbS meets the objectives of the EU Water Framework Directive (WFD) [9], which requires rainwater to be managed close to its source, using natural retention and infiltration processes [4].

Nature-based Solutions for climate change adaptation and disaster risk reduction includes numerous nature-based approaches that aim to increase resilience and reduce social and environmental vulnerability [10], thereby reducing the impact of constructed impervious surfaces. Low Impact Development (LID), Best Management Practices (BMPs), Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage System (SUDS), Green Infrastructure (GI), and Sponge City are some of the different terms referring to NbS used in European and international policies [11].

Through sustainable management, NbS is capable of adapting and addressing water issues and restoring the city’s natural hydrology by reducing flood peaks, increasing infiltration and water storage, reducing stress on the sewer system, and reducing runoff [10]. However, NbS's effectiveness depends on stakeholder engagement to promote the transition from "grey to green" infrastructures and encourage their adoption and implementation through optimal planning and design [8].

1.2 Types of Nature-based Solutions

Nature-based solutions (NbS) are sustainable and innovative approaches, supported and powered by nature, playing a crucial role in satisfying infrastructure needs, addressing challenges related with the consequences of climate change, and providing risk mitigation techniques [8]. Through NbS, GI (planned network of natural and semi-natural areas) seeks to benefit the environment by preserving biodiversity and adapting to climate change, as well as the economy by generating jobs and increasing property values, and society by facilitating water management and green spaces [12]. This strategy helps society appreciate the benefits of nature and encourages investment to maintain and enhance these benefits [13, 12]. The addition of NbS can frequently enhance traditional grey infrastructure, which is still necessary.

Green infrastructure can reduce the amount of stormwater runoff entering sewer systems mainly through the natural retention and absorption of rainwater by the vegetation, drainage, and substrate layers. So, the natural hydrologic cycle is mimicked by enhancing infiltration, and therefore reducing surface runoff, recharging groundwater, and increasing the base flow. Besides, urban GI also improves air quality (through carbon sequestration) and mitigate urban heat islands (which results in a cut in resource demand, energy use, and costs). GI can take several forms, including GR, permeable pavements, vegetation swales/bioswales (which include rain gardens and bio-retention swales), infiltration trenches, and rain barrels [11]. The different NbS infrastructures appear in Figure 1 along with their respective functions, and Table 1 lists the benefits and disadvantages of their implementation. It should be noted that the GRs do not have a characterization in Table 1, as they are the focus of this thesis and will be described in detail later on.

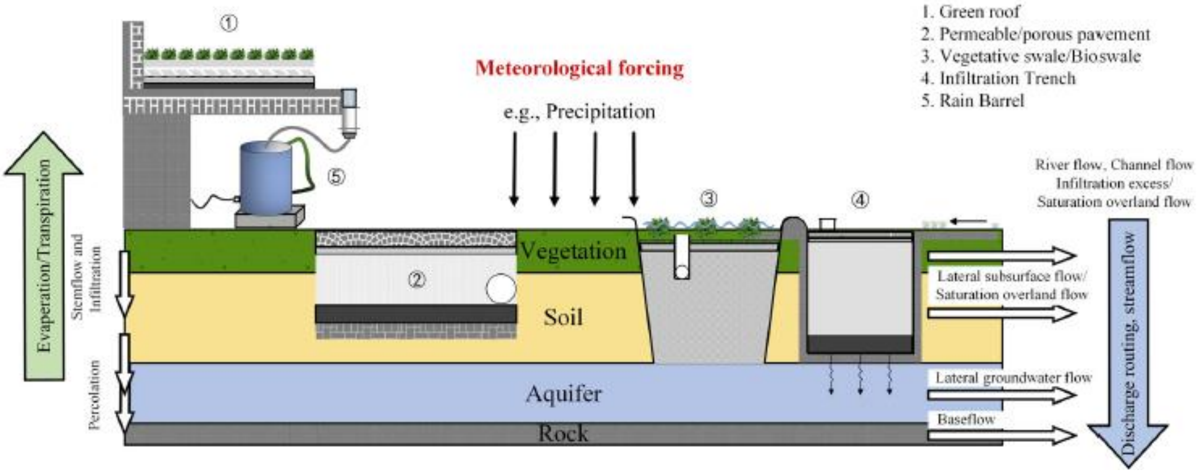


Figure 1: Intermediation of NbS in the hydrological process [11].

Through a vegetation layer supported by a layer of substrate covering the rooftop, GR temporarily store rainwater. By gradually releasing stormwater, they delay peak flow retention. Permeable pavements aim to facilitate the infiltration of stormwater to the underground. A vegetation swale/bioswale is a channel topped with vegetation designed to reduce peak flow by increasing friction along the flow path. An infiltration trench is a gravel-filled trench that temporarily stores stormwater runoff and allows water to infiltrate the soils from bottom and sides of the trench. Lastly, a rain barrel is a water storage container designed to capture rainwater from roofs via a downspout, thus minimizing the risk of local flooding.

Table 1: The advantages and disadvantages of implementing urban NbS [14].

Type of NbS	Location	Summary of Results	Advantages	Disadvantages/ Limitations	Reference
Permeable pavements	China	Flood reduction gradually increases with increasing rainfall amount	Permeable pavements coupled with conventional flood control techniques reduce urban flooding from heavier and longer storms	Permeable pavement has the lowest storage capacity among LID designs	Qin *et al* [15]
	Taiwan	Water retention rates ranged from 9.1% to 61.0%	Permeable pavement minimizes stormwater drainage system load	Runoff at high rainfall intensity limits retention.	Lin *et al.* [16]
	Spain	Permeable pavements retain more rainwater volume than impervious pavement	After 6 months of functioning, it's still capable of fully infiltrating water at low rainfall intensity.	Drained water releases non-negligible load nutrients (e.g., nitrates)	Crespo *et al* [17]
Bioretention	Brazil	Average runoff retention of 70%. Outflow water with low pollutant concentration reduction	Runoff may be used for non-potable applications, lowering the catchment's water demand during the dry season. Flood risks and pollutant	Pollutant removal with low efficiency (concentrations of Fe, Pb, Ni, and Cd above the water guideline limits)	Batalini de Macedo *et al* [18]
	Brazil	The system retained 9-100% of runoff. Dry season (73%) vs. wet seasons (61%)	Bioretention system delays peak flow by 10 min and reduces peak flow by 4-100%	The bioretention system operated below full capacity, showing its performance	Batalini de Macedo *et al* [19]
Infiltration systems	South Korea	Rainfall progression led to decreasing runoff and flow peak magnitudes, frequencies, and durations. Maximum peak flow reduction of 61% (rainfall amount of 40 mm).	Runoff infiltrates into the soil, providing groundwater recharge. Runoff can be temporarily stored or used by the plants.	Rainfall intensity limits volume and peak flow reduction. Land use imperviousness, slope, and runoff limited peak flows.	Flores *et al* [20]

1.3 Objectives

The present master's thesis proposal aims to implement an extensive pilot GR system commercially available in the Portuguese market by LECA, S.A., and to evaluate its hydrological efficiency in an urban area with a Mediterranean climate. The main component of this thesis is laboratory precipitation simulation measurements, which were carried out by the climate of Porto, Portugal. Thus, a series of precipitation simulation events were conducted, varying the duration and flow rate, to objectively assess the impact of implementing a GR on rainwater retention and detention, and on the runoff coefficient, an important parameter when designing downstream drainage systems. Furthermore, this thesis also pretends to assess the quality of the runoff water by measuring the following parameters: pH, conductivity, turbidity and BDO_5.

1.4 Dissertation Organization and Structure

This thesis is divided into six chapters, by the standard format at the University of Porto's Faculty of Engineering.

- Chapter 1 consists of a brief introduction that defines some general concepts and describes the state of the art of the topic, the key aims of this dissertation, and its organization and structure.
- Chapter 2 includes a brief review of the impact of GRs on urban stormwater management as well as a description of the various components of a multi-layer GR. The sub-chapters focus on the contribution of GR to European directives on urban resilience and sustainability, such as the European Green Deal and the Water Framework Directive, and on the benefits and drawbacks of implementing GR in urban areas (stormwater management, rainwater harvesting and water quality).
- Chapter 3 describes the methodology employed. It details the pilot system's configuration, characteristics, and the advantages of using LECA® in the drainage and substrate layers. The selected conditions for each test, including the intensity and duration of rainfall, are specified, along with a description of the necessary equipment needed to carry out its execution.
- Chapter 4 provides the results and discussion of the tests performed comparing to existing literature.
- Chapter 5 presents the main conclusions of this work.
- Chapter 6 sums up all the experimental studies that have been performed throughout this dissertation and discusses additional work that was done along with this thesis.

2 Green Roofs

2.1 Definition

GRs are a kind of NbS, often known as vegetated or living roofs. They consist of a multi-layered structure, including vegetation on the top layer, and are installed on roofs of new or existing buildings (retrofitted roofs).

2.2 Characterization and Classification of Green Roofs

GRs can be classified into three categories: extensive GRs, semi-intensive GRs, and intensive GRs, depending on diverse factors such as the intended use, construction-dependent factors (structure, plant type), and methods (multi- or single-layered construction) [21, 22]. The distinguished characteristics include substrate depth, accessibility to the public, and watering and maintenance requirements.

2.2.1 Extensive

Extensive GRs needs very low maintenance requirements (subject to natural changes, being self-sustaining) and low implementation costs. They can withstand extreme climatic conditions and regenerate easily [23]. Due to the thin growing medium (5–15 cm), only a reduced type of plant species, such as Central European flora or native plants, is suitable for cultivation (including grasses and moss) [22, 23, 24], and the construction cost and maintenance are also lower. The example shown in Figure 2 illustrates an extensive GR design for a private property in nearby Sausalito, California.

When compared to the other types of GRs, extensive ones are a more common option due to weight restrictions: the fact that their substrate layer is thinner, allows them to be implemented easier in already existing buildings (retrofitted roofs). However, GRs may not be able to be installed in all the existing roofs since some may not be able to tolerate unexpected loads [25].

Figure 2: Extensive green roof [25].

2.2.2 Intensive

An intensive GR has a comparable design and management to a ground-level garden and has the potential to provide an attractive and accessible space [25]. Figure 3 illustrates an intensive GR in Porto, Portugal. A diverse range of plants, including trees, shrubs and flower bulbs, can be used on an intensive GR, which requires a thick growing medium (> 25 cm) and regular care in terms of water and nutrient supply [22, 24]. This approach is more often installed in new buildings, to make sure they are designed in such a way that structural support can sustain the additional weight.

Figure 3: Jardim das Oliveiras, Porto, Portugal, as an example of an intensive GR [26].

2.2.3 Semi-Intensive

The semi-intensive GR is an intermediate solution between extensive and intensive concepts, as it has a thicker growing media than extensive GR, but small than intensive ones (15-25 cm). Like so, it requires periodic maintenance and an irrigation system [24].

Table 2 summarize the different GR characteristics [21, 22, 24, 27], and Figure 4 shows a scheme of the layers of the GRs types.

Table 2: GR characteristics

Criteria	Extensive GR	Semi-Intensive GR	Intensive GR
Growing Medium Thickness (cm)	5-15	15-25	> 25
Weight (kg/m^2)	60-150	120-200	> 180
Vegetation	Mosses, sedums, herbs, and grasses	Grasses, herbs, and shrubs	Lawn, perennials, shrubs, and small trees
Cost	Low	Periodic	Regular
Maintenance	Low	Periodic	Regular
Accessible	No	Limited	Yes
Irrigation Needs	No	Yes	Yes

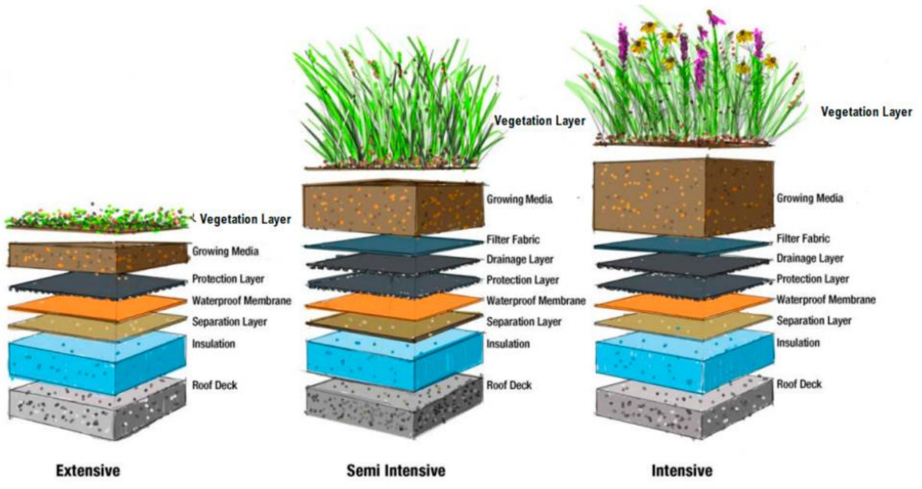


Figure 4: Differences between GR types [14].

2.3 Multilayer System – Components

Multilayer GRs allow the collection and storage of the rainwater that percolates from the substrate layer. The water that is collected into the drainage layer can later be used for a variety of purposes, including the GR itself [24] to be used by vegetation.

The multilayer GR components are: (1) the vegetation, (2) substrate, (3) separation filter, (4) drainage layer, (5) protection mat, and (6) waterproof and anti-root membrane (Figure 5).

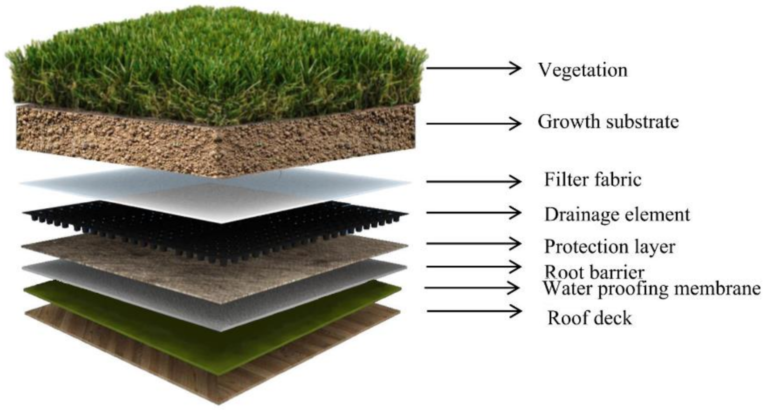


Figure 5: Multilayer GRs system (adapted from [28]).

2.3.1 Vegetation

Vegetation forms the outermost layer of a multi-layered GR system. The survival and performance of the vegetation depends on the species used. The selection of vegetation is based on factors such as plant characteristics, its intended purpose (improve retention, contribute to biodiversity, etc.), climate (temperatures, rainfall, and wind patterns characteristic of the geographical location), and microclimate (referring to shaded areas created by the orientation and placement of the GR concerning the surrounding buildings) [29].

Since extensive GRs target a lower need for maintenance and irrigation, resulting in lower costs, vegetation must correspond to certain characteristics. Low nutritional requirements are necessary to avoid the production of eutrophic runoff and undesired weeds. Lightweight vegetation is also vital due to the building's load constraints. Furthermore, it is important that vegetation species selected are adapted to the local climate where it is going to be installed - a plant species' ability to tolerate water stress and high evapotranspiration is essential in a Mediterranean climate known for its hot summers, high temperatures, and periods of drought.

Succulent plants are considered optimal for extensive GRs by different researchers, with the Sedum species standing out as the most commonly used [30]. These plants resist drought conditions as they possess the capacity to store water in their leaves and reduce transpiration. Nevertheless, there are other plant species that could be used in extensive GR and that tolerate the harsh conditions of rooftops. One example is the aromatic plants (e.g. *Lavandula dentata*, *Thymus vulgaris*, *Rosmarinus officinalis*) that have also the advantage to be used in culinary uses [31].

2.3.2 Substrate

Substrate layer is directly related to the vegetation layer, as its purpose is to maintain their physical, chemical, and biological conditions, ensuring their stability and establishment. The physical parameters are related to the growing media density, water permeability, particle size, and the maximum volume of water and air in saturated conditions. Whereas chemical parameters refer to electrical conductivity, pH index, and quantity of organic matter [30]. Additionally, this layer is also associated with the long-term benefits presented by GRs, such as rainwater retention, improvement of both water runoff quality and thermal conditions, and peak flow decrease. For extensive GRs, organic matter should make up 4% to 8% of the substrate, while for intensive roofs it should be between 6% and 12% [30].

The correct selection of the thickness and composition of this layer is essential to the proper functioning of the GR. Therefore, when a substrate is improperly selected, the consequences may be compaction, water-air imbalances, asphyxiation of the root system, increased weight, reduced drainage, and changes in nutrients supply [30], which will consequently lead to the decease of the used vegetation.

2.3.3 Separation Filter

This layer filters the water, preventing fine substrate particles from passing through to the drainage layer. A GR filter layer is made of geotextiles in the form of nonwovens (directional or randomly deposited fibers of any length) or weaves [22] – Figure 6.

Figure 6: Nonwoven polypropylene fiber filter layer [29].

2.3.4 Drainage Layer

The drainage layer retains the excess water that runs off the substrate through its porosity; when the drainage layer reaches its maximum retention capacity, the water begins to run off to the drainage system. It also provides adequate ventilation for the roots and establishes a balance between drainage and water retention. In addition, this layer reduces the load on the building structure and the risk of a mechanical breakdown. The structural requirements, vegetation engineering objectives, and additional performing functions influence the choice of material and the dimensioning of the drainage layer [22].

The drainage layer commonly employs granular materials with high water absorption capacity or modular panels with a defined water storage capacity (Figure 7). Crushed bricks, expanded clay, lapilli, and expanded slate are among the most widely used aggregates for granular materials. Meanwhile, modular panels, manufactured using high-strength synthetic or plastic materials, such as polyethylene, feature cavities that store and drain excess water [30] from the roof drainage system.

(a) (b)

Figure 7: Modular panels (a) and granular material-expanded clay-(b) as the main components of the drainage layer [30, 32].

2.3.5 Protection Mat

The protection mat layer is placed before the anti-root/waterproof membrane, preventing exposure to stress resulting from the construction and operational actions of the remaining upper layers. Consequently, the layer is intended to protect and isolate the anti-root/waterproof membrane from the layers placed above. To withstand the weight of the upper layers, it is commonly used materials such as geotextiles or polystyrene (with thicknesses of about 3 mm) [30].

2.3.6 Anti-Root Membrane

The anti-root membrane could be installed separately or incorporated in the waterproofing membrane (described next). If installed separately, the anti-root membrane is placed after the protection mat and above the waterproofing layer and is intended to protect the underlying layers from vegetative root penetration. Without the integration of the anti-root membrane into the waterproof membrane, there would be a lower efficiency in mitigating water infiltrations in the building. Anti-root barrier membranes are usually 4 mm thick, characterized by high resistance to microorganisms present in the soil, and can be made of PVC (polyvinyl chloride), and HDPE (high-density polyethylene) [29].

2.3.7 Waterproof Membrane

Characterized as one of the most important components of a multilayered GR system, the waterproof membrane used on a GR is similar to traditional roofing and has the function to prevent any water infiltration coming from the upper layers of the building. This layer's maintenance is very complex because it requires the dismantling of the entire GR, including all the upper layers, in case of leaks.

However, in the case of being installed in a GR, the waterproofing membrane must include either an anti-root barrier over it or an incorporated anti-root product, as well as protection from UV rays and thermal fluctuations. In addition, the waterproofing should be able to deform without cracking when subjected to the movement of adjacent layers or wind action and should be watertight [29].

2.4 Benefits and Limitations of Green Roofs

As mentioned in Chapter 1, GRs have multifunctional benefits (environmental, social, and economic), which include the ability to improve air quality, mitigate the urban heat-island effect, and enhance urban aesthetics.

Given the present climate change scenario and the highly impermeabilization of city centers, GRs are increasingly being promoted as a means of rethinking and developing stormwater management into urban areas, as rooftops account for nearly half of impervious surfaces in developed cities [33] and are unused spaces. GRs can retain some of the rainwater into their drainage and substrate layers, attenuating stormwater impacts within urban environments, such as sewer overflows and flood risks [21], when extreme precipitation events occur.

Furthermore, GRs implementation could also be coupled to other rainwater harvesting methods (e.g. rainwater harvesting tanks), promoting new ways of using precipitation water in buildings (e.g. toilet flushing) or even at the city level (e.g. public gardens irrigation, urban furniture washing) to reduce potable water consumption, in an attempt to decrease the use of this valuable resource.

2.4.1 Stormwater management

Among the environmental benefits, GR systems are strategic tools that contribute to pluvial flood mitigation due to their capacity to detain and retain rainwater, delaying the runoff peak generation [25, 34, 35, 36].

Retention performance depends on several factors, such as vegetation type and substrate depth, porosity, and antecedent moisture [37]. Extensive GRs tend to present a lower retention ability than intensive roofs, since the latter has a thicker substrate layer, allowing it to store and reuse more water through evapotranspiration processes [38].

Thus, the vegetation type also plays an important role in GR retention capacity because of its evapotranspiration process: a higher evapotranspiration rate results in a faster exchange of water from vegetation and also the substrate to the atmosphere [34], therefore allowing a higher rainwater retention into the GR system.

GR performance in mitigating flood risk also depends on the local climate [38, 37]. Several studies have been conducted within the context of GRs' hydrological performance under different climates. However, most focus on reporting its limits in cold and wet climates, due to evaporation and transpiration limitations in such conditions.

Both Viola *et al.* [36] and Johannessen *et al.* [39] conduct investigations regarding this aspect, under different climate cases.

Viola *et al.* [36] explored the influence of five different climate cases and two substrate depths on GR retention capacity. The study highlighted that the retention capacity of a GR is influenced by substrate depth and climate. The greater the substrate depth, the more water can be stored by the active substrate and evaporated from it and vegetation, leading to increased retention capacity. The study also revealed that GRs perform best when rainfall and potential evapotranspiration have the same seasonality, such as in humid subtropical climates, but are less efficient when in counter-phase, as in Mediterranean climates. The authors suggest that it is necessary to explore the detection performance at shorter temporal scales (less than a day), considering it as essential for sewer system design.

Johannessen *et al.* [39] assessed the impact of maximum GR storage capacities and evapotranspiration on stormwater retention in different climatic zones in Northern Europe. Results show that the annual stormwater retention varied widely due to temperature and precipitation differences. Stormwater retention during summer differed from 52% to 91%, although an insignificant retention during winter (0-10%) has been verified.

According to Carter and Jackson [40], vegetated roofs considerably reduce peak discharge during small storms, with 57% of runoff peaks from vegetated roofs delayed by up to 10 min. During heavy rains, Simmons *et al.* [41] and VanWoert *et al.* [42] also observed a similar 10-min delay in peak- to-peak runoff. GR slope and age (or maturity) is another characteristic that could influence its retention capacity, as reported by Getter *et al.* [43], who discovered minor runoff delay on a variety of GR slopes, implying that roof maturity may influence hydraulic conductivity. Villarreal [44] also studied the detention effect of a *sedum* GR with different slopes (2°, 5°, and 8°), through simulated rainfall events (with rainfall between 3.7 mm and 11.4 mm). In doing so, he observed a peak delay of 1 min and found that the peak attenuation of the GR for design storms was as high as 65% (depending on the rainfall intensity).

Research findings have consistently shown that GRs are effective in reducing peak flows during small and frequent storm events. While the results of NbS implemented on a smaller scale have been promising, some suggestions relying only on these solutions may not be sufficient to adequately control runoff during extreme precipitation events [45].

Vojinovic *et al.* [45] addressed the effectiveness of small and large-scale NbS for flood risk reduction. The results obtained demonstrated that small-scale NbS exhibit effectiveness in mitigating low-return period events.

2.4.2 Rainfall Harvest

Rainwater harvesting systems (RWH) have a long history dating back to ancient times in Mediterranean areas [38, 46]. Nowadays, RWH systems have been developed and widely applied in urban areas for private and public buildings, collecting rainwater for domestic non-potable purposes such as garden irrigation, toilet flushing, or recharging the groundwater. Hence, these systems contribute to reducing the pressure on the supply systems, especially in areas with long hot and dry periods [46]. Moreover, RWH systems mitigate pluvial floods in urban areas, due to their ability to enable a large volume of water, storing it in water tanks, mitigating the runoff of intense rainfall events and, furthermore, the runoff peak. In consequence, there is an improvement in urban drainage system management, as assessed by Freni and Liuzzo [47] and Almeida *et al*. [48].

Freni and Liuzzo [47] evaluated how effective rainwater harvesting is in reducing floods in a residential area in Palermo, concluding its vital role in reducing flood volume. However, their efficiency is contingent on the rainfall event since the RWH tanks could reduce the flooded area by 35% for a total amount of rainfall of 50 mm and 100% during small rainfall events (less than 34 mm). RWH systems efficiency could be enhanced if coupled to GR.

The hydrological performance of GRs can be measured by different parameters, being the runoff coefficient the most relevant when coupling NbS to RWH systems, even though other parameters, such as peak attenuation, retention, and runoff delay, are commonly used in the literature. The runoff coefficient is defined as the ratio between the total volume of water runoff from the GR and the total volume of precipitation [37,48]. It depends on the catchment area characteristics and is influenced by the installed green roofs [48]. By storing rainwater, GR reduce the runoff coefficient and the amount of potentially available water sent to the RWH reservoir [48]. The runoff coefficient also depends on GR substrate thickness. Thus, the runoff coefficient is not constant in GR systems over time and is usually standardized for traditional rainwater harvesting systems [48].

Almeida *et al*. [48] examined a RWH system performance in two Portuguese university buildings, considering water consumption, catchment areas, rainfall, and roof types. The study found that extensive GRs covering 50% of the catchment area increased retained water by over 15%. Overall, incorporating RWH and GR systems may be a solution to reduce the impact of heavy rainfall and avoid excessive overflow losses. The conclusion aligns with the findings of Cristiano *et al*. [46], that reported the effectiveness of RWH systems, multilayer blue-GRs (MBGR), and GRs, in mitigating floods and delaying runoff from buildings during periods of intense rainfall. While RWH was economical and easily adaptable for sloped roofs, intensive GR are not, On the other hand, MBGR and intensive GR had a much better retention and runoff delay at the building scale (and extreme events) due to their higher substrate thickness.

Despite their benefits, RWH systems have limitations. One being that their installation may be limited in certain urban areas due to space constraints because its water tanks require large volumes, for which, for example, cities with narrow streets may not have enough space available [44]. Additionally, the tanks can be anti-aesthetic and may not be acceptable in some architectural designs.

Moreover, the feasibility of combining RHW systems with GRs depends on the spatial-temporal variability of rainfall [48].

2.4.3 Water Quality

The increasing popularity of GRs is attributed to their potential environmental advantages, but their impact on runoff water quality is a significant concern. The quality of water can be influenced by its source and exposure to pollutants as it flows over constructed surfaces [49].

The influence of GRs on stormwater runoff quality is substantial, since factors such as the type of plant species, fertilization practices, pH levels, and the composition of the growth medium can affect the quality of the runoff water [50]. In consequence, some studies claim that GR might act as pollutant sources, particularly during the early stages of plant development: nitrogen, phosphorus, potassium, chloride, and heavy metals have all been detected in GR outflow [25]. In addition, it is plausible that certain pollutants may come from the use of fertilizers or even from the growing media components [25, 38].

Therefore, a comprehensive analysis of the collected rainwater is crucial in the evaluation of its potential for reuse in household applications or irrigation [38]. Gnecco *et al.* [54] believe that GRs can be a source of pollution for rainwater runoff. Zhang *et al* [51] also investigated the quality of GR runoff water, in a subtropical monsoon climate, to identify the possible sources and sinks of pollutants in GRs. The study showed that the substrate layer had a significant effect on the quality of the runoff water from the GR, acting as a sink for NH_4^+-N, but as a source of NO_3^--N, K^+, Si^{4+}, and Ca^{2+}.

The author Hashemi *et al.* [49], considered nitrogen, phosphorous, and heavy metals as the primary contaminants detected in the runoff produced by GRs. Nitrogen is considered to be consistently higher in GR runoff than from rainwater [51, 53], due to the substrate composition and the application of fertilizers. On the contrary, certain investigations have suggested that GRs can function as nitrogen and heavy metals sink [54, 55], reducing runoff concentrations. Table 3 summarizes the benefits and limitations of GRs.

2.4.4 Other Limitations

The implementation of GRs as a viable solution for pollution control and restoration of natural hydrology in urban areas is confronted with various challenges that limit their adoption. Implementation of GRs in less developed countries is delayed due to high construction and maintenance costs, problems associated with roof leakage, reduced use of polymers, and lack of knowledge on optimal design to suit different locations and weather conditions [56]. This is despite research demonstrating the social, environmental, and economic benefits of GRs [56]. Dissemination of information on the benefits of GRs to property owners and stakeholders is essential to the promotion of their implementation. Also, interdisciplinary collaboration is a crucial aspect of effective system management.

a) Initial Construction Cost

The high initial construction cost is often considered to be one of the most significant challenges of implementing GRs [56]. Such projects tend to be more costly due to various factors, including the expense of using cranes to lift materials onto the roof, high labor costs, and high insurance premiums [57]. Moreover, GRs add weight to the building, needing changes to slabs, beams, and columns, which makes the project more expensive [57].

GRs provide favorable environmental advantages regardless of their type; however, the installation, construction, and maintenance expenses differ based on the type of GR [61]. Bianchini and Hewage [57] assessed that there is a significant cost difference between a standard extensive and intensive GR in British Columbia, Canada. An extensive GR cost ranges from \$130/m^2 to \$165/m^2, while the cost of an intense GR starts at \$540/m^2. The cost of GRs in Singapore varies between \$40 and \$65/m^2, whereas in the German market, it is comparatively cheaper, ranging from \$15 to \$45/m^2 [58]. Various studies on the cost-benefit analysis of GRs have reported that they are less expensive than conventional roofs [59, 60]. According to Niu. *et al* [59] the net present value of a GR is between 30% and 40% lower during a 40-year lifespan (without considering maintenance) when compared to conventional roofs.

b) Operation and Maintenance Cost

The longevity of GRs and their associated benefits relies on regular maintenance, resulting in a lifespan ranging from 40 to 50 years [57]. The cost of maintaining GRs is affected by the characteristics of the building, the system’s complexity, the vegetation chosen and the current market prices for operation and maintenance services [59]. Depending on the type of GR installed, they also may require frequent irrigation or fertilization [56]. These activities are essential, especially during droughts. The annual expenses associated with the maintenance and operation of GRs in the United States are estimated to range from \$0.7 to \$13.5/ m^2 [58].

c) Weight Load to the Building Structure

Another limitation of the widespread implementation of green roofs in existing building construction is the potential increase in weight load and constant moisture due to the substrate and drainage layers.

The substrate's weight is a major factor impacting the roof structure, particularly in older buildings that have load restrictions and were not designed to accommodate GR. In addition, the presence of wet soil and a drainage layer can lead to a high moisture content in the roof, resulting in constant humidity in the building. This can cause water infiltration and subsequent damage to the structure.

As such, there is one material that is widely incorporated in the growing substrate layer—LECA®—to alleviate the load of the multilayer GR installation and therefore allow for these types of systems to be installed in already existing buildings (retrofit). Another main advantage of Leca is that, although it is a lightweight material, due to its characteristics, it could detain and retain a significant amount of precipitation water (hence, can be used as a drainage layer). This represents a significant role in GRs, as it is described next.

2.4.5 LECA® Advantages in the Drainage Layer

The benefits of LECA-based systems (either vegetated or non-vegetated roofs), particularly stormwater retention and detention on rooftops, were briefly reviewed in the literature using a dataset based on nine papers (refences [61] to [68], described in the points below). Therefore, comparisons are also made between different type of structures with and without LECA to determine whether the latter offers any benefits. The most relevant research focused on rooftops with vegetation, where water losses differ between vegetated and non-vegetated solutions due to plant transpiration. The absence of transpiration is anticipated in the present study due to the non-vegetated configuration. Therefore, this research prioritized research that centered on non-vegetated roofs.

Furthermore, the literature reviewed focuses on the hydrological characteristics of GRs, with particular emphasis on retention and detention.

a) Retention and Detention

Hamouz *et al.* [61] implemented in Trondheim, Norway, a non-vegetated roof system consisting of a layer of LECA® covered by a concrete pavement. The study determined that the retention performance of the LECA-based configuration was approximately 9%. Detention performed effectively, reducing peak runoff by 95% and delaying it by 1 h and 15 min. This study also found that the LECA-based GR retains less water during warmer months than a standard GR.

In addition, the retention performance has been identified as one of the extensively researched hydrological characteristics of GRs [62].

Comparing a conventional commercial roof with gravel ballast and an extensive GR system with vegetation, the average percentage of rainfall retained varied from 48.7% for gravel to 82.8% for vegetation [63]. Vegetated GR systems extend stormwater runoff's duration while simultaneously reducing the runoff volume [63]. It has also been described that vegetated GRs displayed greater annual volumetric retention (75.1%) than non-vegetated LECA® GR systems (54.5%) [64]. On the other hand, the retention efficiency is highly reliant on the amount of rainfall; when it is less than 10 mm, the retention rate is generally greater than 80% [64]. Overall, in the literature, it is mostly concluded that GRs exhibit significantly lower runoff compared to non-vegetated and gravel-covered roofs [61, 63, 64, 65].

It is also claimed that the runoff is higher during the winter than during the summer, as has been reported by Mentens *et al.* [65] that described 80% winter runoff versus 52% summer runoff by the studied GR. Thus, it is important to regenerate the roof's storage capacity, considering its limiting factors (physical layout, rainfall patterns, evapotranspiration in dry seasons, and substrate humidity) [62, 66].

Likewise, there are consistent disparities between vegetated and non-vegetated beds in terms of their detention capacity, with the vegetated beds exhibiting superior performance in both aspects [63]. Stovin *et al.* [65] examined the hydrological performance of nine different GR test beds, concluding that substrates with the highest degree of porosity and permeability demonstrated the least amount of detention; the LECA® substrate (possessing the highest permeability) exhibited the lowest peak attenuation. Among the tested beds with consistent vegetation, the bed that utilizes the substrate containing LECA® displays the highest rate of runoff or the least efficient detention performance. The LECA-based GR with no vegetation exhibited a diminished detention effect with a runoff attenuation of 40%.

The Leca PT, S.A. company [67] developed a comprehensive guideline that outlines the proper use of LECA® Lightweight Aggregate (LWA) in water management systems, including GRs, and permeable pavements. The figure shown below (Figure 8) compares the reduction of runoff intensity in an area managed with LECA® LWA (shown by the blue line) and an impermeable, unmanaged area (represented by the red line).

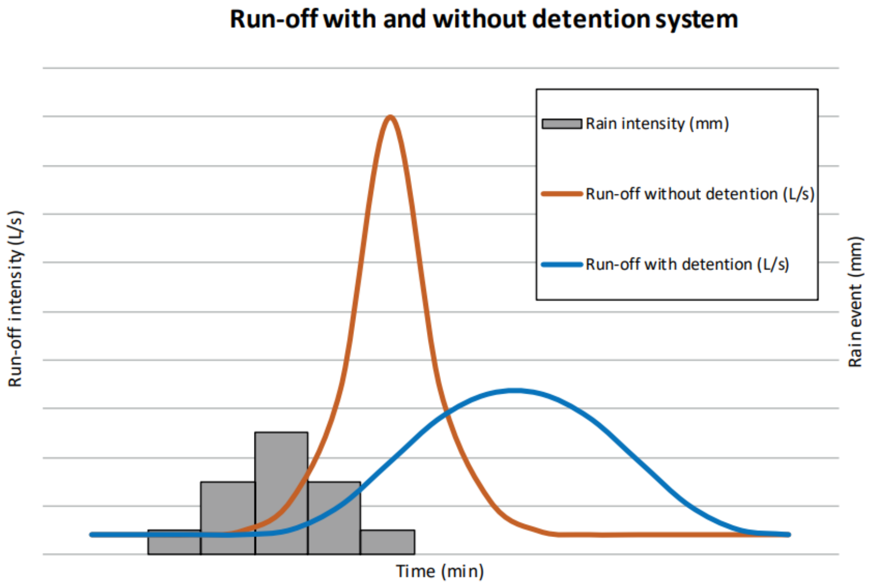


Figure 8: Typical curve of runoff from a drainage system, with and without a detention layer [67].

According to the figure provided, LECA PT, S.A., determined that LECA® LWA effectively reduces the intensity of peak flow and decreases the average runoff intensity. This is achieved by facilitating the slow release of water over a prolonged period.

b) Runoff Coefficient

Schärer [68] studied three combinations of drainage layers with LECA, finding that a GR with LECA alone had the highest runoff coefficient. Combination (1) only included LECA; (2) incorporated LECA, a felt mat and vegetation (Sedum), while combination (3) consisted of a non-vegetated layer with grout material. The lowest runoff coefficients were observed in the non-vegetated LECA-based GR system with cement grout material and the LECA-based sedum roof at 0.21 and 0.22, respectively. The LECA-based GR had the highest C of the three, recording 0.39.

When incorporating a subsurface layer of LECA® LWA into a permeable surface (as depicted in Figure 9), the runoff coefficients exhibit a decrease compared to other surfaces, even under conditions of intense precipitation. The incorporation of highly porous crushed LECA® LWA into a water management solution effectively reduces the runoff coefficient of the surface by retaining and storing rainwater. This facilitates the management of water runoff in the context of severe rainfall events, mitigates the water runoff, and prevents the occurrence of floods.

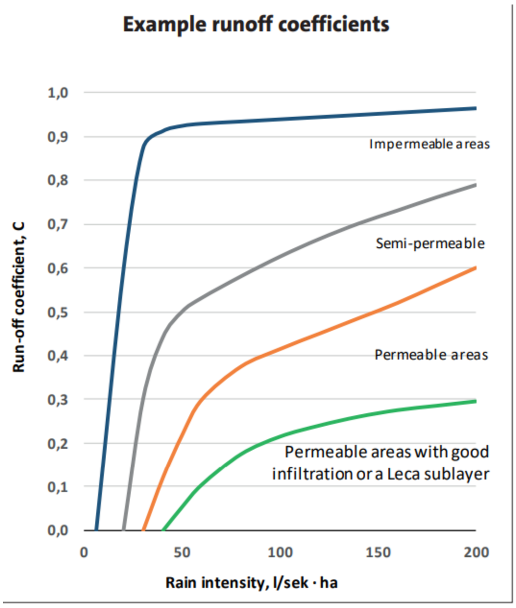


Figure 9: Runoff Coefficient development according to different rain intensities [67].

Table 3: A summary of GR Benefits and Limitations

GR Applications	Location	Hydrological	Summary of Results	References	Advantages/Disadvantages	References
Flood Mitigation	25 different cities	Retention	Climate impact GR retention (more effective in humid subtropical areas than in Mediterranean climates)	Viola *et al*. [36]	Small-scale natural solutions effectively mitigate low return period occurrences: their effectiveness decreased by 67% in reducing runoff volume and 81% in reducing peak runoff for 2- and 100-year return periods.	Vojinovic *et al* [45]
	Northern Europe		Stormwater retention varies with temperature and precipitation. Summer (52% -91%) vs. Winter (0-10%).	Johannessen *et al*. [39]		
	Austin, Texas; Detroit, Michigan;	Peak Runoff Delay	On various GR slopes, runoff delay decreases with roof maturity	Simmons *et al*. [41], VanWoert *et al*. [42], Getter *et al* [43]		
Rainfall Harvest	Palermo	Rainwater harvesting in reducing flood volume	Vegetated roofs delay runoff peaks by up to 10 min. Runoff delay on various slopes diminishes with roof maturity	Freni and Liuzzo [47]	RWH systems have advantages and challenges: spatial constraints in urban areas; the feasibility of RWH and GR combination relies on rainfall patterns	Vojinovic *et al* [45]; Almeida *et al* [48]
	Lisbon, Portugal; 9 cities worldwide		Combining RWH and GR reduces discharges by 20-25%.	Almeida *et al* [48], Cristiano *et al*. [46]		
Water Quality	Chongqing, China	Water Quality	The substrate layer impacted runoff quality, acting as both a source and sink.	Zhang *et al* [51]	GRs aim to improve water quality but can release substrate pollutants (nitrogen, phosphorus, heavy metals) via runoff.	Cristiano *et al*. [46]; Viola *et al*. [36]; Almeida *et al* [48]; Gregoire *et al* [54]

2.5 GR's Contribution to European Urban Resilience and Sustainability Directives -

The implementation of effective urban growth management strategies plays a crucial role in achieving sustainable development in urban areas. This approach offers numerous benefits while simultaneously minimize negative impacts on the ecosystem, such as changes in soil permeability, nutrient availability, and hydraulic patterns, as well as air pollution and the decline of biodiversity and ecosystem services [26].

2.5.1 EU Strategy to Adaptation to Climate Change

The goal of the European Union Strategy on Adaptation to Climate Change is to make the EU climate-resilient by 2050 through supporting the development of the EU and the global community [69]. Its recommendations are intended to shift the emphasis from comprehending the problem to developing solutions and from planning to execution. The strategy has the following four main objectives: to enhance global efforts towards (1) adapting to climate change and to facilitate (2) swifter, (3) smarter, and (4) systemic adaptation [69]. While more systemic adaptation is needed to facilitate the development and execution of adaptation strategies, focusing on NbS like GR, faster adaptation aims to mitigate and provide protection from climate-related risks, and safeguard freshwater availability. This will help its member countries prepare for the effects of climate change. As a result, both Member States and the Union must improve their capacity to adapt, develop their resilience, and address their susceptibility to climate change by improving awareness of the impacts of climate change and identifying effective adaptation strategies. Urban resilience, sustainable land use, inclusive public spaces, and digital urban governance are all important factors to consider in order to support the transformation of the urban system [26]. Furthermore, the Strategy aims to facilitate the use of adaptation plans and climate risk assessments, by techniques such as NbS, because of its versatility and capacity to often outperform traditional technological techniques in ecosystem restoration and service development.

2.5.2 Sustainable Development Goals

As a NbS solution, multilayer GRs have the potential to yield a multitude of advantages across domains such as water management, energy conservation, and the ecosystem [38]. They can also yield further benefits by fostering inter-sectoral collaboration, such as the utilization of harvested water for agricultural purposes [4].

The United Nations approved the Sustainable Development Goals (SDGs) in 2015 with a goal to eradicate poverty, safeguard the planet and ensure peace and prosperity worldwide by 2030 [70]. The 17 SDGs recognize that sustainable development requires a balance between social, economic and environmental sustainability, and that there is a correlation between initiatives in one area and the resulting impact on others [70]. In all circumstances, the SDGs cannot be attained without the creativity, expertise, technology, and financial resources of the entire global community [70].

Therefore, the implementation of this solution has the potential to support the SDGs listed in the 2030 Agenda for Sustainable Development by acting as an effective tool with a variety of advantages, contributing to the sustainable development of urban regions across multiple industries.

Because GR can potentially relieve pressure on the water supply system by reusing harvested rainwater for domestic purposes, increasing the availability of drinkable water, it contributes to Goals 6 “Clean water and sanitation” and Goal 13 “Climate change” as it mitigates the effects of climate change and the risk of floods as well as reducing the heat island effect. GR also enhance the energy efficiency of buildings, thereby reducing the need for climate control energy resources. Another relevant Sustainable Development Goal aim is Goal 17, which focuses on “Partnerships for the goals”, which underscores the significance of collaborative partnerships to effectively improve this technology. For this reason, large-scale implementation of multilayer GR could help create sustainable and resilient urban regions thanks to all its potential advantages - Goal 11: Sustainable Cities and Communities.

The Sustainable Development Goals of the United Nations’ 2030 Agenda are enhanced by NbS’s innovative, scientific, and technological combination.

GRs have the potential to help Europe achieve its SDGs, as well as those of the European Green Deal, by increasing biodiversity, boosting ecosystem services, and fostering sustainable urban development.

It is worth noting that the above-mentioned benefits supporting the contribution of GR to the SDGs are further elaborated in section 2.5.

2.5.3 European Green Deal

Multilayer GR applications at the urban scale will help achieve several SDG objectives, in alignment with the Green Deal policy. The Green Deal is a crucial aspect of the Commission’s plan to execute the 2030 Agenda and realise the SDG established by the United Nations. It aims to safeguard the health and well-being of EU citizens by mitigating the risks and impacts of climate change, while protecting, preserving and enriching the Union’s natural capital [71] – Figure 10.

Figure 10: Different values of the Green Deal [71].

Figure 10 illustrates how the European Green Deal aspires to make the EU a contemporary, resource-efficient, and competitive economy, ensuring no greenhouse gas emissions by 2050; economic growth is unrelated to resource use; and no person or place is left behind.

2.5.4 Water Framework Directive

The EU Water Framework Directive (WFD) is a legislative framework that aims to conserve and manage water resources sustainably within the EU [72]. It mandates the management of stormwater runoff in accordance with sustainable development principles [4, 72]. The directive prioritizes the retention of rainwater at its source, through retention and in-ground infiltration techniques, as previously mentioned [4]. The aim of the WFD is to safeguard and improve aquatic environments via the reduction of priority substance discharges, emissions and losses, whilst also mitigating the effects of floods and droughts [4].

GRs align with the EU WFD by enhancing groundwater recharge and evapotranspiration, thus reducing the urban heat island effect, peak flow and runoff into the drainage system [4]. This leads to mitigating floods and reducing the pressure on the stormwater infrastructures, as well as improvements in stormwater quality. GRs are intended to control stormwater locally and reduce the impermeability of urban areas. Furthermore, promoting and installing GRs enhances public understanding of the importance of water management and conservation, which aligns with one of the fundamental principles of the WFD, involving public participation in water-related decision-making [72].

3 Methods

3.1 Pilot System Installation

Along with Nutrofertil, Leca Portugal, S.A. has developed an extensive GR system ready-to-use, to be implemented in buildings – the LECA® Nutrofertil GR *D* kit. This GR system has been evaluated regarding its drainage capacity, by ITECONS (a Portuguese institute for investigation and technological development) with the aim to make out the first European Technical Assessment (ETA 21/0882 [73]) in Portugal for a GR. It is important to highlight that this type of document – ETA – European Technical Assessment, allows to commercialize construction products to be sold throughout Europe that are not, or are only partially covered by a harmonized standard. Several tests have been performed to determine the runoff coefficient of the LECA® Nutrofertil GR D kit, following the procedure described in "FLL-Guidelines" [22], the German guidelines for GR implementation. Thus, both the system's implementation and the procedure assumed for the precipitation simulations of the present master's thesis were based on these German guidelines.

The evapotranspiration process of the vegetation layer regenerates the retention capacity between rainfall events as it removes stored water from the GR, increasing the available water storage space in the growing medium. For this reason, the vegetation layer is not included in this study, as the objective is to evaluate and determine the hydraulic performance of a roof based on LECA®.

3.1.1 Kit LECA® Nutrofertil Green Roof D Description

The LECA® Nutrofertil GR *D* kit (LECA-based GR system), schematically presented in Figure 11, mitigates rainwater runoff, thereby reducing costs and having an impact on the design and management of drainage systems. Additionally, it protects the waterproofing membrane from detrimental effects such as mechanical damage, ultraviolet radiation, and temperature fluctuations. Therefore, the kit consists of the following layers, starting from the bottom [73, 74]:

- **Protection Layer** (Ecofelt PES-SB300): a geotextile material (reclaimed polyester fibers) that provides mechanical damage protection and moisture retention;
- **Drainage layer** (LECA ® D): a lightweight expanded crushed clay aggregates with a particle size range of 10–20 mm, and a bulk density (wet) of 275 kg/m^3 that absorbs excess water and channels it to the drainage;
- **Filter layer** (Ecofelt PES-SB150): a geotextile that inhibits the transfer of fine particles from the vegetation layer to the underlying drainage layer;
- **Vegetation Support Layer** (Nutreasy): acts not only as a structural element above the drainage layer but also as a medium for water retention and as a support system for the plants and roots that are placed on the surface of the GR, including their nutrient content. The substrate is composed of organic compounds, peat, pine bark with a ratio of 4:15, and expanded clay LECA® Hydro.

Figure 11: Kit LECA® Nutrofertil GR D (adapted from [75]).

3.1.2 GR Installation - LECA® Nutrofertil GR D Kit Description

Figure 12 shows the building process of the pilot system, which started with the construction of the simulated roof structure using wood boards, (Figure 12 (a)), which measures 100 cm in width and length and 36.5 cm in height. The structure was subsequently covered with *PVC AquaLiner* to make it waterproof (Figure 12 (b)). Subsequently the protection layer (Ecofelt PES-SB300) was placed above the waterproof membrane, followed by a 100 mm-thick drainage layer (LECA® D – Figure 12 (c)). Afterward, the filter layer (Ecofelt PES-SB150) was employed, followed by a 150 mm-thick substrate support layer (Nutreasy – Figure 12 (d)).

(a) (b) (c) (d)

Figure 12: Pilot system wooden structure (a) PVS Aqualiner (b), drainage layer (c) and Substrate layer Nutreasy (d).

Figure 13 is used as a schematic representation to enhance the comprehensibility of the several layers constituting the present GR pilot system.

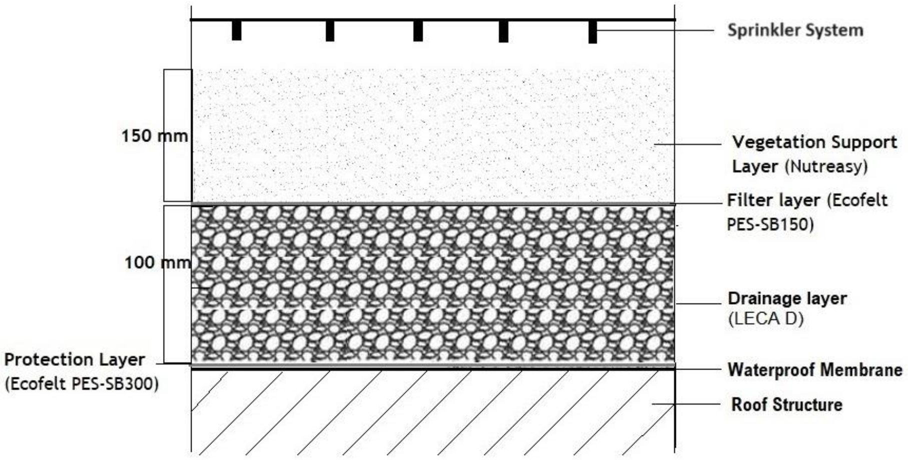


Figure 13: LECA-based roof multilayer components in a cross-section.

At last, the inclination of the roof was modified to conform to the recommended 2% gradient as advised by ETA 21/0882, through the utilization of a mobile device application, as shown in Figure 14.

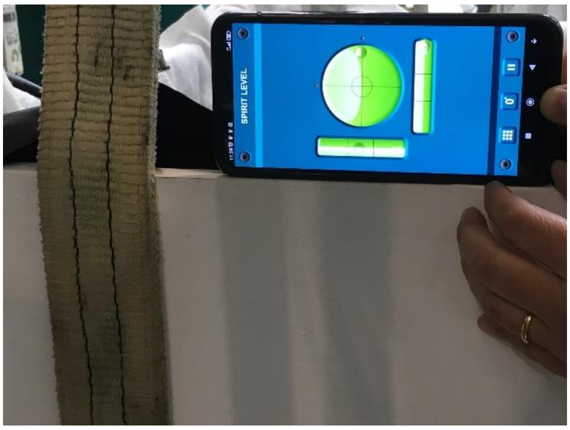


Figure 14: LECA-based GR platform set at 2% slope.

3.1.3 Simulation of Precipitation Events: Measurements Procedure and Equipment

Throughout the testing process, the water flow at the entrance of the pilot system is monitored using the *MV110* ISOMAG converter with a display for magnetic flow meters, present in Figure 15.

Figure 15: MV110 ISOMAG converter for magnetic flowmeters

The accuracy of this converter is specified as ± 0.4% of the reading. The runoff was collected at the outflow and stored either in a bucket or in graduated flasks during the tests, to measure the runoff volume (2 L, 1 L, 0.500 L, and 0.250 L), as shown in Figure 16.

Figure 16: Runoff collection.

The simulations of precipitation were conducted using sprinklers (Figure 17). These were positioned to ensure that the water was distributed as equally as possible across the GR's surface.

Figure 17: Sprinklers used to the precipitation simulation tests.

3.2 Hydrological Performance Assessment

3.2.1 Simulation of Precipitation Events

The aim of the present work was to determine the water retention and detention of a LECA-based GR and its runoff coefficient. As previously described, this was accomplished by employing a LECA-based GR system with an area of 1 m^2 (100 cm length x 100 cm width), and a height of 36.5 cm. The LECA-based GR system was be set up with a 2% slope.

The extensive GR pilot system was subjected to multiple precipitation simulations at different time intervals, as specified in Table 4. The conducted tests were based on both the ETA 21/0882 and the FLL guidelines procedure. These documents specify that before any test, the roof material must be pre-wetted with constant irrigation until a constant runoff rate is achieved for 10 min. This was achieved by spraying the green infrastructure with water until the runoff is uniform and constant for 10 min, as shown in Figure 18. Hydrological simulation performance tests were then determined after 24 h of drainage. For each tested condition, this entire testing process should be repeated three times with 24-h intervals in between.

Figure 18: Example of the outflow considered in the saturation process (constant outflow during at least 10 min).

3.2.2 Intensity and Precipitation Design Flows Definition

In order to define the return period and the time duration of precipitation simulation events of the intended simulated tests, the Intensity/Duration/Frequency (IDF) curves have been consulted. Stormwater drainage studies analyze IDF curves to determine the maximum average rainfall intensities for different durations and return periods. Obtaining these curves involves statistically analyzing historical series of udographic records relating to several years. According to the Portuguese legislation (Decree-Law 23/95) [76], most of the return periods are either 5 or 10 years and precipitation should be considered for 5-15 min.

The precipitation design flow rates (Q) were estimated following the "Manual dos Sistemas Prediais de Distribuição e Drenagem de Águas" and the Portuguese Decree-law no. 23/95 [76, 77]. These documents have established the standards for calculating different precipitation flows, considering the IDF curves mentioned above. The curves are obtained using Eq. 1, wherein a and b represent constants unique to each Return Period (RP) and pluviometry area:

$$I = a \times t^{b} \qquad \text{Eq. (1)}$$

in which:

I - rainfall intensity (mm/h)

t - duration of precipitation (min)

a,b – constant values depending on the return period

Table 4: Simulation Conditions

RP (years)	a	b	t (min)	I (mm/h)
5	259.26	-0.562	5	104.9
			10	71.1
			15	56.6
10	290.68	-0.549	5	120.1
			10	82.1
			15	65.7

Thus, the precipitation conditions selected were based on the aforementioned criteria. In Figures 19 and 20, the IDF curves demonstrate the RP of 5 and 10 years for the Porto region under the chosen conditions (5, 10, and 15 min).

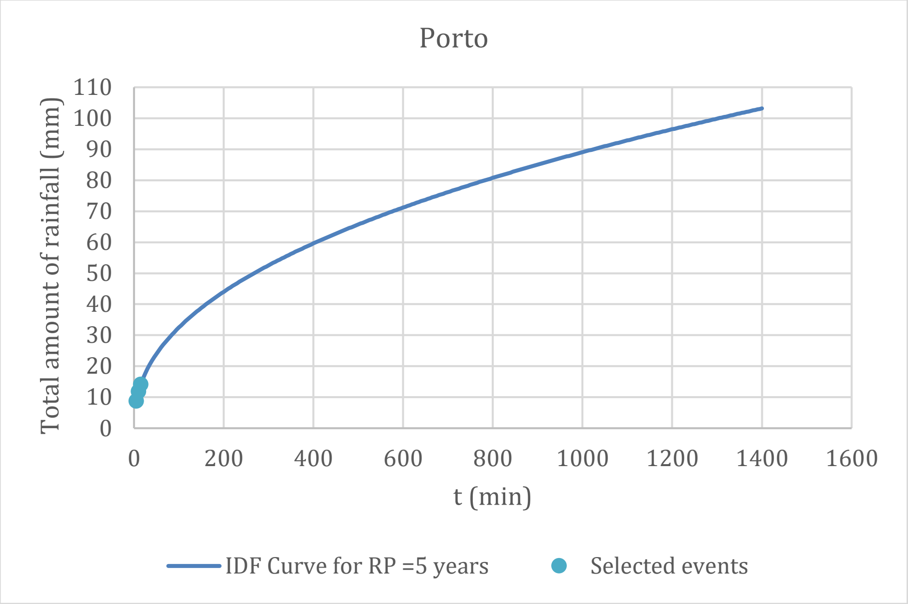


Figure 19: IDF curve for the Porto region, with RP = 5 years.

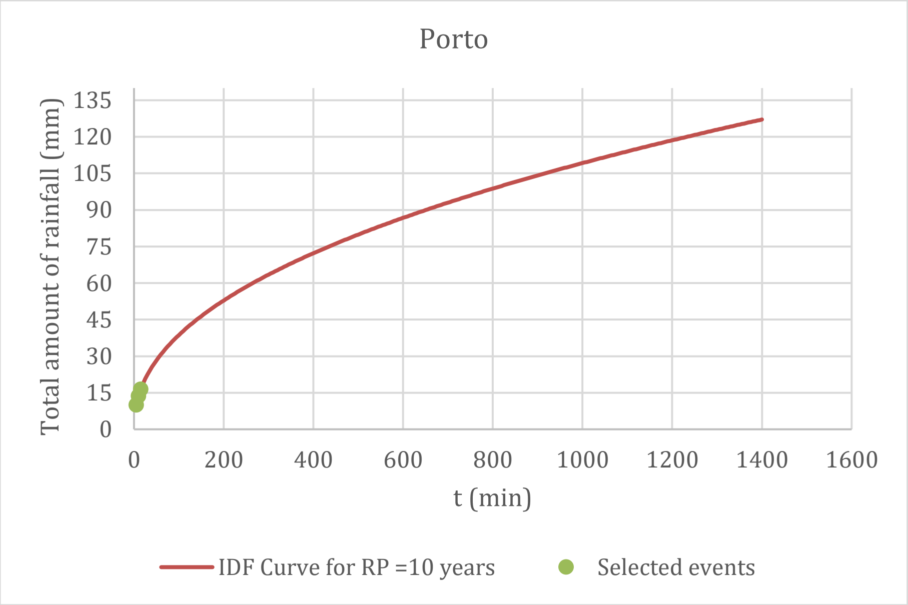


Figure 20: IDF curve for the Porto region, with RP = 10 years.

The calculated flow rate will vary according to the intensity of the rainfall. Thus, in Eq. 3, Q represents the maximum precipitation rate that can occur in this region – design flow. Table 5 shows the different precipitation rates obtained for this study. Note that as the calculation of Q corresponds to the flow entering the GR, the runoff coefficient must also correspond to the input value. Hence, it is assumed that all the precipitation that falls immediately upon entering the GR is fully drained off. Consequently, the runoff coefficient is 1. The area (A) of the GR is equivalent to 1 m^2.

$$Q = C \times I \times A \tag{Eq. (2)}$$

in which:

Q - design flow (L/min)

C - runoff coefficient

I - rainfall intensity (L/min.m^2)

A - area to drain in horizontal projection (m^2)

Table 5: Different flows considered for the precipitation simulations

RP (years)	t (min)	Runoff Coefficient	A (m^2)	I (L/(min.m^2))	Q (L/min)
5	5	1	1	1.75	1.75
	10			1.18	1.18
	15			0.94	0.94
10	5			2.00	2.00
	10			1.37	1.37
	15			1.10	1.10

Thus, the studied intensities represent intense but localized rainfall - as the probability of an extreme event occurring in a short period of time.

According to the ETA 21/0882 (that follow the FLL guidelines), a block rain of 27 L/ m^2 over 15 min is required. This event was adapted to correspond with this thesis' extensive pilot GR system area of 1 m^2 (and subsequently replicated and compared to the experimental system regarding the Porto region, as shown below in Table 6.

Table 6: ETA 21/0882 simulation conditions and the corresponding conditions of the LECA-based system

	t (min)	I (mm/h)	A (m^2)	I (L/min.m^2)	Q (L/min)
ETA 21/0882	15	27	5	1.8	9
Experimental System	15	27	1	1.8	1.8

3.2.3 Parameters Assessed: Runoff Coefficient, Retention, Detention

The performance of the GR was assessed according to its retention (volumetric control) and detention (temporal delay) capacity, two important parameters in hydrological GR performance. As such, it is important to define and distinguish these two parameters.

The detention effect occurs when stormwater that has been temporally detained is subsequently discharged [47, 78, 79], while retention refers to the rainfall that is contained within the roof system and does not discharge from the roof as runoff, and that can eventually be lost through evapotranspiration [47, 78].

In the literature, there is no standard metric that defines detention performance unambiguously [80]. It is assessed through time lag markers such as time to start runoff, peak delay, as well as runoff and peak flow attenuation [80, 81]. On the other hand, retention is assessed using cumulative volumetric retention, or the mean, median, minimum, and maximum retention for each event [80].

To fully understand the distinct features of each term, Figures 21 and 22 display the corresponding representations of the diverse metrics typically used to define the retention and detention capacity in GR studies.

3.2.3.1 Runoff Coefficient

The runoff coefficient (C) was quantified for all the water drained downstream of the LECA-based GR system after the rainfall simulation (Eq. 3) [22].

$$C = \frac{Runoff\ in\ 24\ h\ (L)}{Precipitation\ in\ t\ \min \quad (L)} \qquad \text{Eq. (3)}$$

3.2.3.2 Retention

For each test, retention was defined as an average amount of permanent water retained. Thus, retention is the volume of water that both the drainage and the substrate layers can store at any given time. The retention capacity was determined as follows in Eq. 4 [73]:

$$Retention\ (\%) = 100 - \frac{Water\ discharge\ in\ 24\ h\ [L]}{Rain\ volume\ in\ t\ min\ [L]} \times 100 \qquad \text{Eq. (4)}$$

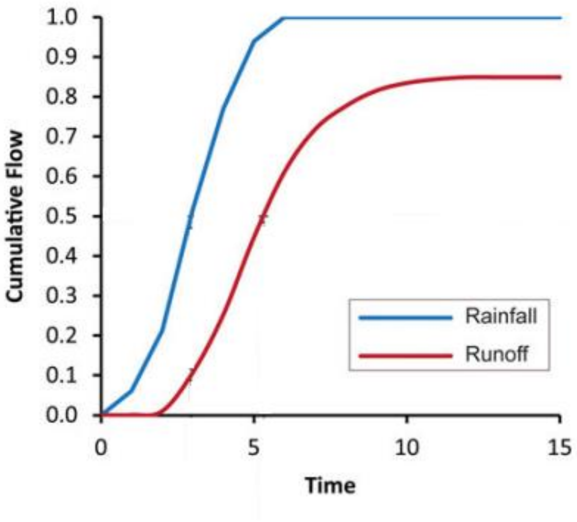


Figure 21: Retention capacity (adapted from [80]).

Retention performance is measured as the proportion of rainfall retained per event in the pilot GR tested. The amount of water retained is affected by the distribution of rainfall intensity, starting moisture content and the characteristics of the GR (layer thickness, slope, material composition, etc.), as well as the drying capacity of the roof [82].

In this context, retention is the opposite of the runoff coefficient. If C is the amount of water that runs off, then retention is the rainwater portion that the GR "absorbs”. This means that the sum of the two must be 100%.

Since peak flow is often associated with maximum erosive damage and sewage overflows during precipitation events, it is important to see the impact of retention on peak runoff.

3.2.3.3 Detention

As previously defined, detention occurs when stormwater is temporally detained before being discharged [47, 78. 79]. As such, detention has three independently quantifiable effects: delaying the start of the runoff, delaying the peak flow rate, and reducing the peak flow rate (Figure 22).

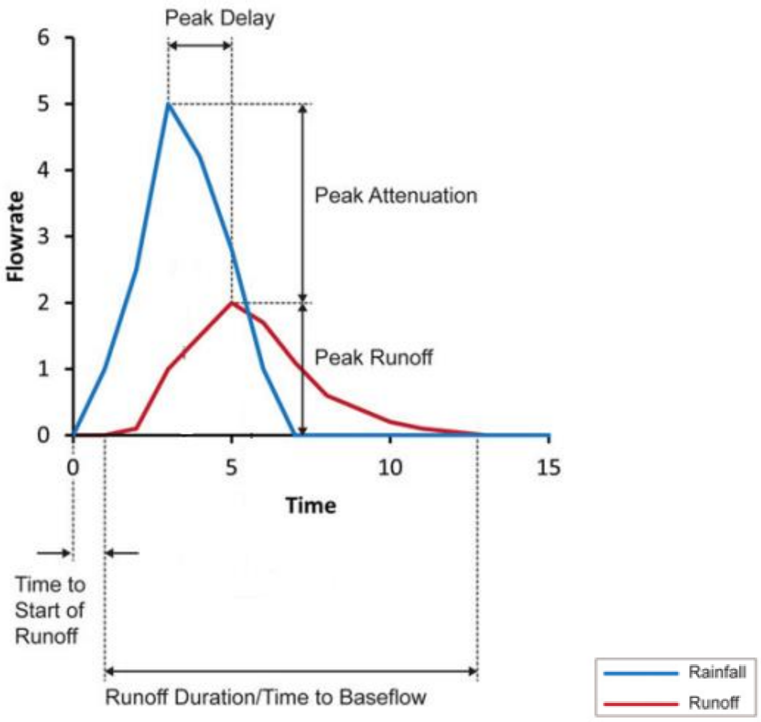


Figure 22: Detention capacity metrics (adapted from [80]).

The runoff delay is determined as the time difference between the beginning of rainfall and the beginning of runoff (basically is the time to start runoff), whereas peak delay is the time difference between rainfall and runoff peaks [83], as shown in Figure 18 and calculated in Eq. 6. The peak time delay is important for calculating sewage surcharge reductions [84]. Peak attenuation is the difference between rainfall and runoff peaks, divided by the rainfall peak [85] (Figure 12 and Eq. 7).

$$Peak\ delay\ (min) = TP_{RO} - TP_{RF} \qquad \text{Eq. (6)}$$

in which,

TP_{RO} – time of the runoff peak (min)

TP_{RF} - time of the rainfall peak (min)

$$Peak\ attenuation\ (\%) = \frac{I_{RF}(mm) - I_{RO}(mm)}{I_{RF}(mm)} \quad \text{Eq. (7)}$$

in which,

I_{RF} - maximum rainfall amount (mm)

I_{RO} - maximum runoff amount (mm)

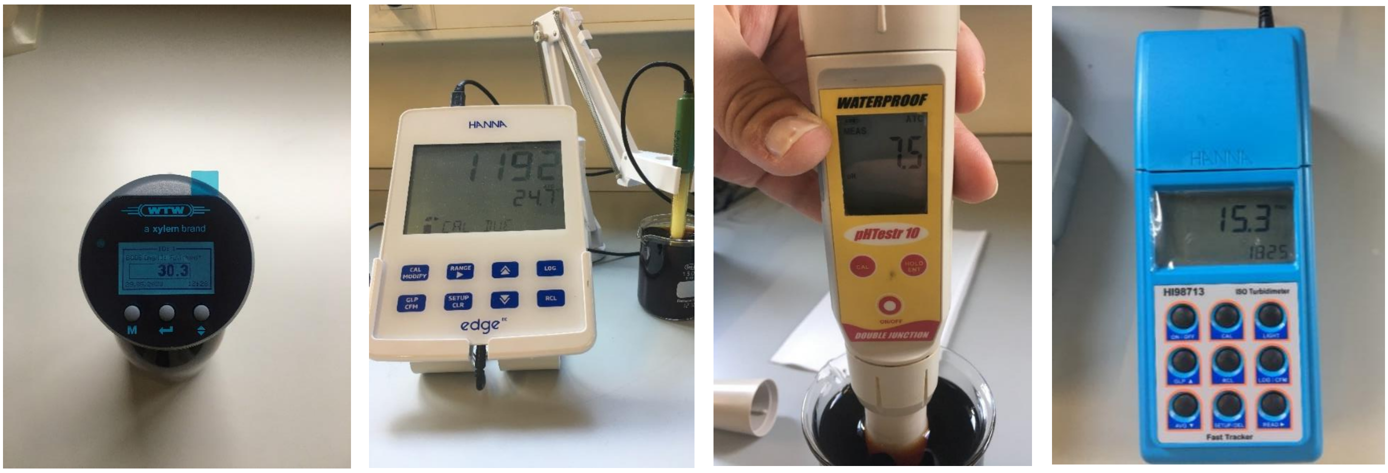
Data were evaluated as the average of triplicates for each test. In addition, the results are always presented in terms of intensity and input flow. Although it would be more accurate to only refer to rainfall in terms of intensity or depth (total amount of rainfall – mm), the tests were always designed and identified in terms of flow rates (L/min). Thus, the inclusion of flow rate into the presentation of results appears almost as a "mnemonic" by the author for identifying the tests.

3.3 GR Runoff Quality

In addition to the hydraulic performance, the runoff's water quality was also examined. For this purpose, pH, turbidity, and conductivity were determined for every runoff test (for the three replicate tests). BOD_5 was determined for the first replicate in each test.

Although there are other important parameters to be tested to assess water runoff quality of GR systems (e.g. total suspended solids, ammoniacal nitrogen, total nitrogen and total phosphorus), the selection of aforementioned parameters was made in light of the primary objective of this thesis, which did not involve a comprehensive evaluation of the quality of runoff water. Furthermore, the chosen parameters were regarded as the most straightforward and immediately testable, considering the available resources in the laboratory.

The pH and turbidity were measured using the *pHTestr 10 Waterproof Pocket Tester* and the *HI-98713 Portable Turbidity Meter*, respectively. The BOD_5 was measured with a *Respirometric BOD Measuring system OxiTop®*, while the conductivity was determined with the *Hanna Edge Conductivity Meter*. Figure 23 shows the devices used, with the example of the water quality results for the first run of the first test (2.0 L/min).



(a) (b) (c) (d)

Figure 23: Example of the collection of the water quality results for (a) BDO$_5$, (b) conductivity, (c) pH and (d) turbidity.

4 Results and Discussion

4.1 Precipitation Events Simulation

The precipitation simulation events were conducted between 22 May and 20 July 2023. Each test lasted six days, from Monday to Saturday (triplicates and the corresponding saturations).

The laboratory tests showed minimal variation over the three runs for each test, which suggests that the methodology used is robust and reliable.

Therefore, the average runoff curves from the three runs of each test condition were calculated for each duration of the rainfall (Figure 24). Once each rainfall simulation started, the runoff was measured every 5 min for 2.5 h long and the time when runoff started was recorded.

Examining the data in the graphs (Figure 24), it is clear that the runoff at the end of the 2.5 h of observations is negligible and that the peak runoff consistently occurs 15 to 20 min after the end of the precipitation simulation.

Figure 25 shows the runoff for the two 15-min events tested (with 0.94 and 1.10 L/min selected conditions), and also a comparison between the runoffs recorded during 15-min precipitation events and the 15-min conducted test in the ETA 21/0882. We can conclude that the LECA-based GR system studied has a greater capacity to reduce the peak runoff at flow rates of 0.94 and 1.10 L/min than the standard case of 1.80 L/min tested in the ETA 21/0882. In all three situations, runoff peak was at min 20. This will be the equivalent of the passage time (t_p), but only on the scale of a micro-basin, which is this LECA-based GR system. In a traditional roof, this t_p will be close to 0 min, as it has no capacity to retain or detain any volume of rainwater. Nevertheless, when compared to the ETA 21/0882 adapted test of 1.80 L/min, the 0.94 L/min and 1.10 L/min presented a 37% and 28.57% difference between runoff peak, respectively.

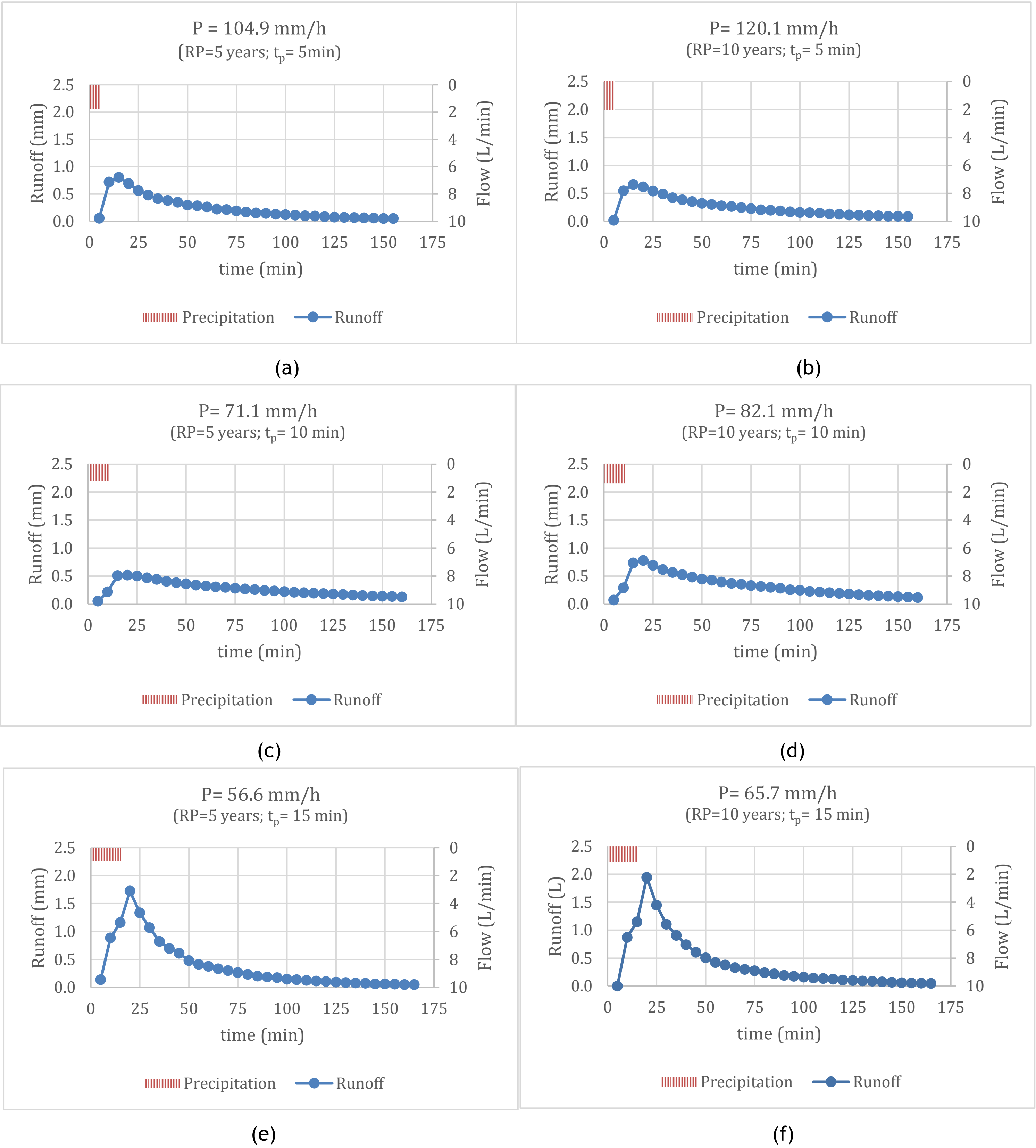
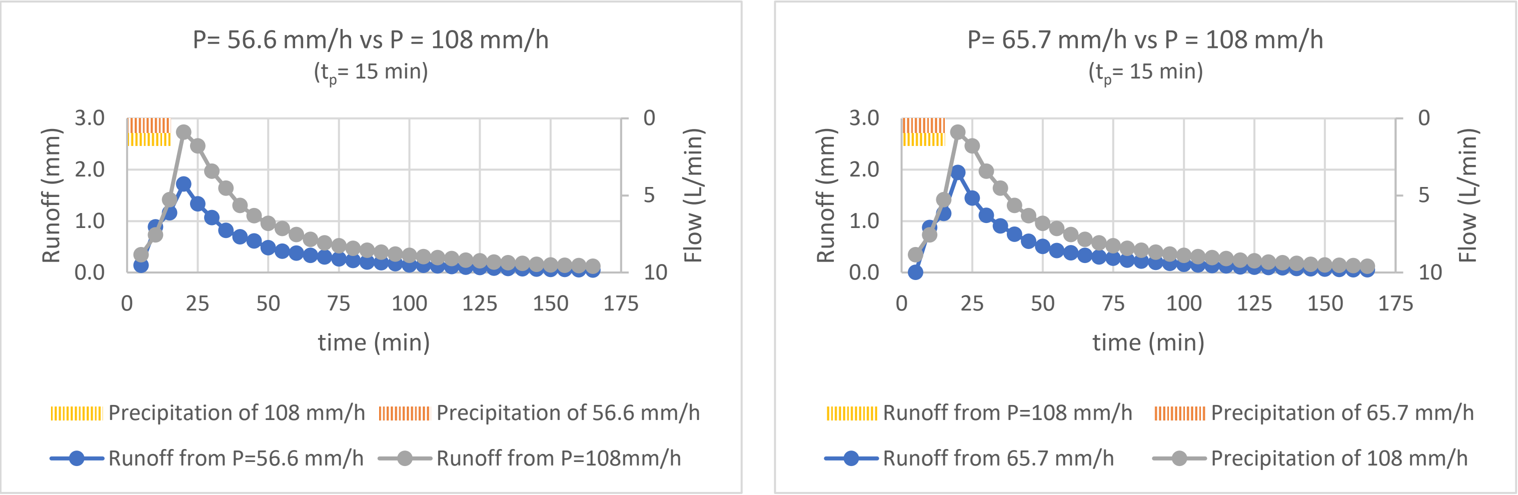


Figure 24: Runoff behavior in each test: (a) 1.75 L/min, (b) 2.0 L/min, (c) 1.18 L/min, (d) 1.37 L/min, (e) 0.94 L/min and (f)1.10 L/min.



(a) (b)

Figure 25: Runoff behavior between the 15-min rainfall tests, (a) 0.94 L/min and (b) 1.10 L/min, both compared to the ETA 21/0882 test of 1.8 L/min.

4.2 Hydrological Performance

4.2.1 Runoff Coefficient

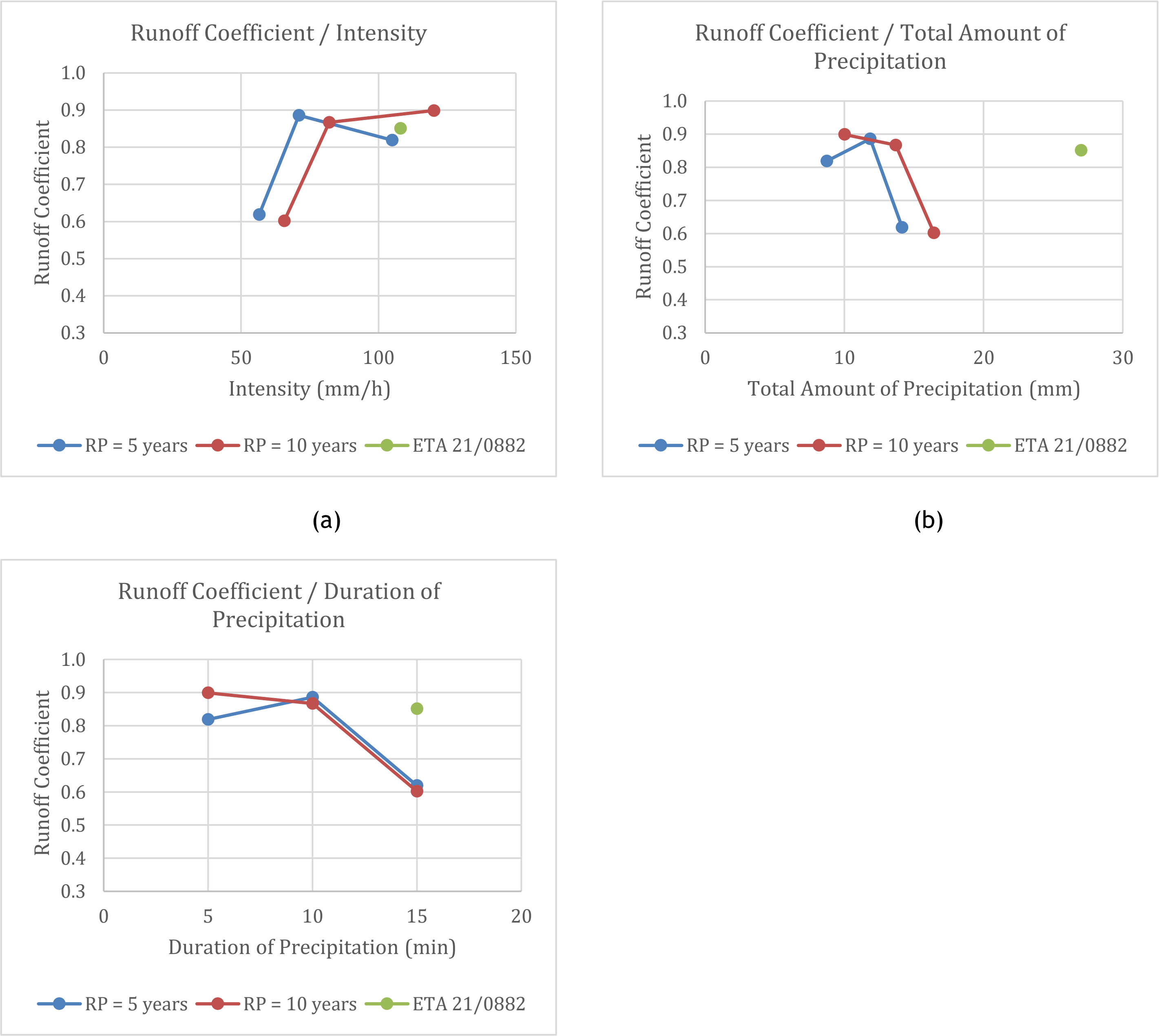
Table 7 displays the results of the runoff coefficient (C) for each total amount of rainfall condition tested and compares it with the results from the test adapted from the ETA 21/0882.

Table 7: Runoff Coefficient

RP (years)	Duration of precipitation (min)	Q (L/min)	Total amount of rainfall (mm)	C (adimensional)
5	5.00	1.75	8.74	0.819
	10.0	1.18	11.9	0.886
	15.0	0.94	14.2	0.619
10	5.00	2.00	10.0	0.899
	10.0	1.37	13.7	0.867
	15.0	1.10	16.4	0.602
ETA 21/0882	15.0	1.80	27.0	0.851

Subsequently, the presented table demonstrates a positive correlation between the runoff coefficient and both the duration of precipitation and total amount of rainfall, as evidenced by an increase in the coefficient for each RP.

The calculated runoff coefficients were plotted against duration of precipitation, total amount of precipitation, and precipitation intensity for each RP (Figure 26) to better comprehend the trends in their values.



(a)

(b)

(c)

Figure 26: Runoff coefficient values as a function of the variables influencing it.

According to Figure 26, there are two observable patterns.

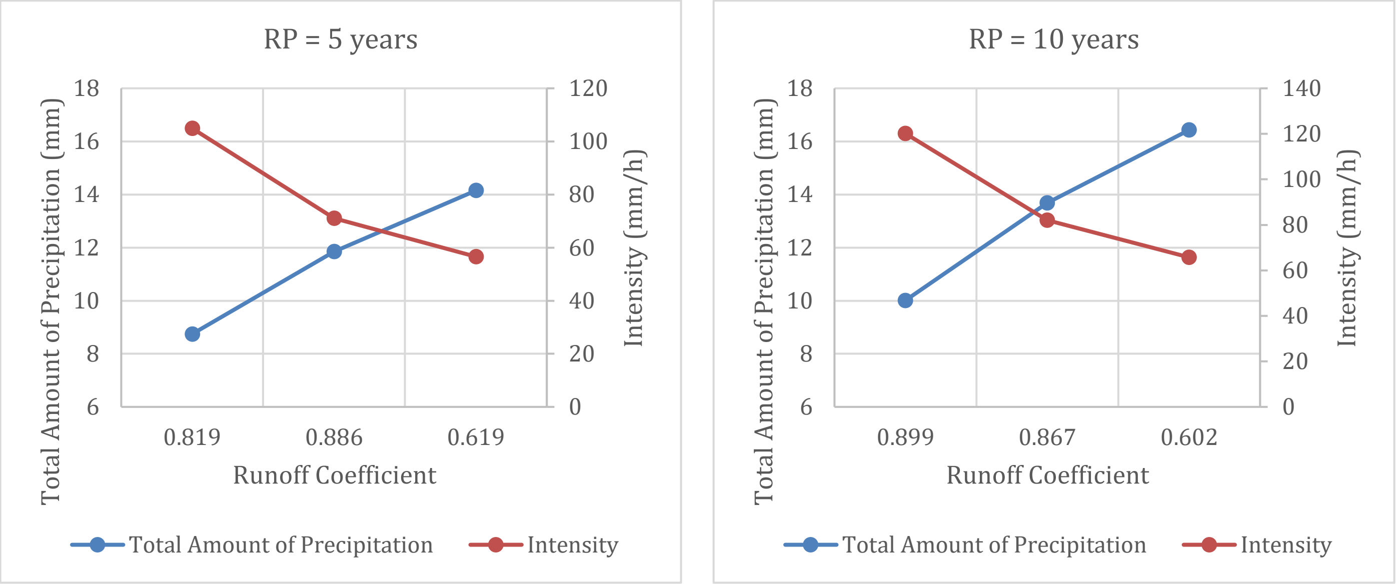
Firstly, for each RP, the runoff coefficient increases with increasing intensity (except for the intensity of 104.5 mm/h (1.75 L/min) for RP 5 y (Figure 26 (a)). The observed tendency is in accordance with the author Colli *et al.* [85], that also found that the runoff coefficient increases with increasing rainfall intensity, meaning that the detention into the constituent layers decreases at higher intensities. It makes sense because exposing a GR to lower intensity rainfall means lower amounts of rain per unit time. This translates into a greater retention capacity of the GR by the substrate and drainage layers, and therefore a smaller proportion of water being drained away (and consequently a lower C).

Secondly, it can be concluded that a reduction in the total amount of rainfall leads to an overall increase in the runoff coefficient (Figure 26 (b)). Although this behavior is to be expected given the calculation of the runoff coefficient (Eq. 3 – ratio between the water drained by the GR and the total amount of rainfall), at first sight it is not in line with the literature. For example, Schärer [66] found that a decrease in precipitation volume leads to a decrease in the runoff coefficient.

As expected, C decreases with increasing rainfall duration (Figure 26 (c)). This is because the longer the rainfall duration, the greater the rainfall intensity. Consequently, the GR gradually loses its ability to retain and detain rainwater, increasing the amount of surface runoff leaving the GR.

It can therefore be concluded that in the case of the LECA-based GR system tested, the runoff coefficient depends more on the intensity than on the total amount of rainfall. In the sense that in this case the total amount of water that rains is different from the way it is distributed in the GR. This can be clearly seen in Figure 26 (a). For RP = 5 years, the runoff coefficient for the 105 mm/h intensity (Q = 1.75 L/min) is lower than for the previous intensity, in contrast to RP = 10 years. This means that there has been a change in the way rainfall is distributed over time.

The graphs in Figure 27 were then drawn to compare the behavior of different intensities and amounts of rainfall for each RP.



(a) (b)

Figure 27: Comparison of the runoff coefficient between different intensities and amounts of rain, for RP of (a) 5 y and (b) 10 y.

In addition, it is worth noting that the runoff coefficient ranged from 0.602 to 0.899, indicating its proximity to the values obtained from a conventional impermeable roof. It is therefore believed that this can be attributed to the saturation process that occurred before each test, where substrate humidity reached 100%, and therefore, with higher humidity, lower retention capacity is achieved, and higher runoff volume is drained. It is also noteworthy that the absence of a vegetation layer on the GR may have contributed to the higher runoff coefficient values observed, since the presence of vegetation and consequently their roots, may help to retain a higher amount of water into the growing substrate layer, besides using some of the retained water to their development processes (growth and evapotranspiration). Therefore, decreases the water runoff volume. However, due to the reduced period of experimental development and simulation events, it has been decided not to include the vegetation layer into this pilot GR system.

Furthermore, it is important to highlight that when the literature compares the runoff coefficient with the intensity and/or total amount of rainfall, they are comparing the same rainfall intensity by varying only the time duration of rainfall. In this case, we are comparing different rainfall events, each one of different duration and with different RPs.

It can also be said that for higher rainfall return periods (RP = 10 y), the amount of rainfall exceeds the maximum water retention capacity of the GR more than for RP = 5 y - Figure 26 (b). This translates into generally lower runoff coefficients for smaller RPs, because the rainfall characteristic of these is also lower.

The runoff coefficient decreases as the duration of precipitation increases, which was expected, since the amount of rain is obtained by multiplying the rainfall time and intensity.

4.2.2 Retention Performance

The investigation of the water retention capabilities of a GR during various precipitation events is of significant interest from a design view. Engineers are interested in determining the proportion of incoming precipitation that is expected to remain on the GR without runoff. Hence, Table 8 summarizes the results obtained for the green cover retention parameter.

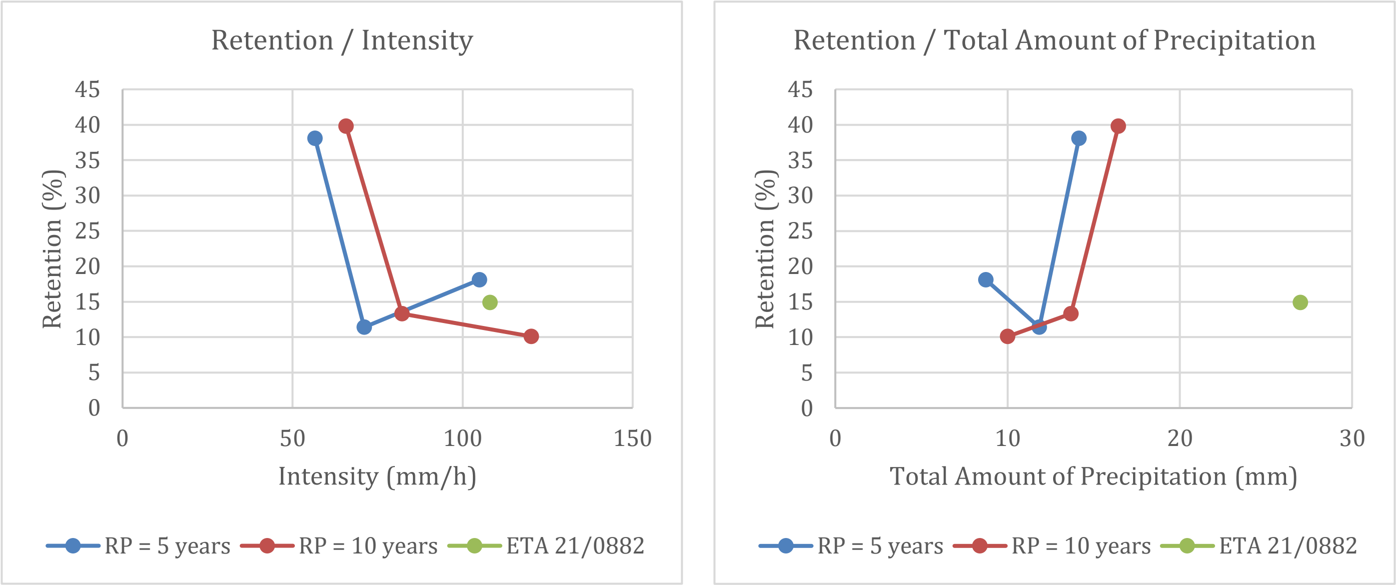
Table 8: Variation in retention performance

RP (years)	Duration of precipitation (min)	Q (L/min)	Total amount of rainfall (mm)	Retention (%)
5	5	1.75	8.7	18.1
	10	1.18	11.9	11.4
	15	0.94	14.2	38.1
10	5	2.00	10.0	10.1
	10	1.37	13.7	13.3
	15	1.10	16.4	39.8
ETA 21/0882	15	1.80	27.0	14.9

The retention varied between 10.1% (for a 5-min precipitation duration) and 39.8% (15 min of precipitation), equivalent to 108.0 mm/h and 39.56 mm/h, respectively, over the whole period.

The capacity of a GR to retain runoff is dependent upon its physical configuration, as stated in the literature. The decrease in runoff can also be influenced by the intensity of rainfall and total amount of rainfall [76, 86].

Furthermore, the depth of the substrate has been widely acknowledged as a significant component that affects the ability of GRs to retain rainwater [87]. Therefore, given that its physical characteristics (such as slope and substrate thickness) remained the same across all tests, it was anticipated that the retention would exhibit some sort of pattern in response to variations in rainfall intensity/total amount of rainfall (Figure 28).



(a) (b)

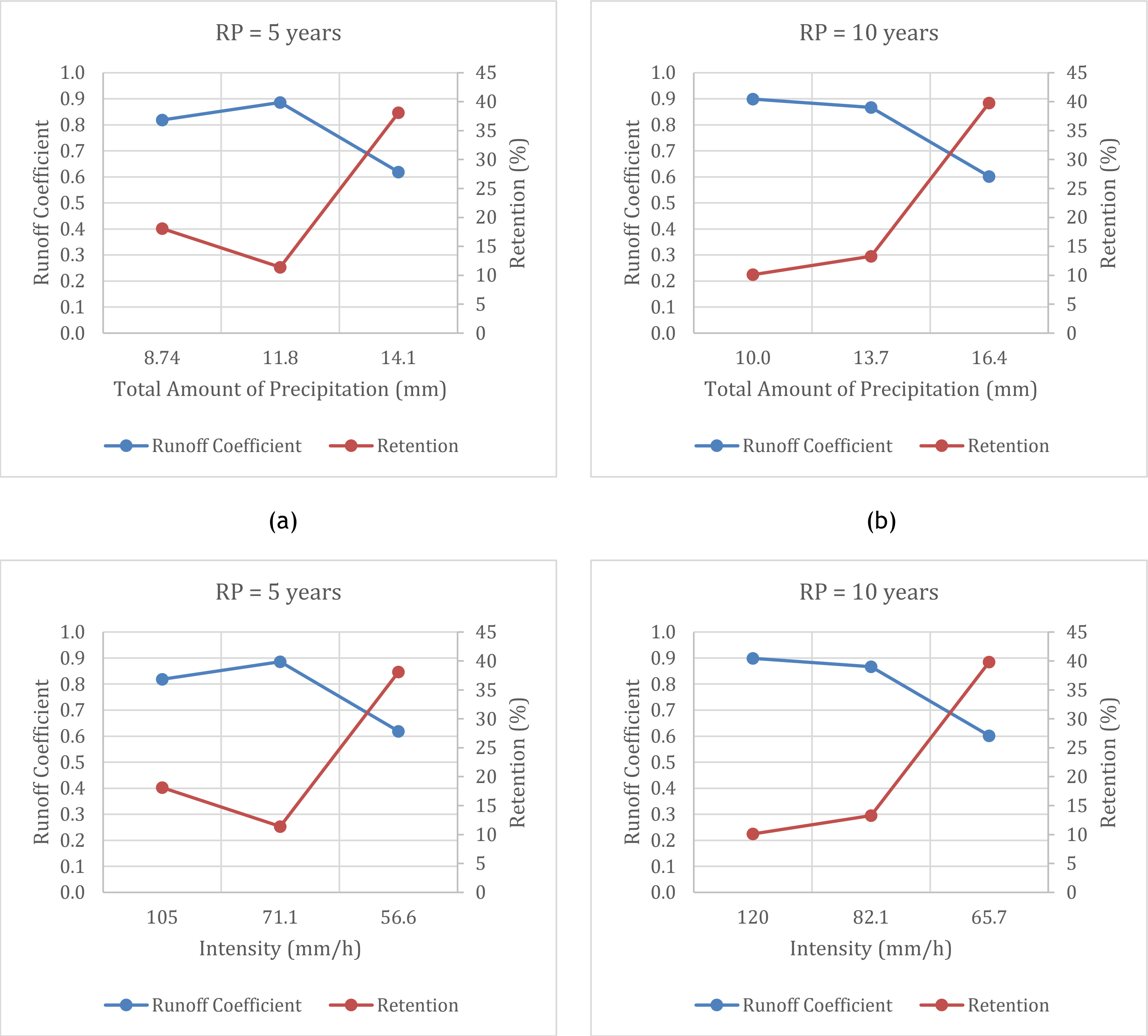
Figure 28: Water retention, in relation to (a) rainfall intensity and (b) total amount of precipitation.

Analyzing Figure 28 (a), it can be seen that retention tends to decrease with increasing intensity. The results reported by the author Alfredo *et al*. [84] showed that increasing rainfall intensity results in a downward trend in GR retention rates, which is in line with what was obtained. This is due to the fact that lower intensities mean that there is less precipitation for the same duration, which results in a slower substrate saturation process, increasing retention.

Regarding the total rainfall amount (Figure 28 (b)), the retention values obtained show an increasing pattern with increasing rainfall amount (except for the 5 min duration test for RP= 5 y, as also observed for C).

In their research on an extensive GR situated in Manhattan, New York, Hakimdavar *et al*. [89] discovered that the retention rates varied according the total amount of precipitation: retention rates were 85% for precipitation events of 20 mm, 62% for occurrences between 20-40 mm, and 51% for events exceeding 40 mm. Moreover, Garofalo *et al*. [37] found that retention decreases with an increase in total amount of rainfall, and that retention ranges from 0-20% when total amount of rainfall exceeds 10 mm. This means that results from the literature regarding the amount of rainfall are, again, contrary to those obtained. Hence, the cause of this phenomenon is the same as for C: the retention is limited by the intensity of the rainfall, and also the way the rain is distributed in the GR influences the retention more than the amount of rainfall itself.

The obtained results for retention align with expectations due to the correlation between the runoff coefficient and retention. The runoff coefficient refers to the amount of water drained by the GR (Eq. 3), while retention refers to the percentage of water it is able to retain (Eq. 4). Thus, they represent opposing characteristics and are expected to display complementary behaviour when subjected to the same conditions. The graphs displayed in Figure 29 illustrate this complementary response between retention and C for the intensity and total amount of rainfall, supporting the results obtained.



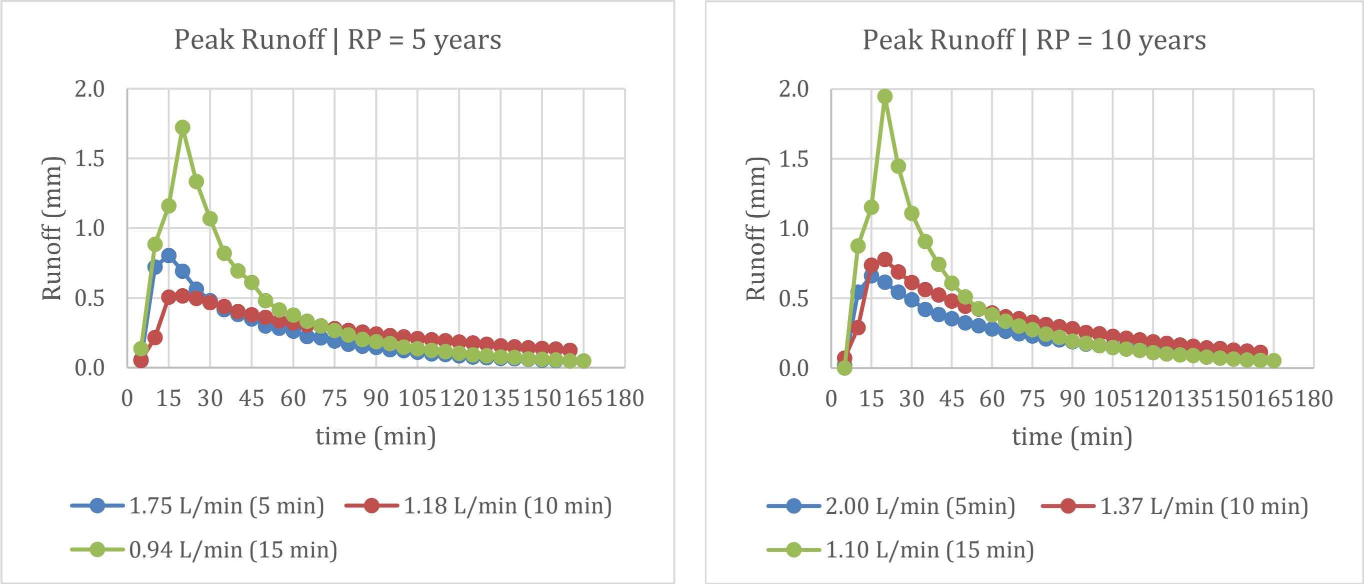
(a) (b)

(c) (d)

Figure 29: Runoff coefficient and retention, in relation to the quantity of rainfall ((a), (b)), and intensity ((c), (d)), for RP of 5 y and 10 y.

However, the results of Garofalo *et al.* [37] have demonstrated that an extensive GR without LECA® exhibits lower retention performance compared to a GR containing LECA® into its drainage layer. In the present study, the retention rate of the LECA-based GR system ranged from 10.1-39.8% for a rainfall depth of 10.1-16.43 mm.

In order to determine the contribution of retention to the reduction of the peak runoff, the latter was compared according to the RP using the graphs in Figure 30. These graphs illustrate the peak runoff resulting from the average of the triplicates for each test.



(a) (b)

Figure 30: Peak runoff for (a) RP = 5 years and (b) RP = 10 years.

It is not surprising that higher runoff peaks are correlated with longer rainfall durations. This is because longer rainfall durations expose the GR to greater amounts of total rainfall. As the GR has the same retention capacity for all rainfall intensities (since it is always equally saturated the day before each test), the greater the rainfall, the less the substrate and drainage layers can absorb rainwater. As such, it can be concluded that GR are less efficient in reducing peak flows during prolonged durations (keeping in mind that all rainfall events analyzed are at design flow).

On the other hand, for smaller amounts of rainfall, both the substrate and drainage layer can absorb and retain most of the rainwater through its porosity, with minimal or no runoff released from the GR.

It is therefore concluded that the LECA-based GR system is less efficient in reducing peak flows during prolonged and intense rainfall events (all rainfall events analyzed are design flows), rather than in small and short rainfall events.

It can be seen that for RP = 5 y the 1.75 L/min and 1.18 L/min tests peaked at the same time and that the 0.94 L/min test, the longest duration test, peaked 5 min later (Figure 30). This is in line with expectations and is due to the reason explained above: GRs have greater retention and detention capacity for shorter rainfall durations (thus lower rainfall volumes) and are therefore able to reduce and delay peak flows more than for longer rainfall durations.

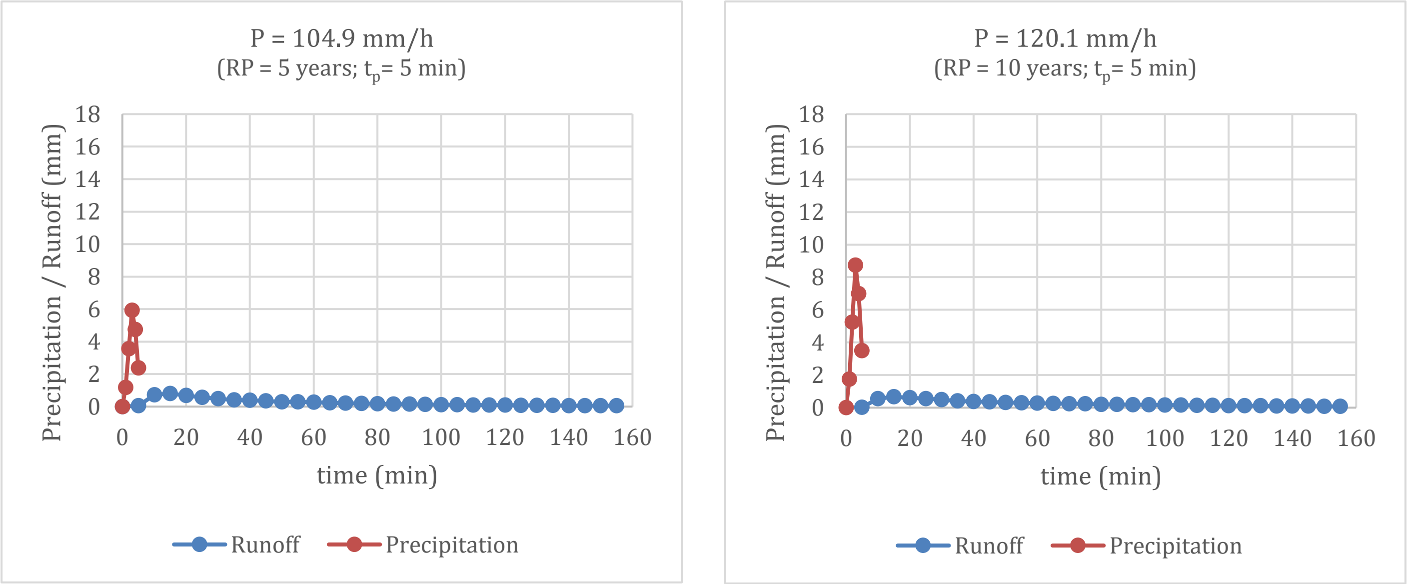
On the other hand, the 10-y RP is characterized by the highest runoff peaks. This is because the higher the RP, the larger the rainfall event. Vojinovic *et al*. [45] concluded that for RPs of 2 y and 100 y, there is a drop in effectiveness of 81% for reducing peak runoff.

4.2.3 Detention Performance

Detention for a given precipitation event can be described using a variety of metrics such as peak attenuation and lag time between precipitation and runoff indicating time delays (start, stop, peak, etc.) [79].

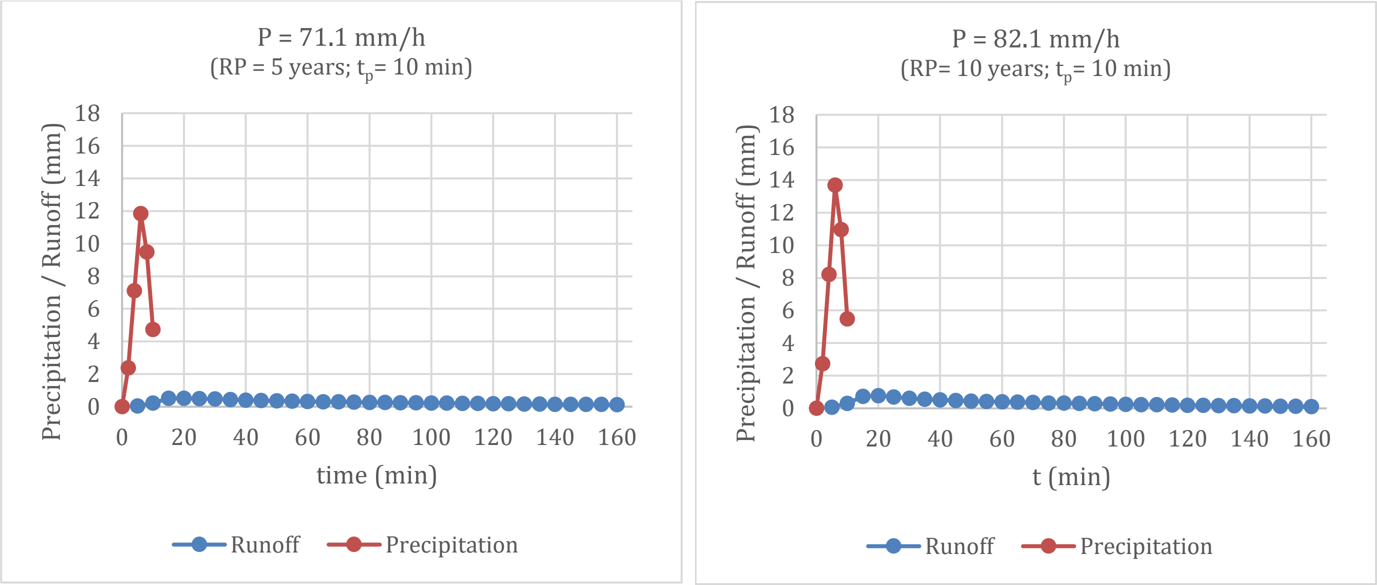
Determining the peak attenuation and peak delay required rainfall hyetographs for each event, which show rainfall intensity fluctuation over time (Figures 31-34).

The detention results are presented on Table 9 in the same way as the other instances, i.e. as the average of the three runs used for each test, but now representing runoff delay, peak attenuation, and peak delay.



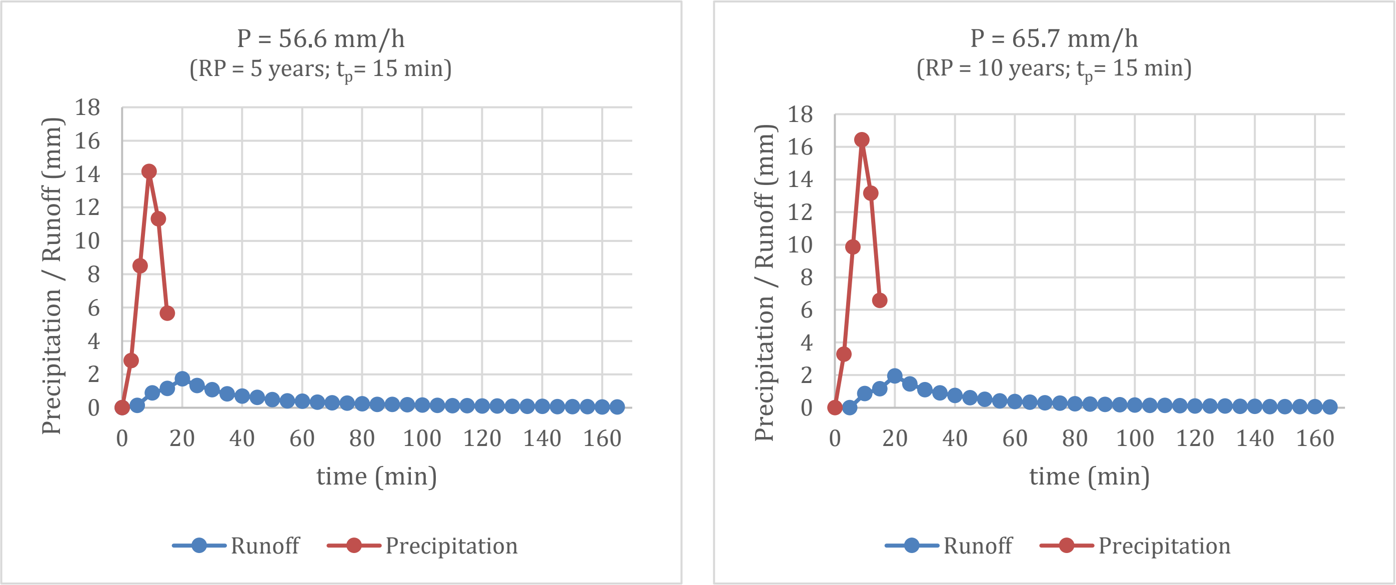
(a) (b)

Figure 31: Hyetograph vs runoff for (a) 1.75 L/min and (b) 2.00 L/min tests



(a) (b)

Figure 32: Hyetograph vs runoff for (a) 1.18 L/min and (b) 1.37 L/min tests.



(a) (b)

Figure 33: Hyetograph vs runoff for the (a) 0.94 L/min and (b) 1.10 L/min tests

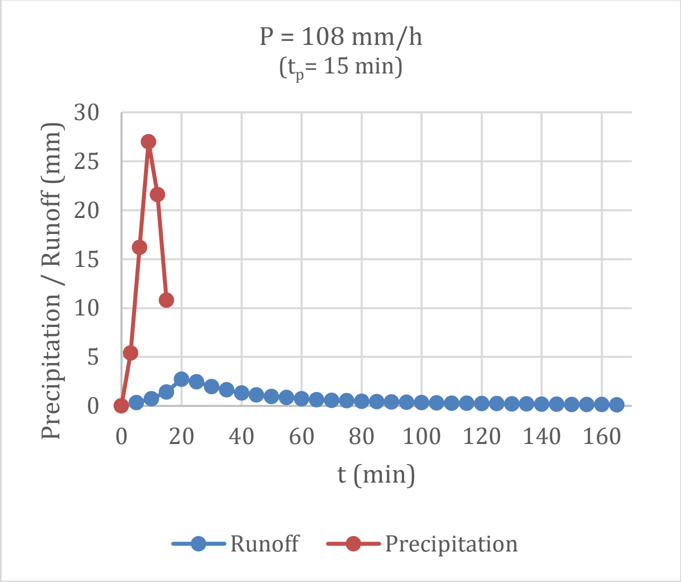


Figure 34: Hyetograph vs runoff for the 1.80 L/min test.

Table 9: Detention performance according to each RP considered

RP (years)	Duration of precipitation (min)	Q (L/min)	Total amount of rainfall (mm)	Runoff Delay (min)	Peak Attenuation (%)	Peak Delay (min)
5	5	1.75	8.7	4.03	86.4	12
	10	1.18	11.9	3.80	95.7	14
	15	0.94	14.2	4.33	87.8	11
10	5	2.00	10.0	3.70	92.4	12
	10	1.37	13.7	3.78	94.3	14
	15	1.10	16.4	6.21	88.2	11
ETA 21/0882	15	1.80	27.0	4.33	89.9	11

The use of the LECA-based GR system showed a significant reduction in peak attenuation, reaching a maximum of 95.7% (Table 9). This suggests that it can reduce the disparity between maximum rainfall and maximum runoff by up to 95.7%. Hence, the water from rainfall with a high peak flow rate infiltrates into the GR layers and is slowly drained, reducing the impact of this rainfall downstream, with a lower peak flow rate being drained.

Moreover, the earliest peak rainfall intensity led to superior attenuation of the peak runoff (5 and 10 min rainfall duration vs 15 min) (Figures 31-34 and Table 10). This is because when the rainfall peak arises as soon as possible (in relation to the complete rainfall duration), the GR will have been subjected to less water at that time, which means that the potential to detain and retain water in the GR for the remaining rainfall period will be greater. Therefore, peak attenuation is mostly caused both by the substrate's storage capacity (which is less than the field capacity) and the drainage layers [90].

Table 10: Peak runoff and rainfall values obtained

Q (L/min)	Peak Runoff (mm)	TP_{RO} (min)	I_{RO} (mm/h)	Peak Rainfall (mm)	TP_{RF} (min)	I_{RF} (mm/h)
2.00	0.66	15	2.64	8.74	3	174.9
1.80	2.73	20	8.20	27.0	9	180.0
1.75	0.81	15	3.22	5.92	3	118.5
1.37	0.78	20	2.33	13.7	6	136.9
1.18	0.52	20	1.55	11.8	6	118.5
1.10	1.95	20	5.84	16.4	9	109.5
0.94	1.72	20	5.17	14.1	9	94.32

As the LECA-based GR was able to attenuate 90.8% (mean) of peaks, it presents a better performance than a common vegetated extensive GR (59.22% of mean peak attenuation) [91].

Furthermore, our LECA-based GR system exhibited the ability to delay peak and runoff occurrences by a maximum of 14 and 6.21 min, respectively, which impact is evident is Figures 30-33. This fairly immediate response is not surprising given the test GR's limited dimensions (1 m^2) and shallow depth (25 mm). Also, the observed peak delay aligns with the findings of previous research conducted by Locatelli *et al.* [82], who also reported a simulated delay of less than 10 min for events occurring with RP of 5-10 y.

There are mainly two reasons for the delay. First off, after the substrate reaches its maximum retention point, it takes some time for it to start draining. Second, the water that is moving through the GR layers takes longer to exit the system. As a result, even after the rain has stopped, the runoff from the GR continues to outflow.

In addition, through Figures 31-34 it is possible to conclude that GRs are less effective at delaying runoff during shorter rainfall events, because the resulting runoff is also shorter than the remaining ones. Therefore, peak delay was found to vary based on the type of event, with greater rainfall intensities causing an overall decrease in the time delay, expecting for the 10 min rainfall duration events, as can be seen from Figure 35. This is due to the LECA-based GR systems lower retention and detention capacity for higher intensities.

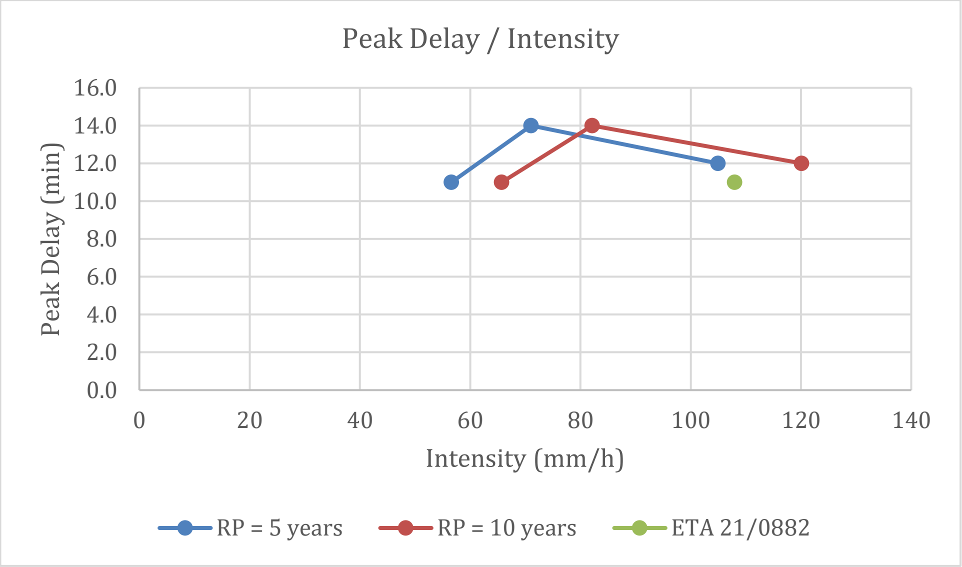


Figure 35: Peak delay vs intensity.

4.3 GR Runoff Quality

The water sample collected upstream of the system was tested once and is classified as potable water. The assessed parameters, namely turbidity, pH, conductivity, and BDO_5, were quantified and are displayed in Table 11.

Table 11: Water sample collected upstream

	pH	Turbidity (NTU)	Conductivity (µS/cm)	BDO_5 (mg/L)
Upstream	7.6	0.12	218.7	1.6

Table 12 shows the Portuguese water quality parameters for human consumption. Comparing Tables 11 and 12, it is possible to state that the incoming water is in accordance with the legal parameters and is, in fact, potable.

Table 12: Water quality for human consumption [92]

Parameter	Maximum recommended value	Maximum permitted value
BOD_5 (mg/L O_2)	-	-
Conductivity (µS/cm)	400	-
pH	6.5-8.5	9.5
Turbidity (NTU)	0.4	4

Water quality sampling was conducted during the timeframe of the experimental tests. The BDO_5 samples were collected at the beginning of the runoff of the first triplicate of each test, through the drainage pipe, and the other parameters from the water runoff collected into the graduated flask. The evolution of water quality is shown in Table 13. It shows the order in which the tests were carried out, making it easier to visualize the evolution of the quality of the runoff in response to the tests over time (and consequently to the total water that runed of from the system washing out the substrate).

Table 13: Water quality's evolution throughout the testing

Test	pH	Turbidity (NTU)	Conductivity (µS/cm)	BDO_5 (mg/L)
1	7.7	9.35	627	30.3
2	7.7	11.3	532	16.3
3	7.8	10.1	592	13.8
4	7.8	7.69	448	11.1
5	7.8	5.50	425	10.3
6	7.7	3.47	401	7.10
7	7.8	2.81	388	5.50

As expected, there is a decrease in the quality of the runoff water compared to the upstream water. This is due to the phenomenon of leaching: after rainfall, the water gradually passes through the substrate, extracting and dragging substances from this layer.

The quality of the water does indeed deteriorate as it passes through the GR, but this problem is mitigated over time. Moreover, the presence of certain substances, in addition to the low levels found, may favor the use of this water for irrigation or infiltration.

Table 14 is provided to compare the values obtained for the water quality of the runoff with Portuguese legislation.

Table 14: Water quality standards for urban, landscape, and irrigation use [93]

Parameter	Recreational and Landscape Uses	Street Washing	Firefighting Water	Cooling Water	Flushing cisterns	Car Washing	Irrigation (1)
pH	6.0-9.0	6.0-9.0	6.0-9.0	6.5-8.5	6.0-9.0	6.0-9.0	-
BOD_5 (mg/L O_2)	≤25	≤25	≤25	≤25	≤25	-	≤ 25
Turbidity (NTU)	≤5		≤5		≤5	≤5	-

(1) Irrigation with access restrictions (upland and agricultural uses): irrigation of crops consumed raw, growing above ground, and where the consumable part is not in direct contact with water; irrigation of agricultural crops intended for processing and not intended for human consumption, including recreational and sporting areas (e.g. golf courses).

When comparing the results of the water quality tests, it is clear that the pH was always within the regulations. In contrast, BDO_5 did not meet the limits established until the second test, whereas turbidity only complied with regulations starting from the fifth saturation (conducted before the 0.94 L/min test).

In terms of water quality, there is a minor increase in conductivity and turbidity readings between the second and third tests (including at the corresponding saturations), whereas a subsequent drop would be expected. This, however, is consistent with the literature. For example, Morgan *et al.* [94] discovered that turbidity levels in vegetated and non-vegetated systems fluctuated significantly over six months for the four tested substrates. They found that the peaks could be caused by the plug slowing solids transport or by the soil mixture in the plug taking until the second irrigation event to be carried through the medium. This could also be related to the fact that the growing media used in GRs drains faster than it stores [95].

5 Conclusion

5.1 Main Conclusions

The evaluation of a pilot GR system's hydrological performance was carried out at the Faculty of Engineering of the University of Porto (FEUP) Hydraulic Laboratory facilities. This assessment considers the system's capacity to retain rainwater, reduce runoff, and delay peak flows. Data were methodically gathered over the time frame of the experimental research study and then analyzed following the execution of the defined seven different events.

The hydrological performance of the LECA-based GR system is consistent with the literature's findings in terms of event intensity, as it exhibits more effective retention and detention of precipitation volumes during low-intensity events. However, the results for higher intensities were very positive. Therefore, the implementation of the LECA-based GR system yields promising results in terms of its ability to manage runoff from various amounts of rainfalls, functioning as an effective source control mechanism. Thus, if the total volume of water remains unchanged, increasing the runoff duration can lead to a significant decrease in the frequency of combined sewer overflows.

When considering the detention capability of the LECA-based GR system, the runoff characteristics are very appealing, even though source control systems usually have difficulty when there is strong but brief rainfall. The LECA-based GR system achieved a mean peak reduction of 90.8%, had a peak delay of up to 14 min and a runoff delay of 3.70-6.21 min. This means that by incorporating the LECA-based GR system in a downstream drainage system sizing process, the design flow is reduced by around 91%. This leads to smaller pipework and lower installation costs for the drainage system (assuming legislation allows this).

The objective of implementing this technology is not to solve the city's flooding problem entirely, but rather to lessen and delay the peak flow. Therefore, the LECA-based GR stands out as a viable option for upgrading existing roof areas due to its increased detention performance, coupled with its capacity to support rooftop detention without standing water pressure on the roof membrane (avoiding standing water concerns). It also brings advantages in comparison to conventional GR, as the evapotranspiration effect does not limit the LECA-based roof performance. Thus, it does not need systematic fertilization or irrigation during dry periods, making it suitable for use in many regions.

5.2 Future Developments

GRs present several advantages, one being the fact that it does not require any additional land outside the building where it will be used, unlike many sustainable ground-level drainage solutions. However, despite their popularity, there's a significant knowledge gap that is an obstacle to widespread its adoption. Most of their benefits remain theoretical, and its performance has mainly been studied in temperate zones. Furthermore, adding to the fact that the precipitation pattern in the Mediterranean region is changing due to the climate change scenario (short but intense precipitation events, that are predicted to occur more frequently), the criteria for selecting and designing GR have to be adapted to each region and the local meteorological conditions (based on the precipitation-flow pattern). As such, it is important to improve GR hydrological performance as a way to contribute to the sustainable urban water management. It is important to highlight that GR systems, if used alone, will not solve the floods problems of urban cities. Instead, their implementation coupled to other mitigation measures, will significantly help to minimize such events into urban scenario. Therefore, the suggestions presented below provide new opportunities to determine the performance of GRs based on climate change scenarios and worsening rainfall events, as well as to understand the true impact of their configuration (different areas, varying depth of layers) on the contribution to city resilience, through its quantification.

Therefore, it would be interesting to assess the real impact of this LECA-based GR system by designing the downstream drainage systems. Moreover, it would be useful to understand the effect of the variability of the GR humidity conditions in the days prior to testing, by monitoring it with sensors. This would allow to differentiate between the possible results for the runoff coefficient and the actual outcomes obtained. Furthermore, the previous situation could also be compared to a replica tested simultaneously under similar conditions, but with a vegetation layer.

In addition, it would be beneficial not only to increase the GR area, but also to test it over a longer period of time, particularly in an outdoor environment. While monitoring rainfall, or even testing the same rainfall simulation events but for the different GR types, varying the slope and depth of the drainage layer, in order to assess the differences in retention and detention performance. There is a study being conducted by Cristina Santos and Cristina Monteiro that aligns with the aforementioned suggestion. They will be testing an experimental LECA® framework in real environmental conditions, comparable in composition to the present LECA-based GR system but with a higher implementation area, over an extended period (1-2 years) in an outdoor setting, together with rainfall monitoring. This thesis marks the preliminary phase of the research that can now proceed.

6 Assessment of the Work Conducted

6.1 Achieved Objectives

Initially, this master's dissertation aimed to assess the hydrological performance of the kit Leca® Nutrofertil GR D, through the following research questions:

(1) What is the runoff coefficient and the retention and detention capacity of the extensive Leca® Nutrofertil GR D in a Mediterranean climate for design rainfall?

(2) How do previous rainfall events affect the performance of downstream drainage systems?

The initial goal was achieved, and the outcomes were highly favorable, aligning with the anticipated theoretical benefits. The utilization of LECA® as a drainage layer also provided advantages over traditional extensive GRs. However, there was no time to design the downstream systems due to the setbacks and delays experienced during the implementation of this thesis, including late material arrivals for the layers, selecting equipment for rainfall simulations in the most homogeneous way possible, and finding a flowmeter capable of reading the low design flows desired.

6.2 Further Studies Carried

Simultaneously with the completion of my master's thesis, I took part in an international conference hosted by the European Federation of Biotechnology, where I delivered a short talk titled "GRs as a Biotechnological Tool for Mitigating Urban Climate Change." The certificate of participation can be seen in Appendix A. Along with my supervisors, I also co-authored a review article entitled "GRs as an Urban NbS Strategy for Rainwater Retention: Influencing Factors-A Review" (included in Appendix A), and I'm currently working on an experimental paper about the studies developed in this master's thesis (in which the dimensioning of the downstream system will be made).

6.3 Final Appreciation

The findings of this thesis apply to the study of LECA-based GRs and are dependent on the specific precipitation patterns that occurred during the study period.

Consequently, the suitability and applicability of these findings to a particular environment in which they are to be implemented represents a significant additional challenge. In climates with different rainfall patterns, separated by periods of drought, this approach is expected to be effective, but it becomes challenging in regions with irregular and prolonged rainfall patterns with multiple peaks.

The efficiency of GR retention in managing stormwater during heavy rainfall is constrained by the inherent limitations of the system itself (physical characteristics of the system – substrate depth and composition, slope, …), whereas the detention performance can be greatly enhanced by the porosity of the LECA® drainage layer. It is important to remember that the aim of implementing this technology is not to completely solve the problem of flooding in the city, but rather to reduce and delay the peak flow.

However, as legislation is generally unable to keep up with the pace of development of these new technologies, the use of LECA-based GR systems to support downstream systems (e.g. pipe diameter reduction) is even more limited.

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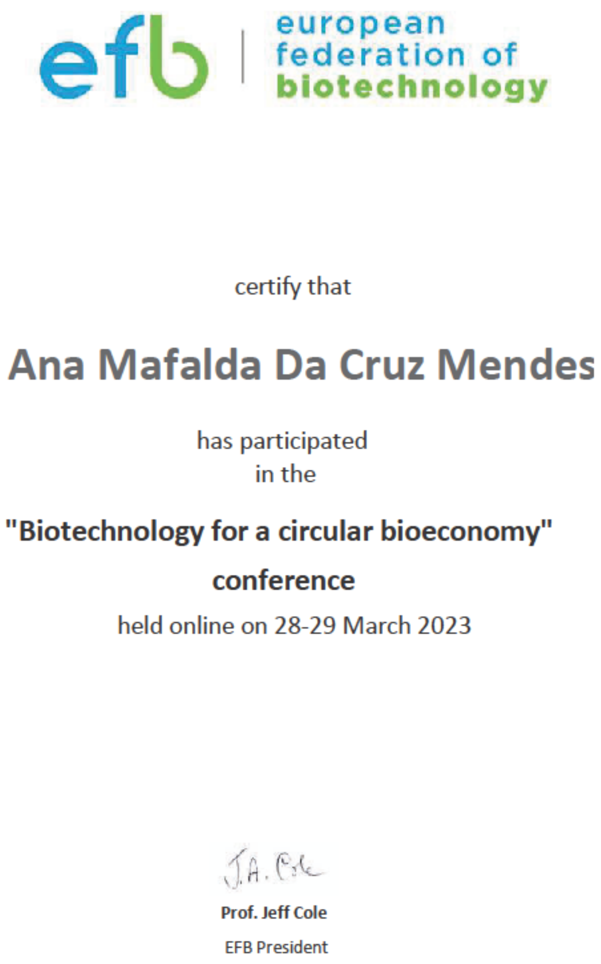
Appendix A

A.1 Short Talk

Figure A.1.1 shows the document certifying participation in the conference "Biotechnology for a circular bioeconomy".



efb | european federation of biotechnology

certify that

Ana Mafalda Da Cruz Mendes

has participated
in the

"Biotechnology for a circular bioeconomy"

conference

held online on 28-29 March 2023

J.A. Cole

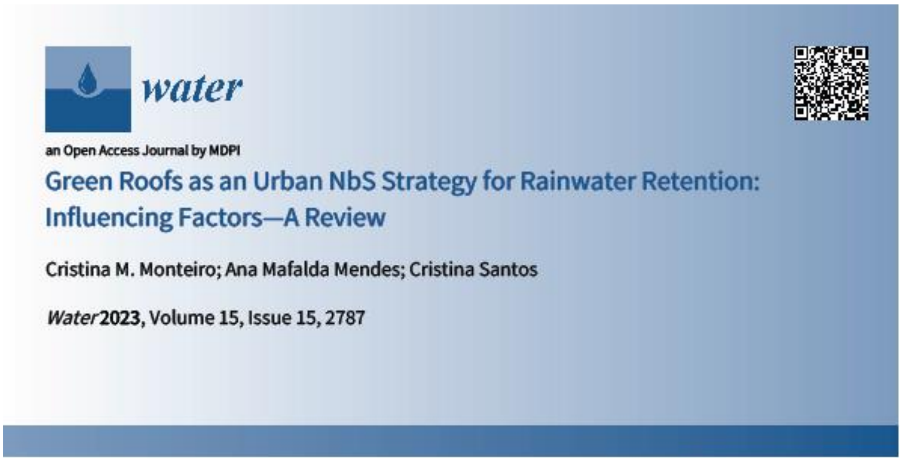
Prof. Jeff Cole

EFB President

Figure A.1. 1: Certify of participation.

A.2 Review Paper

The review article has been published in the peer-reviewed international journal *Water*, and it can be accessed by utilizing the provided QR Code (Figure A.2.1).



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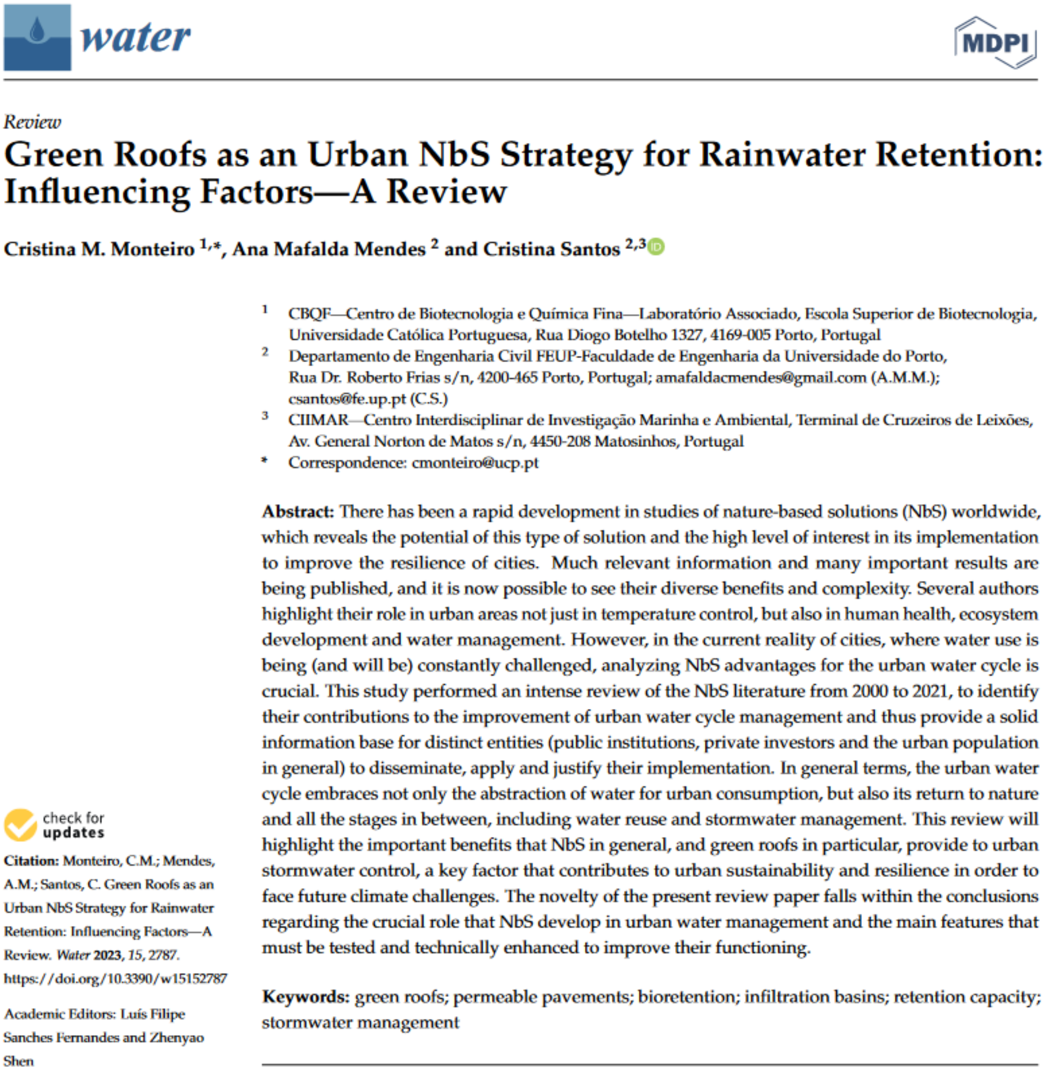
Water 2023, Volume 15, Issue 15, 2787



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Review

Green Roofs as an Urban NbS Strategy for Rainwater Retention: Influencing Factors—A Review

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Abstract: There has been a rapid development in studies of nature-based solutions (NbS) worldwide, which reveals the potential of this type of solution and the high level of interest in its implementation to improve the resilience of cities. Much relevant information and many important results are being published, and it is now possible to see their diverse benefits and complexity. Several authors highlight their role in urban areas not just in temperature control, but also in human health, ecosystem development and water management. However, in the current reality of cities, where water use is being (and will be) constantly challenged, analyzing NbS advantages for the urban water cycle is crucial. This study performed an intense review of the NbS literature from 2000 to 2021, to identify their contributions to the improvement of urban water cycle management and thus provide a solid information base for distinct entities (public institutions, private investors and the urban population in general) to disseminate, apply and justify their implementation. In general terms, the urban water cycle embraces not only the abstraction of water for urban consumption, but also its return to nature and all the stages in between, including water reuse and stormwater management. This review will highlight the important benefits that NbS in general, and green roofs in particular, provide to urban stormwater control, a key factor that contributes to urban sustainability and resilience in order to face future climate challenges. The novelty of the present review paper falls within the conclusions regarding the crucial role that NbS develop in urban water management and the main features that must be tested and technically enhanced to improve their functioning.

Keywords: green roofs; permeable pavements; bioretention; infiltration basins; retention capacity; stormwater management

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Citation: Monteiro, C.M.; Mendes, A.M.; Santos, C. Green Roofs as an Urban NbS Strategy for Rainwater Retention: Influencing Factors—A Review. *Water* **2023**, *15*, 2787. https://doi.org/10.3390/w15152787

Academic Editors: Luís Filipe Sanches Fernandes and Zhenyao Shen

Figure A.2. 1: Open Access Journal Published.

A.2 Experimental Paper Resulting From Thesis Work

At the time of submission of this thesis, an experimental article on the work carried out is in preparation. Besides, the article will include and evaluate the effects of the implementation of the LECA-based GR system on the design of water drainage systems downstream. The paper will be submitted to the *Journal of Environmental Management*.

Appendix B

B.1 Other Information

In some of the tests carried out, mushroom growth was noticed on the LECA-based GR system (Figure A.3.1). Usually, the mushrooms would only last a day, but a new one would grow on the following day. This lasted for about two weeks.

Figure B.1. 1: Mushroom growth on the LECA-based GR pilot system.