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Hydrological Performance of Green Roofs in Urban Areas Exposed to Extreme Rainfall Events

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Abstract

How do green roofs influence stormwater runoff in urban areas exposed to increasingly extreme rainfall events? This paper evaluates hydrological performance of green roofs under changing climatic conditions characterized by more frequent short-duration, high-intensity precipitation. The study focuses on Central European urban environments, where rainfall extremes increasingly challenge conventional drainage systems. The methodological approach combines analysis of long-term precipitation time series with synthesis of theoretical knowledge and experimental data on green roof hydrological responses to different rainfall types. Results demonstrate that green roofs enhance rainfall retention and delay runoff peaks during common and moderately intense precipitation events, reducing instantaneous loads on urban drainage infrastructure. However, during extreme, rapidly occurring rainfall events, retention capacity becomes limited, revealing functional thresholds. From an urban planning and architectural perspective, these findings highlight the need for systematic implementation of green roofs as an integral component of climate adaptation strategies reducing urban vulnerability to rainfall extremes.
Keywords: Climate Change Adaptation; Green Roofs; Stormwater Runoff; Extreme Rainfall Events; Hydrological Performance; Rainfall Retention; Runoff Delay.

1. Introduction

1.1 Climate Change, Urbanized Areas and Rainfall Extremes

Urbanized areas are characterized by a substantially altered hydrological regime. The replacement of original soil and vegetated surfaces with buildings, roads, parking areas, and other impervious structures reduces rainfall infiltration and increases surface runoff (Yan et al., 2025). As a result, rainfall water in built-up areas concentrates more rapidly and enters sewerage and drainage systems in larger volumes. This process increases the sensitivity of urbanized catchments to short-duration rainfall events, particularly where the proportion of impervious surfaces is high.
The significance of this issue is increasing under conditions of climate change. Current research indicates that climate change contributes to the more frequent occurrence of extreme weather events, including intense rainfall, which can increase stormwater runoff volumes in urbanized areas and overload existing infrastructure (Breulmann et al., 2025). From the perspective of drainage performance, the total rainfall depth is not the only decisive factor; rainfall intensity, duration, and temporal distribution are particularly important. Short-duration, high-intensity rainfall events can generate a rapid runoff response even when their total rainfall depth is not exceptionally high.
Conventional stormwater drainage systems have long been based primarily on the rapid conveyance of water away from built-up areas. However, under increasing urbanization and extreme rainfall events, this approach encounters capacity limitations. Therefore, growing importance is being placed on decentralized measures that can capture, slow down, or temporarily store rainfall water as close as possible to the point where it falls. Roof-based stormwater management can also reduce hydrological connectivity between roof surfaces and the drainage network, thereby limiting their direct contribution to flood runoff (Lu et al., 2025).

1.2 Green Roofs as Blue-Green Adaptation Infrastructure

Green roofs represent one of the adaptation elements of blue-green infrastructure that can be integrated directly into building structures. Their significance lies in the use of existing roof surfaces without the need for additional land take, which is particularly important in densely built-up areas. A green roof transforms the roof envelope from an almost impervious surface into a multi-layered system capable of intercepting, temporarily storing, and gradually releasing rainfall water.

The hydrological function of a green roof is based on a combination of several processes. Part of the rainfall water is intercepted by vegetation, part infiltrates into the substrate, part is temporarily retained within the pore space and drainage or retention layers, and part subsequently returns to the atmosphere through evapotranspiration (Nawaz et al., 2015). Compared with a conventional roof, a green roof can reduce the total runoff volume, delay the onset of runoff, and reduce or shift the runoff peak (Mentens et al., 2006). These effects are particularly significant during common and moderately intense rainfall events, when the substrate and retention layers have sufficient available storage capacity.

However, the hydrological performance of green roofs is not constant. It depends on the system configuration, substrate depth and properties, vegetation type, retention layer, roof slope, climatic conditions, and antecedent moisture conditions. A global synthesis of experimental data indicates that green roof retention rates vary widely, ranging from 0 % to 100 %, with an average event-based retention performance of approximately 62 % (Zheng et al., 2021). Such a wide range of values confirms that green roofs cannot be evaluated using a single universal indicator without considering rainfall, climatic, and structural conditions.

1.3 Research Gap and Aim of the Study

A key issue remains the behaviour of green roofs during extreme short-duration rainfall events. During common rainfall events, green roofs can contribute substantially to rainfall retention and stormwater runoff delay; however, during intense rainfall events, their retention capacity may be rapidly exhausted. Long-term observations of an extensive green roof show that not every extreme rainfall event automatically leads to extreme runoff; in the analysed dataset, only approximately 69 % of extreme rainfall events generated extreme stormwater runoff, with the differences mainly associated with the water content in the substrate layer of the green roof prior to the rainfall event (Paus & Braskerud, 2024).

This means that the assessment of green roofs cannot be based solely on rainfall intensity or the return period of a rainfall event. Antecedent moisture conditions, the available retention capacity of the green roof, and the ability of the green roof system to delay stormwater runoff even after partial or complete saturation are also decisive. Model-based assessments of future climate scenarios further indicate that green roofs may remain effective during non-extreme rainfall events, whereas their retention performance during extreme events may decrease substantially, particularly under more humid climatic conditions (Gill et al., 2007).

The aim of this paper is to evaluate the hydrological performance of green roofs in urbanized areas exposed to increasingly extreme rainfall events. The analysis focuses on three aspects: stormwater runoff volume reduction, runoff peak delay, and the identification of functional thresholds during short-duration, high-intensity rainfall events. The paper is based on a synthesis of experimental, modelling, and long-term observational studies and interprets their relevance for climate adaptation in built-up areas, architectural design, and decentralized stormwater management.

2. Materials and Methods

2.1 Study Design and Source Material

The study is designed as a comparative synthesis of published experimental, monitoring, and modelling studies focused on evaluating the hydrological performance of green roofs in urbanized areas exposed to extreme rainfall events. The selected approach draws on experimental measurements, long-term observations, modelling studies, and review papers addressing retention, detention, and the runoff response of green roofs. Such an approach is particularly appropriate because the hydrological performance of green roofs is strongly conditioned by climatic conditions, system configuration, rainfall characteristics, and the antecedent moisture state of the green roof assembly and therefore requires evaluation within the broader context of the specific conditions involved. The analytical framework of the study links rainfall input, the processes occurring within the green roof assembly, and the resulting hydrological response of the green roof system, as shown in figure (Figure 1.)

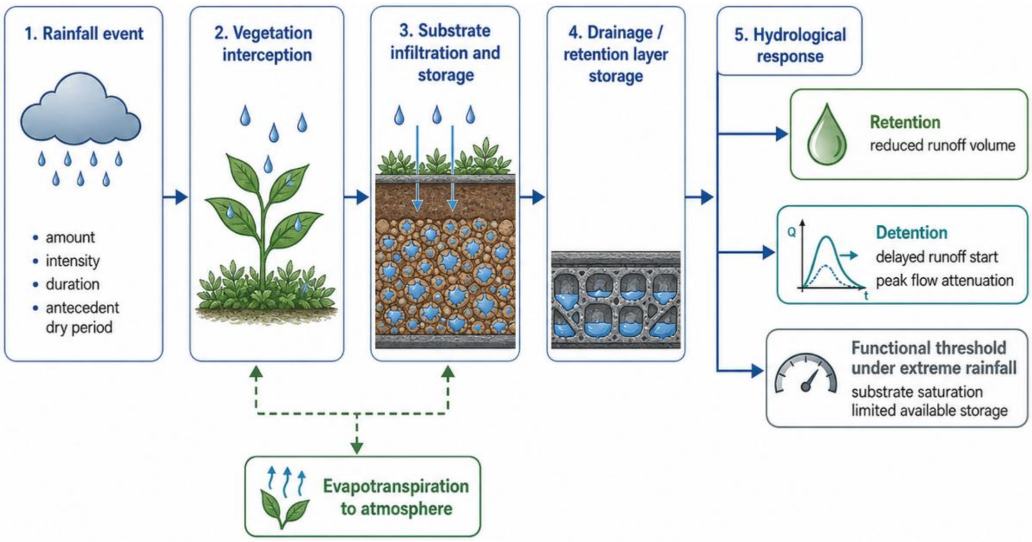

Figure 1. Conceptual framework of green roof hydrological response to rainfall events (Developed by the Authors).

The analysis included sources that directly address the hydrological response of green roofs to rainfall events. Emphasis was placed on studies based on measured runoff from real-scale or experimental green roofs, as these provide evidence on actual retention, runoff delay, and runoff peak reduction. Comprehensive monitoring of an extensive green roof in a temperate climate is relevant because such green roof systems better represent real operating conditions than small laboratory samples or test modules assessed under separate experimental conditions (Nawaz et al., 2015). Long-term observations were also considered, as they capture a broader range of both common and extreme rainfall events and allow the behaviour of a green roof to be evaluated over time (Paus & Braskerud, 2024).
A separate group of sources consisted of modelling and simulation studies. These were used primarily to assess the behaviour of green roofs under different climate scenarios, design configurations, and future climate change conditions. Model-based assessments make it possible to examine the influence of parameters such as substrate depth, substrate type, roof slope, rainfall intensity, and retention capacity, which would be difficult to vary independently in field monitoring (Kim et al., 2021). For assessing the future performance of green roofs, studies using long-term climate data and rainfall projections were particularly relevant, as they allow differences between non-extreme and extreme rainfall events to be evaluated under changing climatic conditions (Yan et al., 2025).

2.2 Evaluation Criteria

The hydrological performance of green roofs was evaluated using three main criteria: rainfall retention, runoff detention, and system functional thresholds during extreme rainfall events. Retention was understood as the portion of rainfall water captured within the green roof assembly during an event that does not immediately runoff from the roof. In the literature, retention performance is most expressed as the proportion of rainfall retained by a green roof at the scale of an individual event or over a longer period (Zheng et al., 2021). A global synthesis of experimental data indicates that green roof retention rates range from 0 % to 100 %, with an average event-based retention performance of approximately 62 % (Zheng et al., 2021). The evaluation criteria used in this study are structured around three interrelated hydrological effects: retention, detention, and the functional threshold under extreme rainfall conditions, as shown in figure (Figure 2.)

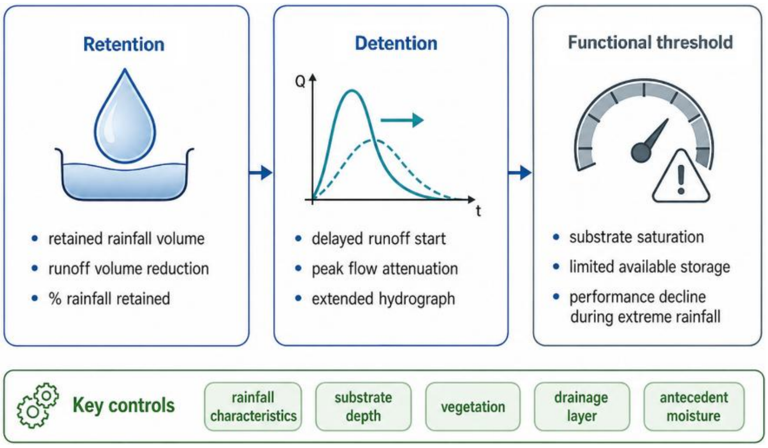

Figure 2. Evaluation criteria used for hydrological assessment of green roofs (Developed by the Authors).

Detention was understood as the temporary storage of water within the green roof system that modifies the temporal pattern of runoff without necessarily resulting in a permanent reduction in the total runoff volume. In the hydrological assessment of green roofs, it is important to distinguish between retention and detention, as retention is primarily associated with runoff volume reduction, whereas detention is mainly reflected in runoff delay, runoff peak reduction, and the prolongation of the runoff response (Stovin et al., 2017). Since individual detention indicators may be sensitive to the temporal resolution, the shape of the rainfall hyetograph, and antecedent moisture conditions, detention was not assessed using a single indicator only, but through a broader interpretation including the delay in runoff onset, peak reduction, and changes in the hydrograph shape.
The third evaluation criterion was the functional limitation of green roofs during extreme rainfall events. In this study, the functional threshold is defined as the state in which the retention capacity of the substrate or retention layer is depleted to such an extent that the system can no longer substantially reduce runoff volume, and its effect shifts primarily toward short-term water detention. Experimental results indicate that when the retention layer is nearly full, retention performance decreases markedly, and the runoff behaviour of the green roof may approach that of conventional roofing systems. (Breulmann et al., 2025). Long-term observations further suggest that the relationship between extreme rainfall and extreme runoff is not straightforward, because it is strongly influenced by the antecedent water content of the substrate (Paus & Braskerud, 2024).

2.3 Analytical Procedure

The analytical procedure consisted of comparing the results of published studies according to the type of rainfall event, the evaluated indicator, and the structural or climatic factors influencing the hydrological response. First, findings related to common and moderately intense rainfall events were identified, as these are the conditions under which green roofs typically achieve their highest retention performance. Subsequently, studies focusing on intense and extreme rainfall events were evaluated, as these conditions reveal the capacity limits of the substrate and retention layers. The results of individual sources were not combined into a new meta-analysis, because the analysed studies differ in their experimental conditions, climatic inputs, types of green roofs, substrate depths, measurement time steps, and definitions of rainfall events. Instead, a comparative synthesis was applied, allowing recurring patterns of hydrological behaviour to be identified. This approach is also appropriate because published research repeatedly highlights the high variability of retention and detention outcomes across locations, roof configurations, and rainfall events (Stovin et al., 2012) (Zheng et al., 2021).

In the final step of the analytical procedure, the synthesized findings were interpreted in terms of their relevance for the design of green roofs in urbanized areas. Particular attention was paid to whether green roofs can be considered an effective adaptation measure under extreme rainfall conditions, under which circumstances their performance decreases, and why they should be combined with other elements of decentralized stormwater management.

3. Results

The schematic framework used for interpreting the runoff response is shown in Figure 3. The diagram compares the expected hydrological behaviour of a conventional roof and a green roof during moderately intense and extreme rainfall events. During moderately intense rainfall events, a more pronounced retention and detention effect of the green roof is expected, expressed through runoff volume reduction, delayed runoff onset, and runoff peak reduction. During extreme rainfall events, this difference may decrease because of progressive saturation of the green roof assembly and depletion of the available retention capacity. The diagram (Figure 3) therefore represents a synthetic interpretation of the hydrological behaviour of green roofs, in which the relative contribution of the retention and detention functions gradually changes with increasing rainfall intensity, and the capacity limitation of the system becomes evident after saturation of the green roof assembly.

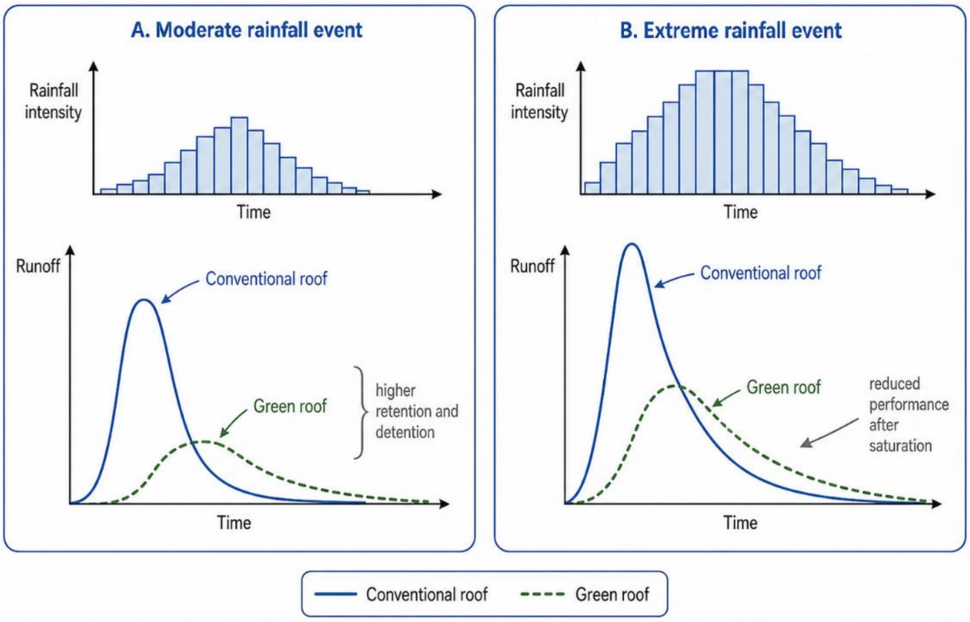

Figure 3. Schematic runoff response of conventional and green roofs during moderate and extreme rainfall events (Developed by the Authors).

3.1 Rainfall Retention Performance

The synthesis of the evaluated studies indicates that green roofs achieve their highest hydrological performance during common and moderately intense rainfall events. Under such conditions, the green roof assembly generally has sufficient available retention capacity to capture a substantial portion of rainfall water within the substrate, vegetation, and drainage or retention layers. The mechanism of runoff reduction is primarily based on rainfall interception by vegetation, infiltration into the substrate, temporary water storage within the pore space, and subsequent evapotranspiration (Nawaz et al., 2015). However, the retention performance of green roofs exhibits high variability. Extensive synthetic assessment of experimental data indicates that green roof retention efficiency is highly variable; at the scale of individual rainfall events, it can range from no retention to complete retention of the rainfall volume, with an average value of approximately 62 % (Zheng et al., 2021). This range confirms that retention is not a fixed property of a green roof, but rather the result of interactions between rainfall characteristics, roof configuration, and the current moisture state of the green roof assembly.

At the event scale, rainfall depth, rainfall intensity, event duration, and the length of the antecedent dry period emerge as decisive factors. Monitoring of a real-scale extensive green roof in a temperate climate demonstrated that retention was statistically associated with rainfall depth, event duration, rainfall intensity, and the antecedent dry period (Nawaz et al., 2015). Recent climate-oriented assessments further confirm that changes in rainfall frequency, rainfall depth, and antecedent dry periods are among the key factors influencing the retention performance of green roofs under climate change conditions (Yan et al., 2025).

From a practical perspective, this means that the same green roof assembly may exhibit substantially different performance under different rainfall inputs.

For smaller and moderately intense rainfall events, a substantial portion of rainfall can be retained directly within the green roof system, thereby reducing the volume of stormwater entering the sewer network. Earlier synthetic assessment of European data showed that green roofs can reduce stormwater runoff primarily by delaying runoff onset, reducing total runoff volume, and extending the period during which excess water is released from the substrate (Mentens et al., 2006). This effect is important from the perspective of urbanized areas, as roof surfaces represent significant sources of rapid runoff.

Conversely, during intense rainfall events, the available retention capacity decreases rapidly. Experimental assessments of intensive retention green roofs indicate that empty systems can capture a very high proportion of rainfall water, in some cases up to 99 %, whereas retention performance decreases markedly when the retention layer is nearly full (Breulmann et al., 2025). This result confirms that the nominal capacity of the roof system alone is not decisive; rather, the critical factor is the available storage capacity at the onset of a given rainfall event.

Model-based assessments of future climate scenarios indicate a similar pattern. Under non-extreme rainfall conditions, green roofs achieved retention rates exceeding 60 % across all evaluated climatic regions (Yan et al., 2025). However, during extreme rainfall events, their performance decreased substantially, with retention rates of approximately 1.8 % – 13.3 % reported under semi-humid and humid climatic conditions. (Yan et al., 2025). This contrast highlights the capacity-dependent nature of green roofs: under common rainfall events, they can substantially modify the water balance of the roof surface, whereas under extreme events their retention effect may be considerably constrained.

3.2 Runoff Delay and Peak Flow Reduction

In addition to reducing runoff volume, an important effect of green roofs is the transformation of the temporal pattern of the runoff response. In urbanized areas, this effect is as important as retention itself, because sewerage and drainage systems are most heavily loaded when runoff peaks from multiple impervious surfaces occur simultaneously. A green roof can delay the onset of runoff, reduce peak discharge, and prolong the duration of the runoff response (Stovin et al., 2017).

The results of the evaluated studies confirm that detention is particularly important where a green roof is unable to fully retain the entire rainfall volume (Stovin et al., 2017). Retention represents a reduction in runoff volume, whereas detention refers to the temporary storage of water and modification of the hydrograph shape. At the event scale, green roof performance should therefore be assessed not only through retained runoff volume, but also through runoff initiation, peak attenuation, runoff delay, and overall hydrograph transformation (Olašák & Palko, 2026b). This distinction is methodologically important, because a system with lower volumetric retention may still provide a significant benefit if it can delay the runoff peak or reduce its magnitude.

Empirical monitoring of a green roof under test-bed conditions demonstrated an average peak flow reduction of approximately 60 % during significant rainfall events (Stovin et al., 2012). At the same time, it was shown that the interpretation of runoff delay is not straightforward, because natural rainfall events often have an irregular temporal pattern and multiple intensity peaks (Stovin et al., 2012). Therefore, detention cannot be assessed solely through a single average delay value; instead, the overall transformation of the hydrograph needs to be analysed.

The detention performance of green roofs also depends on the configuration of the roof layers responsible for temporary water storage and drainage within the green roof system. Laboratory assessment of drainage mats demonstrated that roof slope influenced both retention and detention performance under low and high rainfall intensities (Abdalla et al., 2024). In that study, the retention mat stored up to 8 mm of water and delayed runoff by approximately 25 minutes, whereas the rigid plastic drainage mat stored up to 6 mm of water and delayed runoff by approximately 15 minutes (Abdalla et al., 2024). These results indicate that the hydrological response of a green roof is determined not only by the substrate and vegetation, but also by the technical layers that regulate temporary water storage and stormwater runoff.

The results also indicate that, during moderately intense rainfall events, retention and detention effects complement each other. The available retention capacity reduces runoff volume while simultaneously extending the time required for water to enter the drainage system. During extreme events, however, the relationship between these effects changes. After saturation of the substrate or retention layer, the ability of the system to further reduce runoff volume decreases, whereas a partial detention effect may persist in the form of delayed and prolonged runoff. This behaviour corresponds to the scheme shown in figure (Figure 3).

3.3 Functional Limits under Extreme Rainfall Events

The most pronounced limitations of the hydrological performance of green roofs occur during short-duration, high-intensity extreme rainfall events. During such events, the rate of stormwater input may exceed the immediate capacity of the green roof system to capture, temporarily store, and gradually discharge water into the roof drain. Once the available retention volume is filled, the green roof behaves less as a retention element and more as a component that temporarily modifies runoff. Based on the synthesis of the evaluated studies, the hydrological performance of green roofs can be interpreted as a capacity-limited process in which the retention effect progressively weakens with increasing rainfall intensity and event magnitude, while the detention effect becomes relatively more prominent after the functional threshold is reached. This conceptual shift is illustrated in figure (Figure 4).

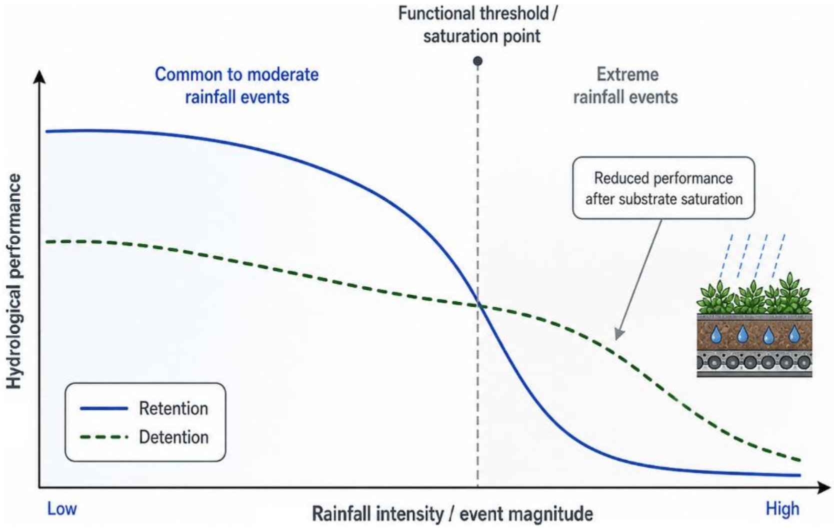

Figure 4. Functional threshold of green roof retention capacity under increasing rainfall intensity (Developed by the Authors).

Long-term 15-year observations of an extensive green roof provide important evidence that extreme rainfall does not automatically result in extreme runoff. Among the observed extreme rainfall events, approximately 69 % resulted in extreme runoff, with antecedent water content in the substrate identified as the key explanatory factor (Paus & Braskerud, 2024). This result suggests that, under the same or comparable rainfall event, a green roof may exhibit a different runoff response depending on whether the green roof assembly is dry or already partially saturated before the rainfall begins.

From a design perspective, this means that a direct correspondence between the return period of rainfall and the return period of roof runoff cannot be automatically assumed. Long-term analysis showed that the assumption of equivalence between rainfall return period and runoff return period did not hold for the green roof (Paus & Braskerud, 2024). Therefore, design practice should consider not only the extremity of the rainfall event itself, but also the initial moisture state of the green roof assembly.

The functional threshold of a green roof becomes particularly evident when the available retention capacity has been reduced by previous rainfall events or prolonged wet conditions. In such a state, even a relatively short but intense rainfall event may generate a pronounced runoff response, because the substrate and retention layers can no longer accommodate additional water volume. Experimental assessment of retention-based green roofs confirmed that the filling state of the retention layer significantly affects the resulting retention performance, with system efficiency decreasing markedly when the layer is nearly full (Breulmann et al., 2025).

Under intense simulated rainfall, even extensive green roofs with a thinner and highly permeable mineral substrate can exhibit an active hydrological response in the form of retention and detention (Giacomello & Gaspari, 2021). This finding is important because it suggests that even technically simpler extensive systems can contribute to stormwater management, although their effectiveness during extreme events is limited by the capacity of the green roof assembly.

The results therefore show that green roofs are effective, but capacity-limited, adaptation measures. Their greatest contribution lies in runoff volume reduction and runoff peak delay during frequent and moderately intense rainfall events. During extreme short-duration rainfall events, their function depends primarily on antecedent moisture conditions and the available retention capacity. In urbanized areas, they should therefore not be designed as an isolated solution for extreme stormwater runoff, but as part of a broader system of decentralized stormwater management.

Overall, the results indicate that the hydrological performance of green roofs is neither linear nor constant, but varies according to the type of rainfall event, the available retention capacity, and the antecedent moisture state of the green roof assembly. This variability is decisive for interpreting their role in climate adaptation strategies for urbanized areas.

4. Discussion

4.1 Interpretation of Hydrological Performance

The results of the synthesis show that the hydrological performance of green roofs is not constant but is conditioned by the characteristics of a specific rainfall event, the configuration of the green roof, and the current moisture state of the green roof assembly. Green roofs provide the greatest benefit during common and moderately intense rainfall events, when the available retention capacity of the green roof assembly is sufficient to capture a substantial portion of rainfall water (Zheng et al., 2021). However, such a range of values confirms that green roofs cannot be evaluated using a single average value without considering the specific type of rainfall event, the green roof configuration, and the initial moisture condition.

From the perspective of result interpretation, it is important to distinguish between retention and detention. Retention directly reduces the volume of stormwater discharged from a green roof, whereas detention modifies the temporal pattern of runoff, particularly by delaying runoff onset, reducing peak discharge, and extending the hydrograph (Stovin et al., 2017). This distinction is especially important during extreme rainfall events. Even when a green roof can no longer substantially reduce the total runoff volume, it may still partially contribute to hydrograph transformation and delay the inflow of stormwater into drainage infrastructure, thereby reducing immediate hydraulic stress on the system.

The most important interpretative finding is that the hydrological performance of green roofs does not respond linearly to increasing rainfall intensity. Under common rainfall conditions, retention may be the dominant effect; during moderately intense rainfall events, retention and detention act in combination, whereas during extreme rainfall events, the retention effect is substantially weakened after saturation of the green roof assembly. Long-term observations showed that only approximately 69 % of extreme rainfall events generated extreme runoff, with the antecedent water content in the substrate layer of the green roof identified as the key factor (Paus & Braskerud, 2024). This confirms that the rainfall depth or intensity alone is not decisive; the hydrological history of the green roof system prior to the onset of the event is also critical.

This finding is also important for design practice. If the green roof assembly is dry before an extreme rainfall event, it may still have substantial available storage capacity. However, if the substrate layer or retention layer is already saturated by preceding rainfall, the green roof system may rapidly reach its functional threshold. Experimental assessments of retention-based green roofs show that retention performance decreases markedly when the retention layer is nearly full, whereas empty systems can capture a very high proportion of rainfall water (Breulmann et al., 2025). This mechanism supports the interpretation of green roofs as capacity-limited adaptation measures rather than universal solutions for extreme stormwater runoff.

4.2 Implications for Urbanized Areas and Building Design

From the perspective of urbanized areas, green roofs are most significant where they can systematically reduce runoff from frequent and moderately intense rainfall events. These events occur repeatedly and constitute a substantial part of the overall stormwater load imposed on existing infrastructure. Reducing runoff volume and delaying the runoff peak can contribute to lowering the immediate hydraulic load on drainage systems, particularly in densely built-up areas with a high proportion of roof and paved surfaces.

However, during extreme rainfall events, a green roof alone may not be sufficient. The results indicate that, during high-intensity events, green roofs should be designed as part of a broader decentralized stormwater management system. Such a system may include storage tanks, retention areas, infiltration elements, permeable surfaces, or roof rainwater harvesting systems. Assessment of roof rainwater harvesting has shown that such measures can reduce hydrological connectivity and thereby limit the direct contribution of roof surfaces to flood runoff (Lu et al., 2025). In practice, this means that a green roof should be regarded as one component within a chain of measures, rather than as a stand-alone terminal element. This interpretation is consistent with the source-control perspective, according to which green roofs should be understood as dynamic decentralized stormwater-control elements whose effectiveness depends on rainfall characteristics, antecedent moisture conditions, and system configuration (Olašák & Palko, 2026b).

Significant implications also arise for architectural and structural design. Hydrological performance is not determined merely by the fact that a roof is designed as a green roof, but primarily by how the green roof assembly is configured. Substrate depth and properties, the retention layer, drainage layer, roof slope, vegetation type, and operational regime influence the ability of the green roof system to capture, detain, and gradually release rainfall water. Laboratory assessment of drainage mats showed that roof slope and the type of drainage layer influenced both retention and detention performance, with the retention mat storing up to 8 mm of water and delaying runoff by approximately 25 minutes (Abdalla et al., 2024). This indicates that the technical layers beneath the substrate can also significantly modify the overall hydrological response of the roof.

Green roofs should not be reduced solely to their stormwater management function. They are multifunctional components of building structures that, in addition to rainfall retention and detention, contribute to the thermal stabilization of the roof envelope, evapotranspiration, protection of waterproofing layers, microclimate improvement, and enhancement of the environmental quality of built-up areas (Olašák & Palko, 2026a). Experimental testing of different green roof assemblies has also shown that the current water content within the assembly and the specific configuration of the green roof influence not only retention behaviour, but also the thermal response of the waterproofing membrane (Juras, 2023). This broader physico-ecological significance supports their inclusion among adaptation measures that integrate architectural, environmental, and hydrological functions.

Within a broader urban planning framework, green roofs can be understood as part of blue-green infrastructure aimed at enhancing the climate resilience of urbanized areas. This approach is consistent with the understanding of urban blue-green infrastructure as a tool for reducing environmental pressures and supporting the sustainable transformation of the built environment (Salimi et al., 2025). In the context of the construction sector, green roofs also align with the broader trend of seeking more environmentally favourable structural solutions, which also includes the development of bio-composite building components aimed at reducing the environmental burden of conventional materials (Bosák & Palko, 2019). This connection indicates that the hydrological adaptation of buildings should be understood as part of a broader transformation of building structures toward higher environmental performance.

4.3 Limitations and Future Research

The present assessment has several limitations. The first relates to the methodological character of the research, which is based on a comparative synthesis of published experimental, monitoring, and modelling studies. This approach makes it possible to identify recurring patterns in the hydrological behaviour of green roofs across different climatic and structural conditions; however, it also relies on a heterogeneous set of input data. The included studies use different climatic inputs, types of green roofs, substrate depths, vegetation types, measurement intervals, and definitions of rainfall events. For this reason, the results were interpreted as a comparative assessment of trends and functional relationships, rather than as a meta-analytical aggregation into a single universal value of hydrological performance.

The second limitation concerns the different interpretation of extreme rainfall events. Some studies define extremes according to return period, while others use rainfall intensity, rainfall depth, or percentile-based approaches. In the case of green roofs, however, the extremity of rainfall alone does not necessarily determine the extremity of runoff, because the initial water content of the substrate plays an important role (Paus & Braskerud, 2024). Future research should therefore systematically link the analysis of design rainfall events with measurements of the moisture state of the green roof assembly prior to the onset of the event.

The third limitation concerns the spatial and climatic transferability of the results. Many available studies originate from different climatic regions, and their findings cannot be automatically applied to Central European conditions. Model-based assessments of future climate scenarios show that the performance of green roofs during extreme rainfall events may differ substantially between drier, semi-humid, and humid climatic regions (Yan et al., 2025). Therefore, for urbanized areas in Central Europe, long-term monitoring of green roofs under real operating conditions and at high temporal resolution for both rainfall and runoff should be further developed.

Further research should focus primarily on three areas. The first is long-term paired monitoring of green and conventional roofs under the same rainfall events. The second is the assessment of combined systems in which green roofs are integrated with storage, rainwater harvesting, or other retention measures. The third is the optimization of green roof assemblies regarding extreme short-duration rainfall, particularly in terms of the substrate, retention layer, drainage system, and operational management. Research oriented in this direction can contribute to more precise design of green roofs as functional, yet capacity-limited, adaptation elements in urbanized areas.

5. Conclusions

The results of the assessment confirm that green roofs represent hydrologically significant, yet capacity-limited, adaptation elements in urbanized areas exposed to increasing rainfall intensity. Their contribution lies not only in reducing the total volume of stormwater runoff, but also in transforming the temporal response of roof surfaces. The green roof assembly can capture part of the rainfall water, delay runoff onset, reduce the runoff peak, and extend the time over which water is gradually released into the drainage system.

The highest hydrological performance of green roofs is observed during common and moderately intense rainfall events. Under these conditions, the substrate, vegetation, and drainage or retention layer of the green roof generally have sufficient available capacity to capture a substantial portion of the rainfall depth. This effect is particularly important in densely built-up areas, where roof surfaces constitute a significant proportion of impervious surfaces and where even partial runoff reduction and delay can contribute to lowering the immediate hydraulic load on drainage systems.

However, during extreme short-duration rainfall events, the functional thresholds of green roofs become evident. Once the available retention capacity is exhausted, the ability of the system to reduce the total runoff volume becomes substantially limited, and the hydrological function of the roof shifts primarily toward temporary runoff detention. Therefore, the key factor is not only rainfall intensity or rainfall depth, but also the antecedent moisture condition of the green roof assembly. The same rainfall event may generate a different runoff response depending on whether the system is dry, partially saturated, or already close to its retention capacity before the rainfall begins.

The findings also indicate the need to critically distinguish between retention and detention. Under common rainfall conditions, the dominant effect may be the reduction of stormwater runoff volume, whereas during extreme events, temporal delay and partial attenuation of the runoff peak may become more important. This distinction is important for green roof design, drainage system sizing, and the realistic assessment of their adaptation function.

These findings indicate that green roofs cannot be considered a stand-alone universal solution for extreme stormwater runoff. Their greatest significance lies in the systematic reduction of frequent rainfall events and in the partial attenuation of the runoff response during more intense rainfall. In the context of climate adaptation, they should therefore be designed as part of a broader decentralized stormwater management system, in combination with storage, retention areas, infiltration elements, permeable surfaces, and other components of blue-green infrastructure.

For architectural and urban planning practice, it is essential that the design of green roofs is not based merely on the formal greening of roof surfaces, but on a hydrologically justified configuration of the green roof system. Substrate depth and properties, retention volume, drainage layer, vegetation type, roof slope, and operational regime should be designed regarding the expected type of rainfall events and the required level of retention and detention. Future research should focus primarily on long-term monitoring of green roofs under real operating conditions, the assessment of their behaviour during extreme short-duration rainfall events, and the optimization of combined roof systems capable of responding more effectively to changing climatic conditions.

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Conflicts of Interest
The authors declare no conflict of interest.

Data Availability Statement
This study is based on the authors' own comparative analytical synthesis of published scientific knowledge on the hydrological performance of green roofs. The underlying data, experimental results, and modelling outputs on which the interpretation is based are available in the cited scientific publications.

Institutional Review Board Statement
Not applicable. The study has an analytical-synthetic character and does not involve research on humans, animals, or the processing of special categories of personal data.

CRediT Author Statement
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References

Abdalla, E. M. H., Alfredsen, K., & Muthanna, T. M. (2024). Impacts of slope and length on the hydrological performance of green roof drainage mats. *Journal of Hydrology*, *632*, 130974. https://doi.org/10.1016/j.jhydrol.2024.130974

Bosák, L., & Palko, M. (2019). Wall Panel Made of Bio-composites. *MATEC Web of Conferences*, *279*, 02010. https://doi.org/10.1051/matecconf/201927902010

Breulmann, M., Merbach, A., Bernhard, K., & Moeller, L. (2025). Enhancing Urban Resilience: Stormwater Retention and Evapotranspiration Performance of Green Roofs Under Extreme Rainfall Events. *Land*, *14*(5), 977. https://doi.org/10.3390/land14050977

Giacomello, E., & Gaspari, J. (2021). Hydrologic Performance of an Extensive Green Roof under Intense Rain Events: Results from a Rain-Chamber Simulation. *Sustainability*, *13*(6), 3078. https://doi.org/10.3390/su13063078

Gill, S. E., Handley, J. F., Ennos, A. R., & Pauleit, S. (2007). Adapting Cities for Climate Change: The Role of the Green Infrastructure. *Built Environment*, *33*(1), 115–133. https://doi.org/10.2148/benv.33.1.115

Juras, P. (2023). Green roof evaluation and comparison during summer in Central Europe climate. *Journal of Physics: Conference Series*, *2654*(1), 012120. https://doi.org/10.1088/1742-6596/2654/1/012120

Kim, S. Y., Na, W., Jun, C., Seo, H., & Kim, Y. (2021). Hydrological Performance of Green Roof Systems: A Numerical Investigation. *Frontiers in Environmental Science*, *9*. https://doi.org/10.3389/fenvs.2021.806697

Lu, Q.-O., Bahramloo, R., Rodrigo-Comino, J., Wang, J., Talebi, A., Tran, Q. T. P., Ghahramani, A., & Sepehri, M. (2025). Evaluating the impact of roof rainwater harvesting on hydrological connectivity and urban flood mitigation. *Results in Engineering*, *25*, 104022. https://doi.org/10.1016/j.rineng.2025.104022

Mentens, J., Raes, D., & Hermy, M. (2006). Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning*, *77*(3), 217–226. https://doi.org/10.1016/j.landurbplan.2005.02.010

Nawaz, R., McDonald, A., & Postoyko, S. (2015). Hydrological performance of a full-scale extensive green roof located in a temperate climate. *Ecological Engineering*, *82*, 66–80. https://doi.org/10.1016/j.ecoleng.2014.11.061

Olašák, J., & Palko, M. (2026a). Green Roofs as a Passive Physico-Ecological Tool for Sustainable Urban Development. *Springer Nature Switzerland*, 857–875. https://doi.org/10.1007/978-3-032-14011-1_68

Olašák, J., & Palko, M. (2026b). Urban hydrological change and green roofs as source - control measures for stormwater management. *MATEC Web of Conferences*, 421, 04001. https://doi.org/10.1051/matecconf/202642104001

Paus, K. H., & Braskerud, B. C. (2024). Runoff from an extensive green roof during extreme events: Insights from 15 years of observations. *Hydrological Processes*, *38*(6). https://doi.org/10.1002/hyp.15220

Salimi, M., Kafi, M., & Khansefid, M. (2025). Advancing Zero-Carbon Cities through Urban Green Infrastructure in Karaj, Iran. *Journal of Contemporary Urban Affairs*, *9*(2), 566–583. https://doi.org/10.25034/ijcua.2025.v9n2-12

Stovin, V., Vesuviano, G., & De-Ville, S. (2017). Defining green roof detention performance. *Urban Water Journal*, *14*(6), 574–588. https://doi.org/10.1080/1573062X.2015.1049279

Stovin, V., Vesuviano, G., & Kasmin, H. (2012). The hydrological performance of a green roof test bed under UK climatic conditions. *Journal of Hydrology*, *414–415*, 148–161. https://doi.org/10.1016/j.jhydrol.2011.10.022

Yan, J., Zhang, F., Chan, F. K. S., Yang, L. E., He, Y., & Zhang, S. (2025). Adapting green roofs to climate change: Insights from case studies across four typical climates in China. *Building and Environment*, *284*, 113477. https://doi.org/10.1016/j.buildenv.2025.113477

Zheng, X., Zou, Y., Lounsbury, A. W., Wang, C., & Wang, R. (2021). Green roofs for stormwater runoff retention: A global quantitative synthesis of the performance. *Resources, Conservation and Recycling*, *170*, 105577. https://doi.org/10.1016/J.RESCONREC.2021.105577