



FIRST-YEAR MONITORING OF THE HYDROLOGICAL RESPONSE OF A MODULAR BLUE-GREEN ROOF UNDER MEDITERRANEAN CLIMATE

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Abstract

Blue–Green Roofs (BGRs) have emerged as an advanced evolution of conventional green roofs by integrating vegetated substrates with engineered detention layers to improve stormwater management and enhance the environmental performance of buildings. Although their adoption is increasing, long-term experimental observations under Mediterranean climatic conditions remain limited. This study presents the first-year monitoring results of a full-scale modular Blue–Green Roof installed at the University of Tuscia (Central Italy). The system was continuously monitored from July 2025 to June 2026 through high-resolution measurements of precipitation, runoff, and substrate volumetric water content. The analyses focused on the seasonal hydrological response of the roof, with particular emphasis on runoff retention and substrate volumetric water content dynamics. During the monitoring period, the roof received 1017.8 mm of precipitation while generating only 255.2 mm of runoff, corresponding to an annual Retention Index of 0.75. The system exhibited a clear seasonal variability, with the highest retention efficiencies recorded during spring and summer and lower values during the wetter winter months. Continuous substrate volumetric water content observations confirmed the strong influence of Mediterranean climatic conditions on the hydrological response of the roof. These findings demonstrate the effectiveness of modular Blue–Green Roofs as Nature-Based Solutions for reducing rooftop runoff and improving the hydrological performance of sustainable buildings, while providing a valuable experimental dataset for future performance assessment, hydrological modelling and the optimization of Blue–Green Roof design.

Key words: Blue–green roof, Stormwater management, Experimental monitoring, Mediterranean climate, Nature-based solutions

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1. INTRODUCTION

Urbanization and climate change are increasing the frequency and severity of urban flooding while exacerbating heat stress and environmental degradation. The widespread replacement of natural surfaces with impervious materials alters the hydrological response of urban catchments, leading to larger runoff volumes and higher peak discharges during storm events. To address these challenges, Nature-based Solutions (NbS) have gained considerable attention as sustainable strategies capable of enhancing urban resilience while providing multiple environmental and societal benefits [1–4].

Among NbS, green roofs (GRs) are recognized as one of the most effective measures for managing stormwater at the building scale. By combining vegetation, engineered substrates, and drainage layers, GRs can reduce runoff volumes, delay peak flows, improve building energy efficiency, mitigate urban heat island effects, and promote urban biodiversity [5,6].

However, their hydrological performance is influenced by several interacting factors, including substrate characteristics, vegetation type, rainfall properties, antecedent moisture conditions, and local climatic conditions [7–9].

Mediterranean regions represent a particularly challenging environment for green roof applications because prolonged dry periods alternate with short, high-intensity rainfall events. Under these conditions, the seasonal evolution of substrate volumetric water content strongly affects the available storage capacity and consequently the runoff retention efficiency of the system [10,11].

Continuous field observations are therefore essential for understanding the long-term hydrological behaviour of green roofs operating under Mediterranean climates.

Blue–Green Roofs (BGRs) represent an evolution of conventional green roofs by incorporating engineered detention layers beneath the vegetated substrate. These additional storage elements temporarily retain excess rainfall, delay runoff release, and improve stormwater management without substantially increasing substrate thickness [12–14].

Although recent studies have demonstrated the hydrological potential of BGRs through both experimental investigations and numerical modelling, long-term field observations remain limited, particularly for modular systems installed under Mediterranean climatic conditions [11,13,15,16].

This paper presents the first-year monitoring results of a full-scale modular blue–green roof installed at the University of Tuscia (Central Italy). Continuous measurements of rainfall, runoff, and substrate volumetric water content were used to characterize the seasonal hydrological response of the system.

As a preliminary contribution, the study focuses on rainfall retention performance and substrate volumetric water content dynamics, providing experimental evidence that will support future investigations on water balance, storage processes, and hydrological modelling.

2. DATA AND METHODS

2.1 Study site and experimental roof

The study was carried out at the Hydrological Experimental Site of the University of Tuscia, located in Viterbo, Central Italy. The experimental facility hosts a full-scale modular Blue–Green Roof (BGR) manufactured by Sempergreen (The Netherlands), designed to combine vegetation with engineered stormwater detention.

The investigated BGR, shown in Figure 1, covers an area of 16 m² (4 × 4 m) and has a total thickness of approximately 170 mm. From top to bottom, the roof assembly consists of a 25 mm Sempergreen Sedum Blanket, providing immediate vegetation cover and rainfall interception; a 40 mm S40 Substrate Roll, which acts as the primary growing medium; a 40 mm Urbanscape Green Roll, made of stone wool and designed to increase water retention while promoting root development; a 60 mm HC60 Storage Layer, providing the main temporary stormwater storage capacity; and a 5 mm T5 Detention Layer, installed directly above the waterproofing membrane to regulate the release of excess water. This passive multilayer configuration combines vegetation, substrate, retention and storage components to temporarily retain rainfall, reduce runoff peaks and improve the hydrological performance of the roof without requiring active flow-control devices. The roof is installed on an elevated wooden structure with a surface slope of approximately 2%, allowing excess water to drain towards a monitored outlet.



Figure 1. The investigated Blue–Green Roof.

2.2. Monitoring system

The BGR has been continuously monitored since June 2025. The analyses presented in this paper refer to the first complete monitoring year, spanning from 1 July 2025 to 30 June 2026.

Precipitation was measured using the nearby macro-rain gauge station installed at the experimental site [17]. Roof runoff was continuously monitored at the outlet



through an automatic tipping-bucket flow gauge, while substrate volumetric water content was measured using a dielectric soil moisture sensor installed at the bottom of the S40 Substrate Roll. Soil temperature was also monitored for environmental characterization.

All sensors were connected to a Campbell Scientific CR1000X data logger, and measurements were acquired every five minutes. The original observations were subsequently aggregated to daily values for the analyses presented in this work.

2.3 Data analysis

The preliminary hydrological performance of the roof was evaluated using continuous observations of precipitation, runoff, and substrate volumetric water content.

Runoff retention was quantified by means of the Retention Index (RI), defined as [18]:

$$RI = 1 - Q/P \quad (1)$$

where P (mm) is the daily precipitation depth and Q (mm) is the corresponding daily runoff depth measured at the roof outlet.

To investigate the seasonal hydrological behaviour of the system, daily substrate volumetric water content observations were analysed together with precipitation and runoff records. Annual and seasonal runoff coefficients together with the Retention Index were computed to assess the overall stormwater mitigation performance of the roof.

3. RESULTS

3.1 Hydro-meteorological conditions

During the monitoring period (1 July 2025–30 June 2026), the experimental site received a cumulative precipitation depth of 1017.8 mm, approximately 28% higher than the long-term annual average (810 mm yr⁻¹) recorded at the site [17]. The monitoring period exhibited the characteristic seasonal variability of Mediterranean climates, with prolonged dry conditions during summer followed by a marked increase in rainfall from late autumn to early spring.

The monthly distribution of precipitation and roof runoff is presented in Figure 2. Winter accounted for more than half of the annual precipitation (537.8 mm, corresponding to approximately 52% of the yearly total), whereas spring and summer received 117.2 mm and 201.0 mm, respectively. January 2026 was by far the wettest month, with 331.8 mm of precipitation, while rainfall remained limited throughout the summer months despite occasional rainfall events.

A cumulative runoff depth of 255.1 mm was measured at the roof outlet during the study period, corresponding to an annual runoff coefficient of 0.251. Monthly runoff closely followed the seasonal distribution of precipitation, with the highest discharges recorded during January (117.3 mm) and February (59.4 mm). Conversely, runoff



remained negligible during most summer months and was absent in April, despite measurable precipitation, indicating an efficient retention of rainfall by the roof under relatively dry conditions.

Overall, the comparison between monthly precipitation and runoff highlights the substantial runoff mitigation provided by the monitored BGR throughout the monitoring period. While runoff increased during the wetter months, it consistently represented only a fraction of the incident rainfall, confirming the effectiveness of the system in reducing stormwater discharge under Mediterranean climatic conditions.

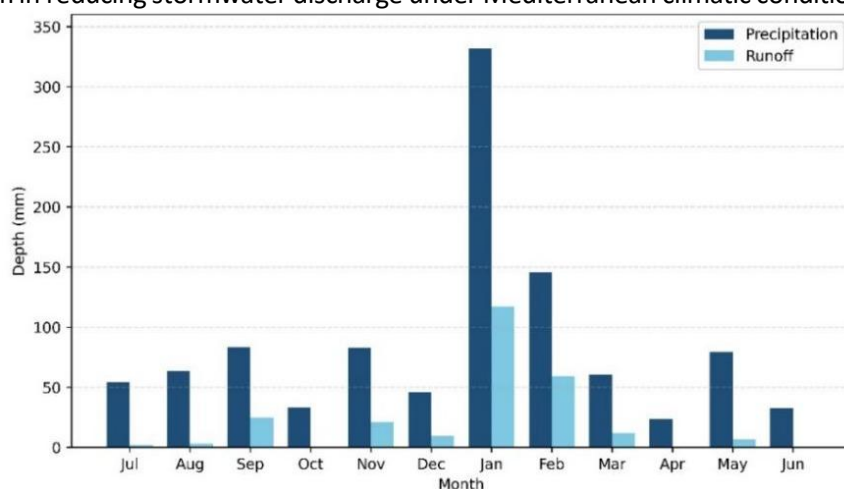


Figure 2. Monthly precipitation (P) and runoff (Q) measured during the monitoring period (July 2025–June 2026). The figure highlights the seasonal distribution of rainfall and the corresponding runoff generated by the monitored BGR.

3.2 Seasonal evolution of substrate volumetric water content

The seasonal distribution of daily substrate volumetric water content (θ) is reported in Figure 3. Water content exhibited a pronounced seasonal variability, reflecting the alternation between dry and wet periods typical of Mediterranean climates.

The driest conditions occurred during summer, when the median substrate volumetric water content was approximately $0.17 \text{ m}^3 \text{ m}^{-3}$ and daily values frequently remained below $0.15 \text{ m}^3 \text{ m}^{-3}$, reaching minimum values close to $0.08 \text{ m}^3 \text{ m}^{-3}$. These low water content levels resulted from the combined effect of limited rainfall and high atmospheric evaporative demand, which progressively depleted the water stored within the growing medium.

Substrate volumetric water content conditions progressively increased during autumn, with a median value of approximately $0.24 \text{ m}^3 \text{ m}^{-3}$. This season also exhibited the largest interquartile range, reflecting the transition from dry summer conditions to the wetter period characterized by increasingly frequent rainfall events. Daily volumetric water content values ranged from approximately 0.09 to $0.35 \text{ m}^3 \text{ m}^{-3}$, indicating repeated wetting and drying cycles.

The highest volumetric water content levels were observed during winter, when the median value reached approximately $0.33 \text{ m}^3 \text{ m}^{-3}$ and most observations remained

above $0.30 \text{ m}^3 \text{ m}^{-3}$. Maximum values approached $0.37 \text{ m}^3 \text{ m}^{-3}$, indicating that the substrate remained close to saturation during prolonged wet periods.

During spring, substrate volumetric water content progressively decreased as rainfall became less frequent and evapotranspiration increased. Although the seasonal median ($\approx 0.16 \text{ m}^3 \text{ m}^{-3}$) was comparable to that observed during summer, the distribution was considerably wider, with values ranging from approximately 0.09 to $0.33 \text{ m}^3 \text{ m}^{-3}$. This behaviour reflects the alternation of rainfall events and subsequent drying phases, which produced a greater variability than that observed during the persistently dry summer period.

Overall, the boxplots clearly demonstrate that substrate volumetric water content followed a well-defined seasonal cycle, with progressively increasing water content from summer to winter and a subsequent decline during spring. These observations indicate that the hydrological state of the roof varied substantially throughout the year and provide a physical explanation for the seasonal differences in runoff generation and retention performance discussed in the following section.

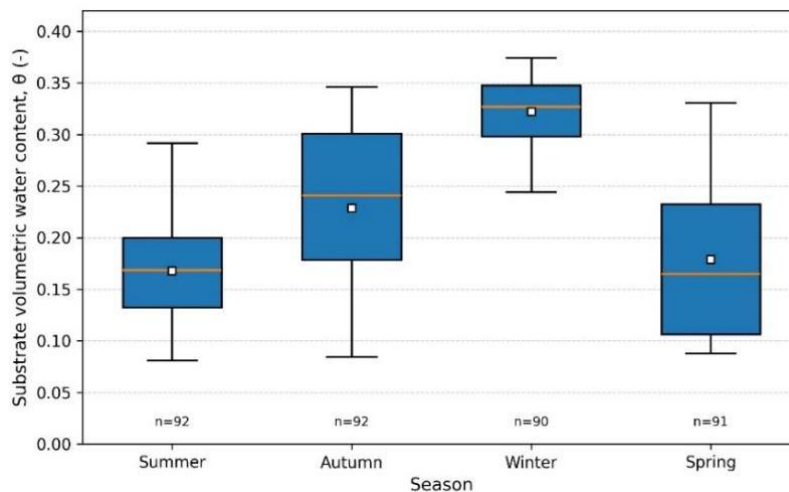


Figure 3. Seasonal boxplots of daily substrate volumetric water content (θ) measured in the BGR during the monitoring period (1 July 2025–30 June 2026). Boxes represent the interquartile range, the central line the median, whiskers the data range excluding outliers, and open squares the seasonal mean.

3.3 Hydrological performance

The monitored BGR exhibited a high capacity to reduce rooftop runoff throughout the monitoring period. Over the one-year observation period, the roof received a cumulative precipitation depth of 1017.8 mm while generating only 255.1 mm of runoff, corresponding to an annual runoff coefficient of 0.251 and an overall Retention Index (RI) of 0.749. These values indicate that approximately three quarters of the incident precipitation were retained within the roof system, confirming the effectiveness of the modular Blue–Green Roof in mitigating stormwater runoff under Mediterranean climatic conditions.

Seasonal differences in retention performance were also evident. The highest runoff mitigation was observed during spring (RI = 0.944), followed by summer (RI = 0.853) and autumn (RI = 0.811), whereas the lowest retention efficiency occurred during



winter (RI = 0.649). Although winter accounted for more than half of the annual precipitation, the roof was still able to retain nearly two thirds of the incoming rainfall, demonstrating a satisfactory hydrological performance even under prolonged wet conditions.

The relationship between daily precipitation and runoff is shown in Figure 4, where each point represents a rainfall day with daily precipitation greater than or equal to 4 mm. As expected, runoff generally increased with increasing rainfall depth; however, all observations remained well below the $Q = P$ reference line, confirming that the roof consistently reduced runoff generation irrespective of rainfall magnitude.

A marked dispersion of the observations can be observed for rainfall depths ranging approximately from 10 to 30 mm, where similar precipitation amounts generated substantially different runoff volumes. Moreover, the seasonal clustering of the data reveals a clear influence of climatic conditions on roof performance. Events recorded during spring and summer generally produced lower runoff volumes than rainfall events of comparable magnitude occurring during autumn and winter. This behaviour is consistent with the seasonal variability of substrate volumetric water content discussed in the previous section and highlights the importance of antecedent moisture conditions in controlling the runoff response of Blue–Green Roof systems.

Overall, the monitored system demonstrated stable runoff mitigation throughout the entire monitoring period, confirming the suitability of modular Blue–Green Roofs as an effective Nature-Based Solution for improving stormwater management at the building scale.

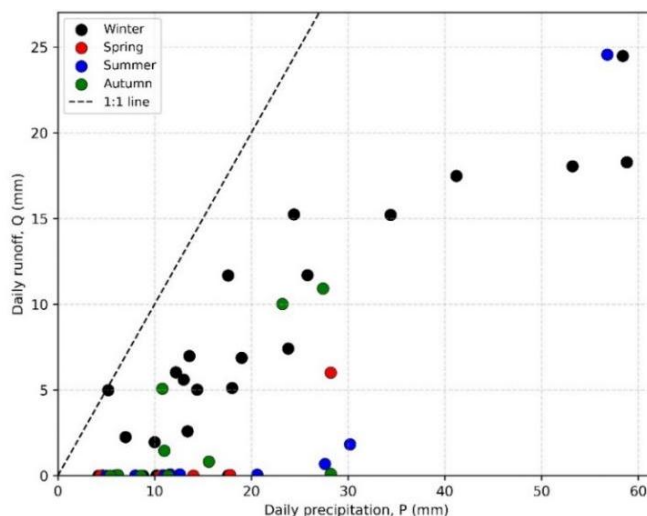


Figure 4. Scatter plot of daily runoff (Q) versus daily precipitation (P) for rainfall days with $P \geq 4$ mm. Colours identify the four seasons, while the dashed line indicates the 1:1 relationship. The separation of the observations below the 1:1 line demonstrates the runoff retention capacity of the Blue–Green Roof and reveals the seasonal variability of its hydrological performance.

4. DISCUSSION

The first year of monitoring demonstrates that the investigated modular Blue–Green Roof provides an effective solution for mitigating rooftop stormwater runoff



under Mediterranean climatic conditions. Despite a monitoring period characterized by annual precipitation approximately 25% higher than the long-term average, the system retained about three quarters of the incoming rainfall, confirming its capability to reduce the hydrological impact of buildings on urban drainage systems.

The observed annual retention efficiency is consistent with the range reported for multilayer Blue–Green Roofs operating under different climatic conditions, where long-term retention values generally vary between 60% and 80% depending on roof configuration, storage capacity and rainfall regime [11–16]. These findings further support previous investigations demonstrating that the introduction of dedicated detention layers substantially improves the hydrological performance of extensive vegetated roofs without requiring thicker substrates [11–14, 19,20].

A clear seasonal variability emerged from both substrate volumetric water content observations and runoff measurements. The highest retention efficiencies were recorded during spring and summer, whereas winter exhibited larger runoff volumes associated with more frequent and persistent rainfall. These results confirm that Mediterranean climatic conditions strongly influence the performance of Blue–Green Roofs and should therefore be explicitly considered during design and performance assessment. Similar seasonal behaviour has been reported for other green roof systems operating under semi-arid and Mediterranean climates [10,11].

From the perspective of sustainable building design, the results demonstrate that Blue–Green Roofs can effectively contribute to the implementation of Nature-Based Solutions by reducing runoff generation directly at the building scale. Unlike conventional stormwater management approaches, which convey runoff downstream, detention roofs temporarily retain rainfall within the building envelope, decreasing the hydraulic load transferred to urban drainage networks during rainfall events. This characteristic makes these systems particularly suitable for climate-adaptation strategies aimed at increasing the resilience of densely urbanized areas [1–4].

The continuous monitoring approach adopted in this study also highlights the importance of collecting long-term experimental datasets for evaluating the real performance of innovative green building technologies. Performance-based assessments derived from field observations provide valuable information for designers, planners and decision makers, supporting the optimization of roof configurations and facilitating the wider implementation of Blue–Green Roofs in sustainable and climate-resilient buildings.

Although this paper presents only the first monitoring results, the collected dataset represents a robust experimental basis for future investigations. Further analyses will focus on the detailed characterization of storage processes, event-scale hydrological behaviour and physically based modelling, providing additional support for the design and optimization of Blue–Green Roof systems.

5. CONCLUSION

This study presented the first-year hydrological monitoring results of a full-scale modular Blue–Green Roof installed under Mediterranean climatic conditions. Continuous observations of precipitation, runoff and substrate volumetric water



content provided an experimental assessment of the roof performance over a complete annual cycle.

The monitored system demonstrated a high capacity for stormwater mitigation, retaining approximately 75% of the annual precipitation despite a monitoring period characterized by rainfall well above the long-term average. The results also highlighted a marked seasonal variability, with the highest retention efficiencies observed during spring and summer and lower values during the wetter winter months. These seasonal differences were consistent with the observed evolution of substrate volumetric water content throughout the monitoring period.

The experimental evidence confirms that modular Blue–Green Roofs can effectively contribute to reducing rooftop runoff while enhancing the hydrological performance of buildings. As Nature-Based Solutions integrated into the building envelope, these systems represent a practical strategy for improving the climate resilience of urban areas and supporting more sustainable stormwater management.

The continuous monitoring dataset presented in this work provides a valuable benchmark for evaluating the long-term performance of Blue–Green Roofs operating under Mediterranean climatic conditions. Future work will extend the present analysis by investigating the mechanisms controlling roof hydrological behaviour through detailed water balance analyses, event-scale investigations and physically based modelling, thereby supporting the optimization of Blue–Green Roof design and their wider implementation in sustainable buildings.

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