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Review

A Critical Review of Existing Methods to Evaluate the Performance of Nature-Based Solutions (NBS) on Commercial Roofs (CR) to Mitigate Urban Flooding

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Abstract: The intensity and frequency of extreme rainfall events have increased in North America and the world due to climate change. Extreme rainfall events, characterized by a heavy volume of rainfall in a short duration, have triggered the onset of urban flash floods. Over the years, flash flooding has been reported in different cities in Canada, which resulted in many losses. Subsequently, different green roofing systems have been adopted to control urban stormwater runoff as part of Nature-Based Solutions (NBS) to mitigate urban flood and build a flood-resilient city. Currently, no specific widely recognized standard or code is dedicated to determining the hydrological performance of green roofs as a whole system. Moreover, there are no test protocols to regulate the design of green roof systems in the market. A comprehensive literature review examines existing research methods adopted to evaluate influencing parameters affecting the hydrological performance of NBS-CR. The results indicate several limitations in experimental and field investigations. Consequently, to address these limitations, it is essential to formulate a multi-functional work plan to develop a standardized test method that can become a common platform for the roofing industry to test and quantify the hydrological performance of their systems.

Keywords: nature-based solutions; commercial green roofs; standards; hydrological performance; experimental tests; field investigations

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1. Introduction

The intensity and frequency of extreme rainfall events have increased in North America and the world due to climate change since the 1950s [1]. Over the past years, extreme rainfall events, which are characterized by a heavy volume of rainfall in a short duration, have triggered the onset of urban flash floods. This is because, during heavy rainfall, the stormwater drainage system can become overloaded. Aged infrastructure in Canada, built before the 1940s and making up approximately 23% of Toronto's infrastructure, is the most vulnerable [2]. Older infrastructure comprises a combined sewer system where one pipe conveys both sewer and stormwater, increasing the risk of an overflow. The situation is aggravated in the presence of clogged catch basins or large surface areas of impervious roads. Climate changes generally account for monthly variations in a combined sewer system. However, during extreme rainfall events, which typically peak in the spring (April and May) and Fall (October and November) seasons, the rainfall runoff exceeds the drainage systems' (pipes) capacity, causing a combined sewer overflow (CSO) [3]. Thus, the potential risk of flash floods and erosion significantly increases during the spring and fall seasons.

Over the years, flash flooding has been reported in different cities in Canada, which resulted in many losses. For example, Toronto, Ontario recorded the most expensive flash flood event in 2013 (Table 1). The total loss cost is reported as one billion CAD for a rainfall intensity of 51 mm/h that lasted for two hours. In the summer months of July and August of 2023, widespread flash flooding caused significant damage (eroded roads, toppled trees, power outages, and displaced people from their homes) in several cities in Canada, such as Nova Scotia, Halifax, Ottawa, and Montreal.

Table 1. Extreme rainfall events insured losses [4].

Canadian City	Date	Cost (Canadian Dollars) (Insured)	Intensity (mm/Hour)	Duration (Hour)	Depth (mm)
Thunder Bay	May 2012	240 million	16.7	6	100
Hamilton	July 2012	104 million	46.7	3	140
Toronto	July 2013	1 billion	51.0	2	102
Burlington	August 2014	166 million	25.0	8	200
Windsor and Tecumseh	September 2016	178 million	50.0	4	200
Windsor and Tecumseh	August 2017	178 million	5.9	48	285
Toronto	August 2018	169 million	36.0	2	72

In September 2023 in Massachusetts, United States, rainfall was 300% above average volumes, destroying homes, commercial buildings, and infrastructure. In the northern cities of Italy in Europe, a flash flood occurred in May 2023, leading to significant losses. An accumulated rainfall of 900 mm was estimated within twenty-four hours. This accounts for an annual rainfall that occurred within one day.

This shows that extreme rainfall events become more frequent due to climate change and urbanization [5], instigating the need to take more active measures in stormwater management to be more prepared for extreme rainfall events. A low-impact development (LID) practice (e.g., vegetative roof assembly—VRA, blue roofs, blue–green roofs, purple roofs) to control urban stormwater runoff as part of a natural-based solution (NBS) is adopted to mitigate urban flood and build a flood-resilient city. Green roofs can be implemented on existing and new roofs. They primarily comprise a Built-in-Place Vegetative Assembly (BVRA) or Modular Vegetative Assembly (MVRA). Several studies illustrate many benefits of installing a green roof system, e.g., reducing runoff, improving air quality, reducing urban heat islands, and prolonging the roof's service life [6], as shown in Figure 1. Green roofs are Nature-Based Solutions (NBS) and Sustainable Urban Drainage Systems (SUDSs).

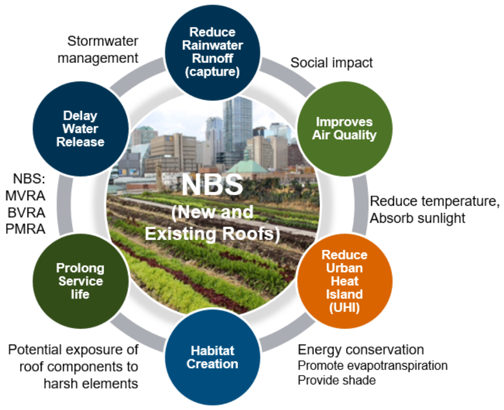

Figure 1. Multiple benefits of adopting LID practices to control runoff as part of NBS.

Nonetheless, to overcome barriers and challenges in determining the effectiveness of NBS in stormwater management, a unified standard test protocol must be established to evaluate the hydrological performance of green systems considering climate change while meeting structural requirements and Authority Having Jurisdiction (AHJ's) requirements.

Currently, no specific widely recognized standard or code is solely dedicated to determining the retention performance of green roofs as a whole system. Moreover, there are no test protocols to regulate the design of green roof systems in the market. However, several guidelines and publications offer recommendations and best practices for achieving effective retention performance. Some of these include FLL Guidelines for the Planning, Execution, and Upkeep of Green-Roof Sites. Although primarily focused on green roof planning, construction, and maintenance, the German FLL guidelines touch upon stormwater management. While they do not explicitly define retention performance standards, they offer guidance for achieving effective stormwater retention [7], specifying requirements for runoff coefficients based on structural thickness, bulk materials, and roof pitch. They specify annual water retention in percentage and runoff coefficients for extensive and intensive green roofs and also specify the maximum water storage/retention for extensive and intensive green roofs. It is important to note that these guidelines are specific to German conditions and regulations. Advancements in green roof technology and environmental standards have since evolved. As a result, this guideline does not provide guidance for the retention/detention performance of green roofs, blue roofs, or blue–green roofs at extreme rainfall events.

Before implementing a green roof, it is essential to acknowledge that guidelines may vary based on location, climate, and local regulations. Local municipalities or authorities typically set codes and regulations and may outline requirements or recommendations for managing stormwater on green roofs. Depending on where you are situated, regulations regarding building codes and the management of stormwater might encompass rules concerning the performance of water retention. These regulations are generally established by local government bodies or relevant authorities, which could specify the requirements or recommendations for managing stormwater in the context of green roofs, such as the Toronto Green Roof Standard 2021 [8].

Moreover, there are no test protocols to regulate the design of green roof systems in the market. System regulations are significant in developing uniform design and testing requirements considering climate change while meeting structural requirements to mitigate urban flooding. Moreover, regulations improve system quality, increase consumer availability, and accelerate mitigation efforts.

The existing ASTM standards (ASTM E2397/98/99) [9,10] provide a standard test method for a single module but do not address the whole system performance or quantification. It should be noted that the hydrological performance of a vegetative roof system can not be determined based on a single module.

The National Building Code of Canada (NBCC) [11] provides climatic data on rainfall intensities for different zones in Division B, Appendix C. Division B, part 4 of the NBCC [11] specifies structural loads for conventional structures, establishes requirements for ponding instability checks due to rain loads, and specifies roof slope requirements and secondary drainage requirements. If a flat roof is too flexible, rainwater will not accumulate evenly over the roof but will flow to form ponds in a few local areas. This may lead to an instability similar to buckling, which can cause the roof to fail due to local overloading. There is potential for the primary drainage system for a roof to become blocked due to freeze–thaw conditions. Roofs in these areas should be designed accordingly.

NBCC [11] provides a reference for a guideline on the vegetative roofing system and the performance of protective materials to the German Landscape Research, Development and Construction Society (FLL) [7] and the National Roofing Contractors Association. On the other hand, the National Plumbing Code [12] provides drainage requirements (primary and secondary), specifications for the drainage system's capacity, and procedures for calculating hydraulic loads and drainage sizes. Both codes do not provide guidance on the hydrological performance of the NBS-CR.

The current gap is that design guidelines and best practices recommend optimizing these factors to improve runoff reduction and overall hydrological performance. Although research studies, industry guidelines, and local stormwater management regulations can provide valuable guidance for assessing and improving green roof systems' runoff performance, no single standard is dedicated explicitly to the runoff performance of different NBS-CR assemblies. Therefore, the primary objectives of this research are to investigate parameters influencing the hydrological performance of NBS-CR and the methods adopted to investigate the NBS-CR performance. This is achieved as follows:

(i) Conduct, in laboratory, experimental tests to investigate parameters influencing the hydrological performance of NBS-CR and evaluate performance;
(ii) Review field monitoring studies to investigate parameters influencing the hydrological performance of NBS-CR and evaluate performance;
(iii) Identify research gaps and research limitations;
(iv) Provide future recommendations.

1.1. Structure of the Literature Review

This paper presents a literature review conducted in a critical and systematic analysis of existing research and literature on the quantification of green roof performance. This literature review aims to identify gaps in the literature and synthesize relevant findings. The benefits of adopting a green roof system to mitigate urban flooding and adapt to climate change to build resilient cities are widely established in research. However, this review aims to identify the best strategies to identify parameters influencing the quantification of NBS performance. This paper reviews different systems of NBS on commercial roofs (CR). This paper analyzes the findings from experimental and field research studies to quantify the hydrological performance of NBS-CR and identify trends, patterns, contradictions, and gaps in the literature. The review focuses on publications from 2000 to 2024. Studies related to numerical modeling, water quality, or soil erosion were excluded. The findings were evaluated and categorized. Subsequently, research limitations of the methods were identified. Finally, this paper makes recommendations to address these limitations (Figure 2). This literature review is structured by addressing the following:

1. Studies addressing the influencing parameters: (i) Climatic characteristics, (ii) Performance indicators;
2. Background of NBS-CR;
3. Review of experimental studies on parameters influencing retention performance;
4. Review of field investigations on parameters influencing retention performance;
5. Gap in the knowledge;
6. Conclusions;
7. References.

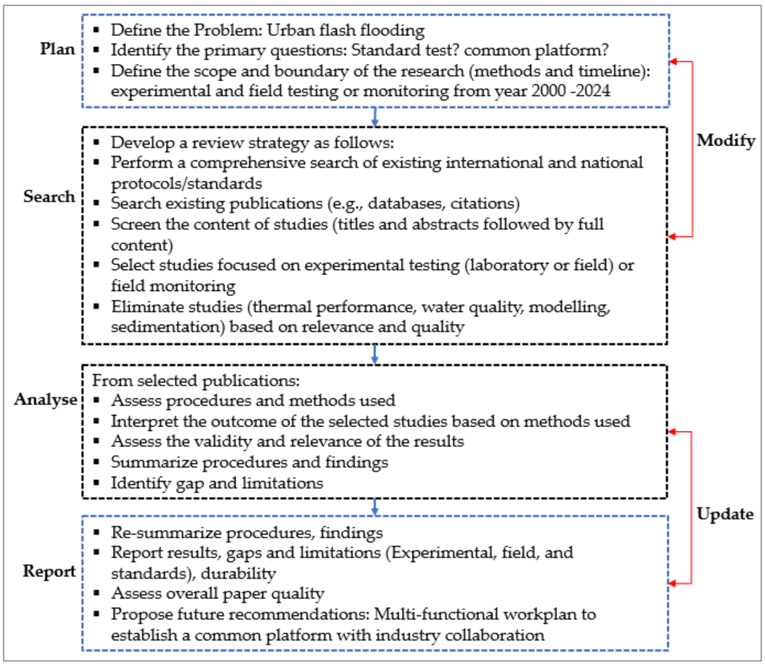

Figure 2. Flow chart of the critical review.

1.2. Background on NBS-CR

Within the NBS-CR, different concepts of retention and detention systems are available in the North American market, e.g., traditional Green Roof (GR), Sponge Roof (SR), Blue Roof (BR), Blue–Green Roof (BGR), and Purple Roof (PR) that claim to have the capacity to control water runoff generated by rainfall storms. Different components and combinations are available in the market, and we want to investigate them in our project towards standard development.

In general, these systems can be categorized into (i) traditional vegetative systems where rainwater percolates through the system and drains out upon reaching field capacity (GR); (ii) retaining (storing water volume) systems that have higher capacity than a standard roof to retain water, which are equipped with control devices (orifices or weirs) to manage water retained or detained (BR); and (iii) detaining (controlling water volume released) systems where a detention layer is added to slow down and control runoff volume (BGR and PR). Blue–green roofs (BGR) integrate the concepts of both GR and BR, retention and detention, respectively. Purple roofs (PR) are also a retain and a detain system similar to BGR; nonetheless, they have a light system that retains less water and delays outflow by 8–24 h, making them potentially superior systems for extreme back-to-back rainfall events [13].

It is essential to understand that the amount of runoff controlled depends on the design of the NBS-CR, how it performs, and the function it serves. Thus, a roof designer must establish a connection between local climatic conditions, climate change, plant resiliency, crop coefficient, and NBS-CR performance to optimize the design of a stormwater management system, as shown in Figure 3. Crop coefficient is used to predict evapotranspiration. It is defined as the ratio of the actual plant evapotranspiration to a reference plant evapotranspiration (k_c) [14]. The goal is to design a resilient system capable of withstanding a changing environment while maintaining its functionality throughout its service life.

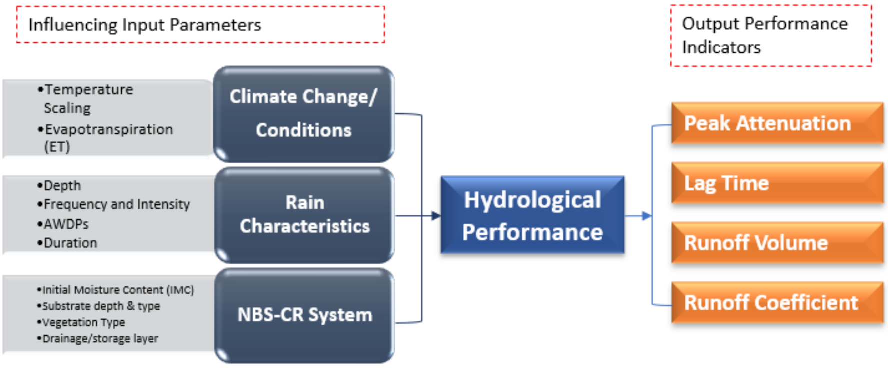

Figure 3. Parameters influencing the hydrological performance of NBS-CR.

Several research studies investigated the hydrological performance of extensive green roofs in the field through field monitoring of buildings' rooftops by utilizing the rooftop surface [15–21] or by building multiple individual platforms [22–25]. On the other hand, few studies conducted experimental work using an artificial rain simulator with predetermined rain characteristics [19]. Research emphasizes critical parameters influencing the hydrological performance of different roofing systems (retention, detention, and retention and detention), as shown in Figure 4.

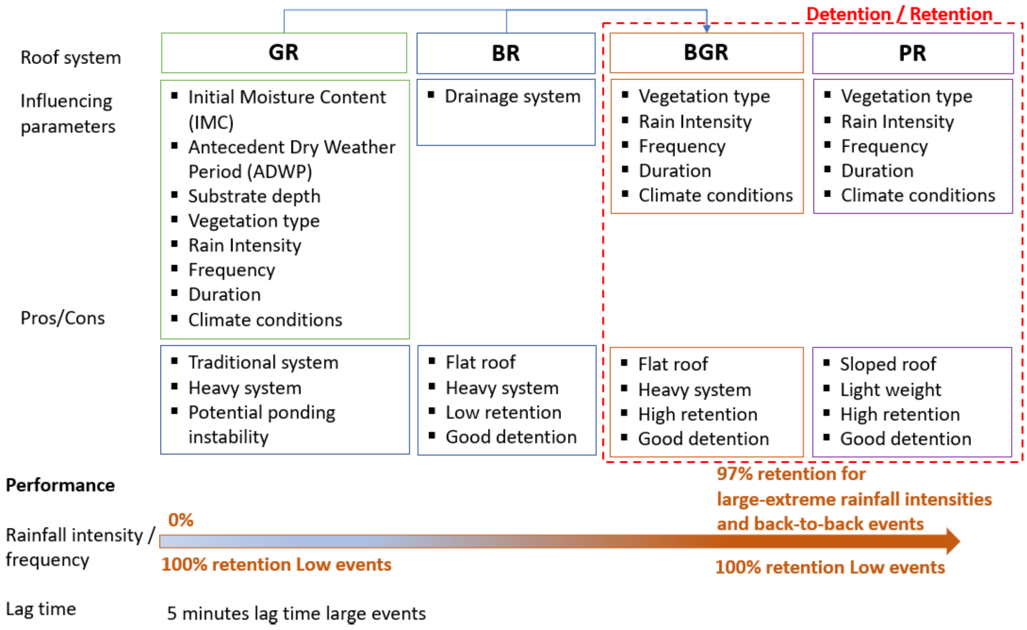

Figure 4. Characteristics of different roofing systems used on commercial buildings.

2. Review of Experimental Studies on Parameters Influencing Retention Performance

Several experimental studies [26–31] utilized an artificial rain simulator to test specially designed small-scale roofing platforms that incorporate a drainage system. In general, an artificial rain simulator is employed because it enables controlled and methodical assessments of rainwater management, plant development, and various environmental aspects commonly linked to green roofs.

The primary emphasis in these experimental investigations is placed on assessing the hydrological effectiveness of various GR system configurations with different soil compositions across diverse conditions. This aimed to drive enhancements in the design and functionality of tested systems for increased sustainability and more effective stormwater management. The most employed metric for quantification of the hydrological performance is the water retention capacity of GR is runoff reduction (RR) [32]. The runoff coefficient (RC) indicates the green roof system's capacity, while the hydrograph provides insights into its runoff response.

Findings suggest that the retention capacity of the GR system is influenced by several contributing interrelated parameters, such as rainfall characteristics (rain depth, intensity, frequency, and duration) [28,30,33] and the initial moisture content (IMC) and antecedent dry weather periods (ADWPs) [30]. Moreover, the GR is influenced by vegetation type, substrate type, substrate depth, storage capacity, and slope of the green roof [22,34,35]. The following sections summarize existing literature on the hydrological performance of NBS-CR using in-laboratory (rain simulator) experimental testing.

2.1. Influence of Rain Characteristics

Researchers [27,28,30,33] investigated the influence of rainfall intensity on the hydrological performance of NBS-CRs.

The author [33] investigated the hydrological performance of a GR by exposing the system to predetermined rainfall intensities of 1.8 mm/min and 3.5 mm/min for 15 min. The rainfall intensities were based on a statistical study.

This study investigated the influence of rainfall intensity, frequency, and duration on the hydrological response. This was achieved using a rain simulator sized 5000 × 1000 × 1000 mm (16.4 × 3.3 × 3.3 ft) and equipped with overhead 60 nozzles/m^2 constructed in a laboratory in Germany. The slope of the roof surface was 2% and 9%. The substrate depth was 100 mm. The simulated tests were completed within four days. The interevent (time between each test) was 3, 18 and 24 h. The results of this study indicate that extensive green roof has a mitigation capacity depending on the initial moisture content of the substrate before the start of a rainfall event. However, the hydrological response is diminished following back-to-back rainfall events due to substrate saturation. The green roof runoff increased from 4% to 73% between the first day of testing, when the substrate was dry, and the following day's test after only a 3 h inter-event period.

A reduction in the peak runoff intensity was detected only in the dried condition. It was concluded that, following a series of heavy rain events, the extensive GR lost its ability to function effectively due to substrate saturation. On the other hand, increasing the system slope to 9% did not significantly affect system performance, similar to the findings by [26,34].

The retention performance of GRs was experimentally investigated by [19]. The authors investigated the influence of variable rain intensities and the growing media's IMC on the roof's hydrological performance. The green system was tested at rainfall intensity between 0.8–2.5 mm/min for 30 and 90 min rainfall considering temperature scaling (1.4 climate factor). The growing media comprised sedum plants with an added layer of lightweight expanded clay beneath the substrate. The layer of expanded clay detains water for an extended period, improving the system's ability to attenuate runoff, delay water flow, and reduce peak flow during heavy rainfall events. The results indicated that the hydrological performance of the roof was highly affected by the growing media's IMC for short- and long-duration rain events. For example, the IMC, in this case computed based on water balance, increased from a field capacity of 15 mm to 55 mm, and the centroid delay decreased from 20 min to 5 and 10 min. The peak attenuation was 93%.

The main goal of [30] was to experimentally determine the runoff coefficient using a rain simulator capable of replicating intense rainfall events at rates of 1.8 mm/min (110 mm/h) and 2.5 mm/min (150 mm/h) based on the local climate of Rio de Janeiro in Brazil. Weather data (temperature, instant rain, and cumulative rain) were collected over 24 h and 96 h between February and July 2017 to study the influence of local climate on the retention performance of GR. The highest cumulative rain was 122 mm at 34 °C in June. Five platforms sized 2000 × 890 mm (6.6 × 2.9 ft), with heights between 240 and 280 mm (less than 1 ft), were constructed and placed outdoors. The base of the platform had a slope of between 3 and 4%. The drainage system directs water into a gutter. The experimental program comprised system calibration followed by testing. The experimental results indicated that intense rainfall events have a shorter start runoff time [30]. For an intense rainfall event of 1.9 mm/min (116 mm/h), the runoff start time was 6 min, while for a 2.4 mm/min (145 mm/h) runoff start time was 5 min.

Moreover, ADWPs and rainfall intensity influence the retention performance. The retention capacity of the GR is higher after a drier day compared to a wet one. Interestingly, the author found that the retention capacity of GR increases with increasing rainfall intensity. For example, the retention volume of GR is 68–82% for a rainfall intensity of 1.9 and 2.4 mm/min (116 and 146 mm/h).

The green roof performance was experimentally investigated by [28]. A rain simulator 1000 × 1000 × 700 mm (3.3 × 3.3 × 2.3 ft) equipped with a drainage pipe was used to simulate seven natural rainfall events between May and September in Korea. The simulated rainfall events ranged from 0.01–0.13 mm/min (0.4 mm/h to 7.6 mm/h), referenced as E1–E7. The results indicated that they were 42.8–60.8% effective in reducing runoff for 200 mm soil depth and 13.8–34.4% effective in reducing runoff for 150 mm soil depth. This indicates that deeper soil substrates (200 mm) exhibit twice the retention capacity compared to substrates with a depth of 150 mm. Moreover, the growing media (type and particle distribution size) could limit the retention capacity of the GR system in accordance with the inherent field capacity of the growing medium. Increased ADWPs between heavy storm events improve water retention capacity. Otherwise, the green roof system alone may not effectively reduce water runoffs during back-to-back or intense rainfall events.

The authors of [27] conducted experimental work on a small-scale rain simulator sized 500 × 500 × 200 mm (1.6 × 1.6 × 0.7 ft). The authors categorized rainfall events into summer and spring–fall for the experiments using a statistical analysis of historical rainfall events in Korea between 1999 and 2011. The highest rainfall intensity amounted to 0.3 mm/min (20 mm/h) in the spring and fall 0.6 mm/min (40 mm/h) in the summer. The rainfall conditions are not equivalent to a flash flooding event. The ADWP ranged from half a day to 5 days. The soil layer had a depth of 100 mm (4 in). The substrate was a mix of different percentages of perlite, cocopeat, and charcoal topped with Sedum grass. Underneath the soil layer was a textile and low drainage plate. The results showed that GR had a good retaining capacity during the summer (higher rainfall intensity) but no runoff. However, runoff was dependent on rainfall intensity and total rainfall depth. The retaining capacity was 29 mm and 27 mm when rainfall intensity was 0.25 and 0.3 mm/min (15 and 20 mm/h), respectively. As rainfall intensity increased above 0.3 mm/min (20 mm/h), the retaining capacity decreased.

2.2. The Influence of Substrate Characteristics

Green roof substrates have different storage capacities, defined as field capacity. Moreover, the soil hydrological state of the soil is influenced by substrate composition and particle size distribution. During frequent and intense rainfall events coupled with low evapotranspiration conditions, substrates reach their field capacity, leading to unfavorable conditions for vegetation thriving. Therefore, choosing an appropriate vegetation type for a specific climate is crucial for sustaining the GR system. According to [36], Sedum and meadows have proven effective in retaining water, making them resilient in arid climates. Sedum inherently stores water within their cells, reducing evaporative water. According to German roof greening guidelines (FLL) [7], a suitable air-to-water ratio plays a significant role in extensive roofing. The guideline specifies that growing media should have a water-holding capacity of at least 25% (v/v). The annual water retention of 60% for extensive and semi-extensive green roofs. Growing media depth should not exceed 200 mm (semi-intensive GR type) to prevent exceeding the structural capacities provided by building code requirements [7]. For intensive NBS-CR with an overall depth higher than 200 mm, it is necessary to assess the structural capacity of the roof system to ensure that it can support the NBS-CR.

This section reviews literature that focuses on the effect of substrate characteristics on hydrological performance. Several studies [27–29,31,34,35,37] have found that substrate characteristics that include substrate depth, substrate type, vegetation type, and moisture content (initial moisture content—IMC and field capacity—FC) have a significant influence on the hydrological performance of NBS-CR. In a general trend, as rainfall intensity increases, the retaining capacity of the GR decreases [19,27,28,33–35,37]. Several authors [19,34,37] emphasized that it is essential to recognize that the system's effectiveness in flood control may greatly rely on the soil field capacity and physical characteristics (substrate depth, vegetation type) on the hydrological performance of GRs [27,28,34,35], including the influence of the IMC [19].

One study [34] investigated the effect of vegetation type (Radix Ophiopogonis, Iris, Sedum Spectabile) and depth of growing media substrate (50, 100, 150 mm), IMC, structure slope (2, 7, 12%) and rainfall intensities (mean low: 0.3 mm/min, mean high: 0.7 mm/min) on hydrological performance. Ten platforms sized 1000 × 1000 × 300 mm (3.3 × 3.3 × 0.9 ft) were constructed from stainless steel frames. Rainfall simulators were used to simulate rain depths ranging from 17 to 30 mm over 30 to 60 min, corresponding to rainfall intensities lower than 1 mm/min. The IMC of the soil was monitored using a series of embedded moisture sensors. The results shown in Figure 5 illustrate a strong relationship between retention capacity and lag time and the antecedent moisture condition. As the IMC of the substrate increased from 25 to 44%, the system capacity to retain water decreased from 55% to 15%. Moreover, the time to runoff is decreased from 26 to 6 min. In this study, substrate depth did not result in a significant change in system retention capacity. The type of vegetation used, such as Radix Ophiopogonis, had lower runoff retention than the Sedum Spectabile vegetation. The retention capacity and delay of the onset of runoff are higher at low intensities (mean 0.34 mm/min) than at high-intensity events (mean 0.7 mm/min). On the other hand, there is a slight decrease in retention capacity following slope increases from 2% to 12%.

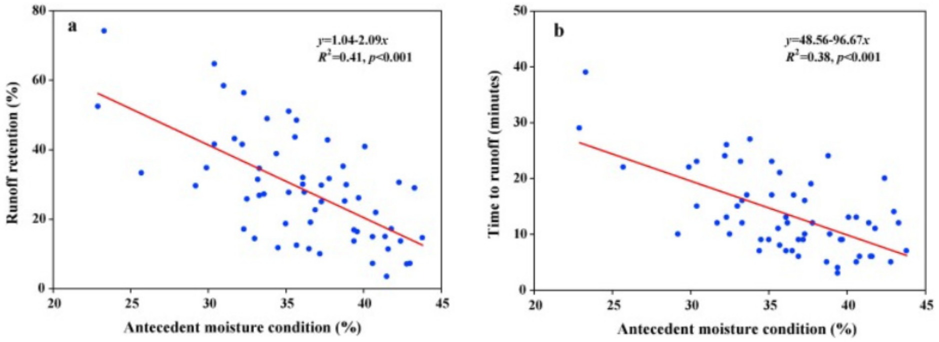

Figure 5. Relationship between retention and antecedent moisture content (%)—(**a**), time to runoff and antecedent moisture content (%)—(**b**) (Reproduced from [34]).

Moreover, the selection of vegetation species influences the GR system's retention capacity [27–29,31,35].

This author [35] conducted experimental work in the UK during the summer to investigate the influence of vegetation type (Heuchera micrantha, Salvia officinalis, and Stachys byzantine) on the retention performance of GR. Two rainfall events were applied at saturated and unsaturated conditions at 0.5 mm/min (9 mm of rain in 20 min) intensity. The author accounted for the effect of different evapotranspiration rates depending on the vegetation type in a controlled laboratory environment. This was achieved by varying ambient temperature and humidity conditions in the lab. The results indicated that Stachys and Salvia exhibited the highest ET, then Heuchera, while Sedum had the lowest ET. In all trials, the bare substrate consistently showed the lowest ET. Vegetation species exhibiting high ET rates, such as Salvia and Stachys, could retain 72% water due to ET effects compared to 46% retention for sedum plants.

Also, ref. [29] investigated 18 constructed GR modules sized 1150 × 1150 mm (3.8 × 3.8 ft) under a canopy sized 2800 × 5000 × 250 mm (9.2 × 16.4 × 0.8 ft) that excluded natural rainfall events to measure the water balance in Australia. Different vegetations were used for the growing media employed in this study: (1) bare unplanted substrate (as a control); (2) Sedum pachyphyllum; (3) Lomandra longifolia; (4) Dianella admixta; (5) Stypandra glauca; and (6) a mixture of Lomandra longifolia, Dianella admixta, and Stypandra glauca. The rainfall intensity was 0.8 mm/min (49 mm/h), equivalent to a 1% annual exceedance probability for Melbourne. A total of 92 rainfall events were simulated for 15 months of the study, and data were collected for 65 of these events. The ADWPs in the simulated rainfall experiment were 0, 2, 4, 6, 9, and 12 days. Rainfall was experimentally simulated using overhead nozzles 1300 mm high from the modules. The moisture content of the soil was measured gravimetrically before a rainfall event and 24 h after the rainfall event, along with ET quantification. This was considered an experimental limitation because it did not allow ET quantification on the day of the rainfall event. The results indicated that the retention performance of a GR was not only influenced by rainfall intensity (although it is a significant driver for water retention) but also by the type of vegetation selected. The variations in water retention among plant species became noticeable during more substantial rainfall events. Modules planted with S. glauca and the mixed variety exhibited lower retention than those with L. longifolia.

Results indicate that different vegetation types inherently have different capacities to hold/store water (maximum water storage capacity). Some species have a higher capacity to deplete stored water. The amount of available water storage prior to a rainfall event determines the retention capacity of the GR Shallow-rooted Sedum plants, which tend to enhance maximum water capacity.

Experimental tests were conducted by [31] using a rainfall simulator in a hot tropical climate in Brazil. A uniform rainfall intensity of 2.5 mm/min (150 mm/h) was applied for 7 min over three module systems comprising two trays sized 500 × 500 × 200 mm. The tested systems comprised different vegetated soils, bare soil, and fiber–cement roof sheets for wet and dry soils exposed to the environment. Vegetation type comprised a mix of succulent species: 70% Callisia repens (turtle vine), 15% Portulaca oleracea (yellow purslane), and 15% Aptenia cordifolia (baby sun rose). A 5–7-day rainfall is considered a dry condition. A sample of 50 cm^3 soil was collected for laboratory gravimetric measurements. The results indicate that GRs are less efficient in retaining water during wet conditions; however, they are a good option when intense rainfall occurs during extended dry periods compared to a conventional roof. The author found that bare soil was drier as it drains faster than vegetative soil. Succulent vegetation loses less water and, hence, retains less water. This emphasizes the importance of understanding the types of vegetation species used in a particular climate where frequent rainfall occurs.

This authors of [37] conducted experimental work investigating the hydrological performance of extensive green roofs. The test was conducted in a controlled laboratory environment without consideration of the evapotranspiration process. The experimental work uniformly simulated two rainfall events recorded on 12 March 2005, and 13 March 2005. The experimental tests included (i) low rainfall intensity using unsaturated substrates, (ii) high rainfall intensity using substrates that are initially saturated, and (iii) low-intensity initially saturated. Gravimetric measurements of the moisture content of the growing media were conducted to determine the substrates' saturation level. Moreover, a rainfall event of 2.5 mm/min (150 mm/h) was applied within 6 min, corresponding to the value used in drainage requirements for New York City (NY), USA. For each test, the growing media was at field capacity. The findings demonstrated that water was entirely discharged within 24 h after a heavy rain event, suggesting that the system lacked the capacity to retain water.

A summary of experimental studies investigating parameters influencing the retention performance of NBS-CR based on experimental investigation is summarized in Table 2.

Table 2. Review of experimental studies on parameters influencing the retention performance of NBS-CR.

Ref.	Variable	Climate Conditions. Location	Rain Simulator (Small Scale)	Rain Intensity, I_a	Findings
[33]	Rain intensity	Mild continental climate (warm–humid summer, very cold winter). Quinto Vicentino, Italy	Extensive GR. 5000 × 1000 × 1000 mm with 300 nozzles	1.8 mm/min (9 mm/5 min) 17 mm/5 min 18 or 24 h FLL	The mitigation capacity of the GR system depends on IMC, F.C., and ADWPs. GR's ability to retain water diminishes following back-to-back events due to saturation. Lower retention following intense rain events.
[19]	IMC, Rain intensity	Norwegian cities	Extensive GR. Sedum, expanded clay layer, 130 mm	0.8–2.5 mm/min between 30–90 min 5–74 min, 6 h	Hydrological performance is highly affected by the growing media's IWC for short and long-duration rain events. The IWC increased from a field capacity of 15 mm to 55 mm, and the centroid delay decreased from 20 min to 5 and 10 min. Peak attenuation was 93%.
[30]	Rain intensity	The tropical Savanna monsoon climate. (Heavy rain from March to December). Rio De Janeiro, Brazil	Extensive GR. 5 modules sized 2000 × 890 mm placed outdoors. The bottom drainage is into two taps towards a gutter and a pliviometer. The gutter slope is 0.3%.	1.8–2.5 mm/min (110–150 mm/h) 1.8 (115 mm/h) 6,7 days 2.4 mm/min (145 mm/h), 4 to 14 days	GR reduces lag time in intense rain events but does not affect peak runoff reduction. ADWPs lead to higher retention capacity. Retention capacity is higher at higher rainfall intensities, 68 and 82% for 116 and 146, respectively.

Table 2. *Cont.*

Ref.	Variable	Climate Conditions. Location	Rain Simulator (Small Scale)	Rain Intensity, I_a	Findings
[34]	Rain intensity Substrate depth type.	Combination of cold desert, cold semiarid, temperate continental, and cool continental climate. Gansu, China	Extensive GR. 10-platforms sized 1000 × 1000 × 300 mm. Raised above ground by 500 mm. Drainage: middle of drainage layer connected by a pipe 25 mm.Substrate depth: 50, 100, 150 mm, Type: Radix, Sedum, Iris. Roof slope: 2, 7, 12%	Low: 21 mm, 60 min, 0.34 mm/min. High: 20 mm, 30min, 0.6 mm/min	Factors influencing hydrological performance substrate material, substrate depth, slope. Higher retention capacity is observed for substrates that have higher field capacity. Radix Ophiopogonis had lower runoff retention compared to the Sedum Spectabile vegetation. Higher retention lag time for low-intensity events. A slight decrease in retention capacity following slope increases from 2% to 12%.
[29]	Plant type Wet/dry	A temperate oceanic climate (warm summers, mild winters). Melbourne, Australia	Extensive GR.18 modules sized 1150 × 1150 mm. Different vegetations: (1) bare un-planted substrate (control); (2) Sedum pachyphyllum; (3)Lomandra longifolia; (4) Dianella admixta; (5) Stypandra glauca; (6) mixture of Lomandra longifolia, Dianella admixta and Stypandra glauca	0.8 mm/min (49 mm/h), ADWP (0, 2, 4, 6, 9, 12 days)	Rainfall depth is the main driver for water retention. However, proper selection of vegetation species influences the retention capacity. High ET reduces retention. Species roots reduce the storage capacity of the substrate. Limitations: ET was not quantified on the day of the experiment.
[31]	Rain Intensity Plant type Wet/dry	The tropical Savanna monsoon climate. (Heavy rain from March to December), Rio De Janeiro, Brazil	Extensive GR. 6 modules sized 500 × 500mm on rooftop (6% slope). Runoff is controlled using a stopwatch.	Intense rainfall, 2.5 mm/min (155 mm/h) and 7 min. Wet and Dry soil conditions	GR is less efficient in retaining water during wet conditions. Bare soil was drier as it drained faster compared to vegetative soil. Succulent vegetation loses less water and retains less water. Emphasize proper selection of vegetation species for a particular climate where frequent rainfall occurs.
[35]	Vegetation type and ET	Maritime climate, Yorkshire, UK	Extensive GR Heuchera micrantha, Salvia officinalis, and Stachys byzantine	0.5 mm/min (9 mm/20 min)	Stachys and Salvia exhibited the highest ET, then Heuchera, and Sedum had the lowest ET. Bare substrate showed the lowest ET. Vegetation species exhibiting high ET rates, such as Salvia and Stachys, could retain 72% water due to ET effects compared to 46% retention for sedum plants.
[28]	Substrate depth	Humid continental climate with dry winter. Seoul, Korea	Extensive GR.1000 × 1000 × 700 mm, Substrate depth 150 or 200 mm.	E1–E7 from (0.04 to 0.13 mm/min)	Increase ADWP, improve retention capacity, and decrease delayed time (td). High I has a negative relation with delayed time. GR is effective for low-I events.
[27]	Rain intensity	Humid continental climate dry winter. Seoul, Korea	Extensive GR. 500 × 500 × 200 mm. Drainage: four at the corners and one at the center base.	Spring–Fall: 2–20 mm/h. ADWPs: 1–5 days Summer: 2–40. ADWPs 0.5–3 NE.	As rainfall intensity increased above 20 mm/h, retaining capacity decreased.
[37]	Rain intensity. FC.	The tropical Savanna climate Monsoon climate, Brazil	Extensive GR.4 platforms 1220 × 61 mm. One control and 3vegetation. Sedum plants.	Uniform rainfall, Low I, short duration. High I. 1 h duration. 0.3–0.4 mm/min (18 to 25 mm/h).	Retention capacity is reduced following an intense rainfall event.
[26]	Rain intensity, slope	Mild Oceanic, Augustenborg, Sweden	Controlled field test. GR. Sedum moss, 300 mm substrate, Slopes 2, 5, 8, 14°	0.4, 0.8, 1.3 mm/min	ET significantly reduces runoff. Runoff initiates once FC. is reached. The roof slope does not influence the runoff.

3. Review of Field Investigation Studies on Parameters Influencing Retention Performance

Rainfall events are defined as having an inter-event dry period of at least 6 h, following an approach widely used for green roof retention analysis [15,23,32]. A rainfall event is any rain event (>1 mm) separated by a six-hour dry period.

3.1. *Influence of Roof System Configuration and Regional Climatic Conditions*

Researchers [17,21,38–41] found that the hydrological performance of a roof depends on the installed roof configuration and regional climatic conditions (oceanic, Mediterranean, temperate zone, subtropical, Nordic region, humid continental) that the roof is exposed to.

For example, BGRs, are integrated roofing systems that incorporate both vegetative (green) and water-retention (blue) components. The storage component of the BGR is considered a water source (passive irrigation) of the vegetative layer through capillary action [20]. This system outperforms a standard GR in extreme rainfall events or back-to-back events. It is worth noting that the longest field monitoring was conducted by [21,38,39] as follows.

In an oceanic climate, ref. [21] conducted six years of field monitoring of a full-scale BGR in Hamburg, Germany. Hamburg has an oceanic climate. Less runoff was observed during the summer periods. The author recorded one heavy-intensity rainfall event in which the system had a high retention capacity, resulting in less runoff and higher detention times. Over time, there was growth in the vegetation biodiversity due to water storage, which sustained water availability during dry periods. Moreover, BGR contributed to the increase in the evaporative cooling process. The author attributed this improvement to the application of a detention system. In general, ref. [42]'s research showed that designing a slope-free BGR reduces the runoff coefficient.

In the Nordic climate zone in four cities in Norway, ref. [38] conducted field monitoring of a full-scale extensive green roof for three to eight years. Each city has a different climate: Bergen and Sandnes are classified as temperate oceanic climates and have mild winters with few frost days and precipitation, mainly rain throughout the winter. Oslo has an inland climate with warmer summers and colder winters, which are classified as a warm-summer humid continental climate. Trondheim has cooler summer temperatures and is classified as a subpolar oceanic climate. The author found that increasing the substrates' field capacity increased the system's retention capacity. The author stressed the limitation associated with the event-based characterization of the retention performance of GRs in different regions due to event irregularities and the challenge of capturing a heavy or extreme rainfall event.

In a humid continental climate with four distinct seasons, ref. [39] examined the effects of rainfall, evapotranspiration (ET), ADWP, and seasonal variation on the retention performance of an extensive green roof on a commercial building in Syracuse, NY, USA. The results indicated that the GR performance was unaffected by ADWP exceeding two days. The monitoring period was extended from June 2010 to November 2013. This study defined evapotranspiration as the evaporation of the soil surface and transpiration from the sedum stomata (ET), according to [43].

In the Mediterranean climate in Palermo, Sicily, Italy, ref. [41] conducted a field study to monitor the hydrological performance of BGR (69 m^2). The investigation was carried out for 434 days (14 months) from December 2020 to February 2022. The average annual precipitation was 817 mm, with approximately 76% of the total annual precipitation occurring in autumn and winter. Specifically, the average monthly precipitation in winter amounts to around 104 mm. The results of this study are limited to 54 rainfall events with rainfall depth over 4 mm, which does not explain the hydrological performance of the BGR in the case of a heavy event that occurs alone or back-to-back. However, the results underscore the significant influence of rainfall characteristics, initial soil moisture in the green layer, and the initial water storage in the blue layer on the system's ability to retain water.

In a humid subtropical environment in Penrith, Australia, ref. [13] collected data for one year from April 2021 to May 2022, during which the city experienced multiple floods. Perth has a humid subtropical climate. This study concluded that purple roofs outperformed all other tested systems. The onset of runoff (lag time) was delayed by 773, 211, and 86 min for small, medium, and large rainfall events, respectively, compared to a conventional roof, and 110, 59, and 14 min, respectively, compared to a GR, as shown in Figure 6. The findings indicated that the purple roof was an effective alternative to the GR system during extreme events (>50 mm) or when the substrate was saturated, contrary to the GR system, where its performance diminished when it reached capacity. During extreme events (five occurred within the monitoring time), the lag time was 553 and 74 min for purple roofs, respectively, compared to conventional and green roofs. Reductions in runoff for the purple roof compared to conventional and green roofs were 88% and 55%, respectively.

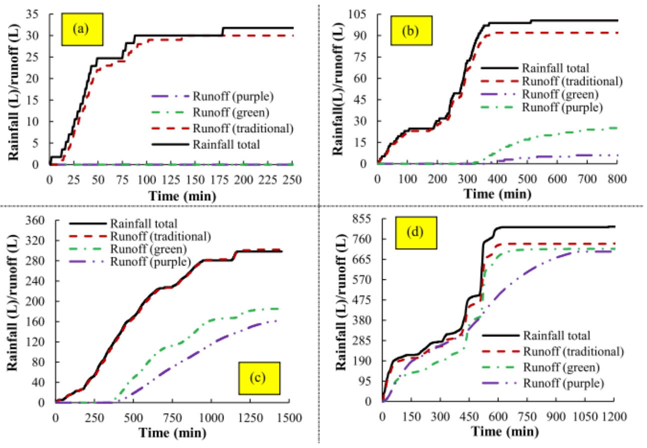

Figure 6. Rainfall and runoff from different roofs over time during a (**a**) small rainfall event of 4.6 mm, (**b**) medium rainfall event of 14.5 mm, (**c**) large rainfall event of 42.9 mm, and (**d**) extreme rainfall event of 118.2 mm (reproduced from [13]).

In Michigan, USA, ref. [40] constructed twenty-one roof platforms, each measuring 1220 × 1220 mm (4 × 4 ft). The platform slope is 2%. The authors constructed different roof systems, including a LiveRoofStandard (S), LiveRoof Standard and RoofBlue RETAIN (SB), LiveRoof Lite (L), LiveRoof Lite and RoofBlue RETAIN (LB); Substrate and Rockwool (R), RoofStone Pavers (RS); Membrane only (M); Gravel Ballast (G); and Gravel and RoofSponge (GR). Natural rainfall was recorded for eight months. The percent of retention is illustrated in Figure 7. Figure 7 illustrates that the retention performance of the different roof systems is reduced as the rainfall depth increases.

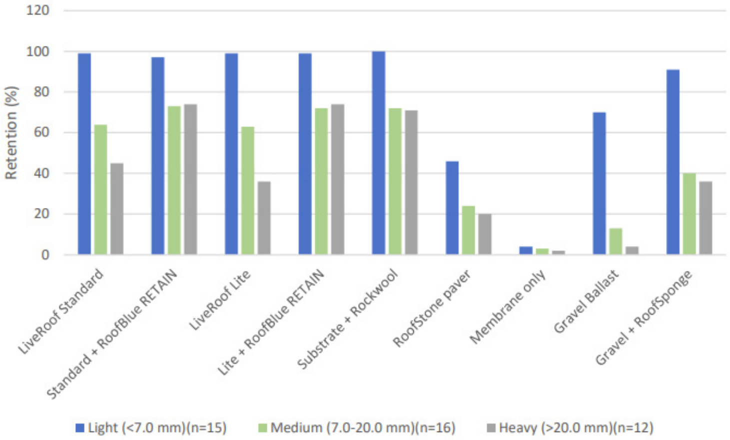

Figure 7. Retention percent (%) of each roof system based on natural rainfall for eight months (reproduced from [40]).

In the Mediterranean climate in southern Italy, a study [44] investigated the retention performance of BR on a building rooftop. The BR covered an area of 4600 × 5720 mm (15.1 × 18.8 ft) with 64 tray modules spaced at 400 mm. The trays size were 645 × 417 × 115 mm (2.1 × 1.4 × 0.4 ft). The results indicated a reduction of 34% and a mean peak attenuation performance of 60% compared to a conventional roof. Although the author outlines the benefits of BR on hydrological performance, the effect of site characteristics and the scale/configuration of the plot on performance remains unclear.

In the humid subtropical climate of Nanjing, China, ref. [45] monitored extensive GR covered with sedum vegetation from May to November 2016 (6 months). The other collected data for 71 rainfall events. There were 20 days with more than 25 mm of rain, eight days with more than 50 mm events, and one day with a rain depth of 152 mm (July). The resulted indicated that the retention performance was variable from 11 to 100% depending on the intensity of the rain. Retention decreased with the increase in rainfall from 97% for a very small event to 14% for a heavy event. Monitoring limitations due to malfunction restricted recording of heavy rainfall events. The author also emphasized the importance of ADWPs proceeding with rainfall events in increasing the system's retention rate. The author did not investigate the impact of vegetation type, Sedum, in a humid subtropical climate.

Ref. [17] conducted a comparative study on BGRs exposed to heavy rainfall events (1 and 1.5 mm/min) in a temperate climate. The BGR had an overall surface area of 285 m^2. It comprises several platforms sized 500 × 500 × 200 mm (1.6 × 1.6 × 0.7 ft) and blue roofs installed on the rooftops of buildings in Seoul, Korea. Both types of roof configurations were exposed to actual rainfall events. For blue roof, the maximum rainfall event recorded was 1.5 mm/min (90 mm/h), while the BGR was 1 mm/min (60 mm/h) in July 2014. The findings indicated that the BGR outperformed the blue roof in effectively managing prolonged rain events. Nonetheless, the blue roof is a more cost-effective choice when compared to the green–blue roof and is a suitable option for retrofitting in urban areas.

During high-intensity events, water infiltrates the soil faster, resulting in the soil reaching field capacity faster. As field capacity is reached, surface runoff will occur [46]. In green roofs, evapotranspiration is very high, significantly reducing runoff [47]. The authors of [47] investigated the effect of evapotranspiration (ET) on the water retention capacity of green roofs for over 29 months. The author monitored the moisture content of the substrates of four extensive green roofs in the UK. The substrate's moisture content varied seasonally during dry periods due to ET. Rainfall runoff is reduced during summertime due to increased evapotranspiration [26]. Systems with vegetative layers had a higher water loss rate than non-vegetated systems.

3.2. The Influence of GR System Characteristic

Increasing the depth of the substrate was investigated by [25]. The authors investigated the effect of different depths (100, 200, 400 mm) of vegetative substrates under extreme rainfall events on hydrological performance. A total of 21 small-scale platforms sized 500 × 500 × 500 mm (1.6 × 1.6 × 1.6 ft) with drainage layer and filter fabric atop a steel base. The platforms were implemented on a rooftop in South Korea, two vegetation (vegetated or non-vegetated) and control (plot with standard frame only). South Korea has a humid continental climate characterized by hot and humid summers and cool, dry winters. The annual precipitation ranges from 1100 to 1360 mm, with approximately 50% of this precipitation occurring during the summer months from June to August.

Data were collected for 40 rainfall events with a cumulative precipitation of 440 mm. The monthly rainfall rates for June, July, and August were roughly 63, 93, and 284 mm per hour (1, 2, 5 mm/min), respectively. This corresponds to 9, 14, and 17 mm of monthly rainfall. The findings suggest that when it comes to enhancing runoff performance during severe rainfall events, greater substrate depth has a more significant impact in reducing runoff rate than the vegetation type, similar to findings by [20]. Nevertheless, the type of vegetation employed will play a role in counteracting the acidity of rainwater, thereby improving water quality. Water retention increases with the increase in substrate depth. Substrate retention was found to be 1.6–3.6% higher than the use of a drainage layer/protection mat. The author [48] also investigated the impact of 75 mm and 125 mm substrate depth on the GR hydrological performance in the Mediterranean climate in Portland, Oregon, USA, for one year. The authors found that retention is highly influenced by rain depth and length of the ADWP. The difference in retention performance was more significant for small rain events and long ADWP. The authors found that for large events higher than 35 mm, there was no significant change in the hydrological performance of the roof when the substrate was deeper (75 to 125 mm).

Ref. [20] investigated the influence of substrate type and thickness, drainage layer thickness, and orifice size on the retention performance of BGR and BR. The researchers aimed to measure and compare various parameters related to stormwater retention, such as rainfall runoff, evapotranspiration, and water storage capacity. The authors assessed green roof discharge during seasonal (spring-fall 2021) rainfall events to quantify the amount of water retained by GR, BR, and BGR using different substrates: organic FLL soil. An intensive farm is divided into three plots that grow produce annually. It is comprised of 28 platforms separated by pathways. Each platform measures approximately 19,000 mm (62.3 ft) in length and 760 mm (2.5 ft) in width, while the paths between them are about 450 mm wide. The substrate is 250 mm in depth. The utilization of passive irrigation through the drainage layer has been demonstrated to enhance and maintain the growth of farms. Although various plant species from different families were planted in each examined plot, their hydrological performance remained consistent across all plots. This suggests that the predominant factors influencing performance were the high-quality organic substrate and the extended drainage layer rather than the specific choice of plants.

In a continental climate in Toronto, Ontario, Canada, ref. [49] monitored the performance of three systems GR, BGR, and BR. The authors investigated the retention performance of GR and BGR installed with high organic substrates or FLL substrates designated as GR-organic and GR-FLL, respectively, in all grown Sedum plants. The green roof facility layout comprises an array of rows with multiple green beds. Six modules sized 2400 × 1200 mm (7.9 × 3.9 ft) were monitored and analyzed. The author examined the thermal and discharge performance of the system. The study's objective was to examine the impact of multiple design variables (substrate thickness and type) on green roofs' retention/detention performance based on seasonal fluctuations. The author recommends assessing the trade-off between the benefits of stormwater management and thermal performance in selecting the substrate type and type of plants it can support, considering local climate conditions. This is because seasonal temperature fluctuations influence the retention of different growing media. For example, organic-based substrates can retain more water than FLL substrates, which may not be suitable for growing drought-tolerant plants. Moreover, high retaining water substrates may create thermal fluctuations within the thin roof layers. BGR with organic substrates had a 63% retention capacity compared to 43% of the GR. On the other hand, utilizing FLL-inorganic substrates for BGR did not increase the retention capacity of GR. Blue roofs had a slightly higher retention capacity (52%) using small orifices of 2.4 mm.

In a monsoon climate in Beijing, China, ref. [29] investigated, via 3-year field monitoring of the influence of two substrates, depths of 100 mm and 150 mm, the system performance of a green roof. The author also investigated the frequency of light rainfall events <10 mm. Six platforms were 1000 × 1000 mm (3.3 × 3.3 ft) in size and raised from the ground by 1219 mm (4 ft). Runoff from the green modules drains through a pipe into a tipping bucket system. The depth of the growing media (local soil, engineered soil, and lightweight medium) was 100 mm and 150 mm, respectively. The results indicated no significant difference in performance between the two systems under light rain (<10 mm) and short antecedent dry weather periods (ADWPs). Rainfall intensities were from 0.04 to 2.76 mm/min, and maximum rainfall events were (0.2 mm to 131.6 mm). The limitation of this study is that the investigation is confined to a specific climate zone characterized by short ADWP periods and the frequent incidence of light rainfall events (<10 mm). More extended periods of monitoring, which are challenging and time-consuming, are required to cover variability in rainfall events and the potential occurrence of an extreme event.

In a subtropical climate in northeastern Italy, ref. [50] constructed 36 platforms raised 1000 mm (3.3 ft) above ground for a full surface area of 0.44 m^2 for two years (2014–2016). The objective was to investigate the effect of different vegetation types (herbaceous perennial (HE), Sedum (SE), and suffruticose (SF)), substrate types (120 mm in depth volcanic substrate (VS), 120 mm in depth recycled substrate (RS)), and drainage (PL)/storage layers (ML) on the hydrological performance of GR. According to [51,52], monthly evapotranspiration and crop coefficient were calculated. Runoff for VS is higher than RS and not affected by PL or ML. However, using different vegetation species, the ML reduced runoff more than the PL. For rainfall events higher than 25 mm, retained rainfall volume varied (20–80%) depending on the rain depth and the ADWPs. The lowest retained volume of 33 mm was recorded after two weeks of rain of 124 mm. Retention capacity (85–95%) was higher for a medium rainfall event of (10–25 mm). Low rainfall events (less than 10 mm) had 100% retention. Regarding plant species suffruticose (SF), plants reduced runoff by 15.2% compared to Sedum (SE) plants.

Ref. [22] examined four substrate compositions and thicknesses in a field experiment (40 and 80 mm decomposed granite (CDG) and 40 and 80 mm Rockwool layers. Sixteen platforms sized 1100 × 1000 mm (3.3 × 3.3 ft), including a rock wool layer, were constructed atop a rooftop in Hong Kong and monitored over ten months. The rainfall events were classified into three categories (light, medium and heavy). Extreme events (typhoon-related) were excluded from this study. Incorporating a rockwool layer as a substitute for soil substrate renders the overall system lighter and maximizes the retention capacity of green roofs. The retention capacity of the system is further improved when a rainfall event is proceeded by a dry period. The effectiveness of this new detention system in enhancing performance is most pronounced when the system reaches its field capacity following a series of consecutive rainfall events.

In the maritime climate in Yorkshire, UK, ref. [36] examined the contribution of the substrate type and depth on the retention performance of GR. The platform size is 1000 × 1000 mm (3.3 × 3.3 ft) using different substrates such as coarsely crushed brick, coarsely crushed tiles, and Lytag of 75 and 150 mm substrate depths. The mean rainfall depth was 4 mm for a total rain depth of 155 mm between December 2009 and June 2010. The retention capacity of the roof system is affected by the choice of substrate, which in turn depends on the substrate's water-holding capacity. The soil's water holding capacity and particle size distribution were determined for each growing medium. Substrates with greater water holding capacity resulted in increased water retention within the system.

3.3. The Influence of Rainfall Characteristics in Different Climatic Regions

The hydrological performance of the GR is influenced by rainfall characteristics such as rainfall intensity and duration [23,53–55] and IMC [18,32].

In a humid continental climate in Syracuse, NY, USA, ref. [18] found a substantial impact of rainfall intensity on runoff and the influence of initial soil moisture content on the retention performance of a green system. Ref. [18] investigated the hydrologic performance of an extensive GR (substrates thickness less than 150 mm) with Sedum vegetation. The authors instrumented the roof with moisture sensors to measure seasonal moisture changes while the field capacity of the substrate was determined in the lab. The available water retention capacity is the variance between the substrate's current soil moisture level and maximum capacity. Data were collected between October 2014 and July 2016 (21 months). The retention depth was determined by subtracting the runoff depth from the rainfall depth. Initial soil moisture was calculated as the mean of the four sensors during the time step just before the commencement of precipitation. Summer recorded the highest intensities of rainfall events (8 mm/h) at a lower frequency than spring (5 mm/h) and fall. The highest rates of evapotranspiration were estimated during the summer and fall seasons. These results showed that evapotranspiration plays a crucial role in restoring the retention capacity between rainfall events, similar to the findings of [46]. The results ascertain findings indicating that a rainfall event's size influences retention rates [23]. Hence, several researchers [18,25] suggest that long-term monitoring is required to capture seasonal fluctuations [38].

The impact of different climatic conditions on the retention performance of green roofs was investigated by [16] in three cities in Canada (London in Ontario, Halifax in Nova Scotia, and Calgary in Alberta). These cities have different weather conditions (humid-continental, humid-maritime, and semi-arid-continental). Water storage and evapotranspiration were monitored continuously. The results indicated that drier regions, i.e., Calgary, have greater cumulative retention (67%) compared to London (48%) and Halifax (34%). Retention performance is most influenced by climate in the case of moderate-sized storms. This is attributed significantly to the occurrence of initial moisture conditions of the substrate prior to rainfall events. The IMC is affected by weather characteristics (relative humidity, temperature, net radiation). Therefore, IMC can serve as a performance metric applicable to any climatic condition. Field monitoring results demonstrate that collecting IMC data after a rainfall event might be the most effective way to gauge a system's retention capacity. Ref. [16] found that drier climates have higher water retention than wet climates. Thus, accounting for the initial moisture content and the extent of how much water is retained mainly depends on the GR system response. For larger events (>45 mm), the average retention of green roofs ranged between 16 and 29% in all cities. Green roofs comprising modular live roof setups with 150 mm growth media depth were placed atop buildings in each designated city. Field monitoring extended from September 2012 to November 2014. In conclusion, longer dry periods led to higher retention capacity in Calgary city except in isolated large events that led to drainage. Thus, the author concludes that IMC should be utilized as a retention indicator in performance evaluation for different climatic regions. When the substrate of a green roof reaches its field capacity, it constrains the roof system's retention capacity. Therefore, assessing the IMC for various types of rainfall events, including extreme ones, is vital. The overall retention was considerably more significant on the green roof in the semiarid climate (75%) than in the maritime climate (43%). This disparity was primarily attributed to elevated evapotranspiration between storms on the semiarid roof, leading to a more extensive restoration of substrate retention capacity [16]. The study assessed performance considering climatic variations but did not incorporate the rise in the frequency and intensity of rainfall events attributed to climate change. The results showed that retention capacity is decreased for significant events.

In the Mediterranean climate in Adelaide, South Australia, ref. [32] investigated the retention performance continuously for two years in a dry climate for two types of green roofs: intensive (media depth: 300 mm) and extensive (media depth: 100 mm) in the dry climate experienced. The results confirmed the effectiveness of utilizing any green system configuration to improve hydrological performance compared to a conventional roof system. The author examined the influence of different parameters (rainfall depth, intensity, ADWPs, and duration) on water retention. The author used a multiple variable regression analysis to assess roof performance, considering all influencing parameters. Higher ADWPs between rainfall events give enough time for the growing media to dry, increasing its water storage capacity. This, in effect, decreases runoff volume due to the increased retention capacity of the growing media and increased evapotranspiration process in warm conditions, similar to the findings of [55]. The retention coefficient is reduced as rainfall depth increases in large rainfall events (>20 mm).

In a humid subtropical region in NY, USA, ref. [55] monitored three (3) different systems of GR systems between 2011 and 2012: (i) a vegetated mat system installed, (ii) a built-in system, and (iii) a modular tray system. In NY, rainfall events such as 3 mm/h may lead to CSOs [56]. This highlights the importance of the regional conditions where the GR system is installed. In NY, where the infrastructure is old, both the wastewater and stormwater runoff are conveyed into one pipe such that a rain volume of 1.3 mm can cause a CSO. The findings of this study indicated that a roof system's retention and peak attenuation depend on the rain event. As the total rainfall volume increased, the peak attenuation decreased. Green roofs can withstand light rainfall (<5 mm), especially after dry periods. However, as rainfall volume is above 10 mm, the influence of IMC, substrate field capacity, and evapotranspiration on retention performance becomes prominent. Also, retention performance is affected by system installation and the overall storage capacity of the GR system. The same installation in different locations will yield performance variations.

In the subtropical region in Auckland, New Zealand, ref. [15] instrumented six hydraulically independent areas on a full-scale field rooftop. Cumulative precipitations were collected for 12 months. This study's findings revealed that the soil's Initial moisture content, coupled with low evapotranspiration, led to low retention and had the most significant influence on the retention capacity of the system. On the other hand, seasonal variations did not impact the runoff response. The system was capable of regulating runoff response throughout the year efficiently.

In Michigan, USA, ref. [54] quantified the effects of the variable roof slope on the hydrological performance of GR. The hydrological performance of 12 platforms sized 244 × 244 mm (8 × 8 ft) of extensive green roofs was examined. The platforms were constructed atop rooftops with four slopes (2%, 7%, 15% and 25%). Some studies [53,57] found that as the slope increased, the retention values decreased. This effect was particularly pronounced for slopes ranging from 2% to 15% and from 2% to 25%.

A summary of all literature reviews on the parameters influencing the retention performance of NBS-CR following field investigation is summarized in Tables 3–5.

Table 3. Review of field studies on parameters influencing retention performance (2021-2023).

Ref.	Variable	Climate/Location	NBS-CR Details	Rainfall Intensity	Month	Findings
[13]	Rain intensities Roof system	Subtropical climate (hot-humid summer, cool to mild winter). Sydney, Australia	GR, PR, conventional, small-scale: raised platforms sized 1200 × 6000 × 150 mm	Categorized rainfall	13	Purple effectively mitigates performance, especially during heavy and extreme events or when the substrate reaches capacity during back-to-back events. Runoff reduction was 88 and 55% compared to conventional and GR.
[41]	Rain intensities IMC, roof system	Mediterranean climate (Hot-dry summer, mild-wet winter) Palermo, Sicily, Italy	BGRs, Full-scale rooftop 2% monitoring (69 m^2). Vegetative layer and storage layer	54 events over 4 mm rain depth	14	Emphasize the influence of rainfall characteristics, initial soil moisture in the green layer, and the initial water storage in the blue layer on the system's ability to retain water.
[21]	Roof system, long term	Oceanic climate (wet-windy, mild winter). Hamburg, Germany	BGRs Full-scale rooftop monitoring	Rain depth >0.2 mm	72	Growth in the vegetation biodiversity due to water storage, which sustains water availability during dry periods
[58]	Pipe sizing the drainage system	Macedonia's climate (warm, dry summers and autumns, cold winters, heavy snowfall) Macedo de Cavaleiros, Northeast, Portugal	Extensive GR, sloped impermeable smooth roof. Flat roof	Rainfall intensities for all three roofing scenarios were <2 mm/min	NA	Reduction in water runoff by 16% compared to conventional roof system.
[40]	Roof systems	Humid continental climate. East Lansing, MI, USA	Small-scale: 21 platforms (1220 × 1220 mm). LiveRoofStandard (S), S and RoofBlue RETAIN (SB), LiveRoof Lite (L), L and B (LB); Substrate and Rockwool (R), RoofStone Pavers (RS); Membrane (M); Gravel Ballast (G); and G and RoofSponge (GR).	Categorized rainfall	8	The retention performance for different GR systems is reduced as the rainfall depth increases.
[49]	Substrate type. System type	Continental climate (dry climate, hot summers, very cold winter) Toronto, ON, Canada	BGR, BR., GR. Small-scale. Six modules sized 2400 × 1200 mm on the rooftop sectioned into three systems with a middle drainage hole. Substrate depth 100 mm GR, 50 mm BGR	Maximum rainfall depth 47 mm. June–November.	3	Organic-based substrates can retain more water than FLL substrates, which may not be suitable for growing drought-tolerant plants.
[20]	Plant species. Roof systems	Continental climate. Toronto, ON, Canada	BGR, BR., GR Full scale. Intensive rooftop farm-3 plots (11 × 20 m). Continuous beds (19,000 mm long by 760 mm wide) separated by a 450 mm path. Soil depth 250 mm	From 7 mm to 103 mm rain depth	5	Rooftop performance: mean retention, peak attenuation, and peak delay ranges of 85–88%, 82–85%, and 7.7–8 h. Influencing performance were the high-quality organic substrate and the extended drainage layer.
[25]	Substrate depth	Hot, humid summers, cool-dry winters. (Monsoon climate in Korea	Extensive GR small scale. Twenty-one platforms (500 × 500 × 500 mm), nine vegetation and nine no vegetation, three control. Soil depth of 100, 200, and 400 mm	Extreme rainfall 63, 93, 284 mm/h	3	Higher substrate depth has a more significant impact in reducing runoff rate than the vegetation type.
[24]	Substrate depth, type	Monsoon-influenced climate. Beijing, China	Extensive GR, 6 GR modules sized 1000 × 1000 × 400 mm Substrate depth: 100, 150 mm.	Rain 0.2 to 132 mm, intensity: 0.04 to 2.76 mm/min.	72	No significant difference in performance between the two systems under light rain (<10 mm) and short ADWPs.

Table 4. Review of field studies on parameters influencing retention performance (from 2016 to 2021).

Ref.	**Variable**	**Climate, Location**	**System Details**	**Rainfall Intensity**	**Duration (Month)**	**Findings**
[50]	Plant species, Substrate type, Drainage storage	Subtropical climate, Northeastern Italy	Extensive GR, small-scale in the field 36 platforms (0.44 m^2) raised 1000 mm above ground. Middle drainage hole. Volcanic substrate (120 mm), recycled substrate (120 mm)	Variable rainfall events	24	Runoff for VS is higher than RS. and not affected by PL. or ML. ML reduced runoff more than PL. Events > 25mm, retained rainfall volume varied (20–80%) depending on ADWPs. Retention capacity (85–95%) was higher for a medium rain event of (10–25mm). For <10mm, 100% retention. Species suffruticose (SF.) reduced runoff by 15.2% compared to Sedum (SE.) plants.
[44]	Roof system (BR)	Mediterranean Climate, Catania, South Italy	BR rooftop size: 4600 × 5720 mm. 1.6% roof slope. 64 tray modules. Spaced at 400 mm. 645 × 417 mm. 115 mm in depth.	73 events.26 used. 169 mm/h	24	BR had 34% runoff reduction and 60% peak attenuation compared to a conventional roof. BR. was empty before successive rain events.
[19]	Rain Intensity, IMC	Local climatic conditions Bergen, Oslo, Trondheim, Norway.	Extensive GR, Rooftop 88 m^2, 2%, 1000 mm AG. GR underlaid with 200mm expanded clay	Local climatic conditions	12	The performance of the roof is dependent on multiple variables, including the initial moisture content of the substrate.
[18]	Evapotranspiration (ET)	Humid continental climate. New York, NY, USA	Extensive GR, Live roof Setup 300 × 300 mm. Substrate depth 150 mm	>20 mm 11 events	21	Evapotranspiration plays a crucial role in restoring the retention capacity between rainfall events.
[45]	Extreme rainfall event (Monsoon)	Humid subtropical climate. Nanjing, China	Extensive GR, five-story rooftop area 1101 m^2, divided into two independent sections: bare and GR Pre-grown vegetated (Sedum lineare) modules 300 × 500 × 110 mm. The substrate layer is 70 mm	16 days 2–10 mm 13 days 10–25 mm, 20 days >25 mm 7 days (>50 mm)	6	Retention performance was variable from 11-100% depending on the intensity of the rain. Retention decreased with the increase in rainfall events. For heavy events> 50 mm, retention was 14% compared to a very small event < 2 mm with a retention capacity of 97%.
[48]	Substrate depth	Mediterranean climate in Portland, OR, USA	Extensive GR, small-scale 75 mm and 125 mm substrates	5–10 mm and >35 mm events	12	Retention is highly influenced by rain depth and length of the antecedent dry weather period. The difference in retention performance was more significant for small rain events and long ADWPs.
[38]	Field capacity	Subpolar/Oceanic climate, continental, island climate, 4-cities in Norway	Extensive GR, 16 small-scale rooftop areas (5–16m^2), 5.5–27% sloped roofs	1 mm/5 min to 3.3 mm/5 min	3–8 years	Increasing the field capacity of the substrates was found to increase the retention capacity of the system. Limitations in the event-based characterization of the retention performance of GRs in different regions due to event irregularities and challenges in capturing a heavy or extreme rainfall event.
[17]	Different BGR systems	Humid continental climate with dry winter. Seoul, Korea	Conventional roof (50 m^2), BR (no vegetation) (50 m^2), BGR (vegetation and storage layer), Rooftop Area (285 m^2), substrate depth 200 mm	60 mm/min (BGR), 90 mm/min (BR)	July (BR), Sep (BGR), 2014	BGR outperformed the BR in effectively managing prolonged rain events. Nonetheless, the blue roof is a more cost-effective choice when compared to the BGR and is a suitable option for retrofitting in urban areas.

Table 5. Review of field Studies on Parameters Influencing Retention Performance (from 2007–2016).

Ref.	Variable	Climate Conditions, Location	System Details	Rainfall Intensity	Duration (Month)	Findings
[16]	Roof system	Warm summer, cool winter: London, ON. Extreme Temperatures: Calgary, Alberta. Warm winter, Cool summer: Halifax, Nova Scotia.	Extensive GR, rooftop. Live roof setup modules sized 300 × 300 mm. 1. Conventional asphalt 2. gravel ballast 3. white membrane roof. Substrate depth 150 mm	Rain depth: 846 mm 326 mm 1196 mm	24	Retention was more significant on the GR in the semiarid climate (75%) compared to the roof in the maritime climate (43%). Due to elevated evapotranspiration between storms on the semiarid roof, leading to a more extensive restoration of substrate retention capacity.
[23]	Rain Intensity. Soil Type	Maritime, moist, and Temperate climate, Sheffield, England	GR: Three platforms sized 300 × 1000 mm. Substrate 80 mm. Sedum carpet, Meadow flower, and unvegetated	Rain depth <2 mm.	4 years	Rainfall event's size influences retention rates. Non-vegetated soil has a higher retention capacity than soil with grown vegetation, reducing runoff due to evapotranspiration.
[22]	Substrate composition and thickness	Tropical climate (humid-hot summer, cold, dry winter). Hong Kong, China	Extensive GR.16-raised platforms (1100 × 1000 mm) placed outdoors, rooftop. Drainage pipe, Incorporate 40 mm rockwool panel	No	10	Rockwool layer substitute to soil substrate renders the overall system lighter and maximizes the retention capacity of GR. The retention capacity of the system is further improved when a dry period follows a rainfall event.
[32]	Rain depth, Intensity, ADWPs, Duration Substrate depth	Mediterranean climate, Adelaide, South Australia	Extensive GR intensive (Substrate depth = 300 mm) and extensive (Substrate depth = 100 mm)	Variable rain events	24	Higher ADWPs between rainfall events give enough time for the growing media to dry, increasing its water storage capacity.
[55]	Roof systems	Humid continental climate New York, NY, USA	3- GRs: (i) a vegetated mat system installed, (ii) a built-in built-place system, and (iii) a modular tray system	0 to 50 plus mm rain depth	Four seasons	10 mm, the influence of IMC, substrate field capacity, and evapotranspiration on retention performance becomes prominent
[36]	Substrate IMC and capacity	Maritime climate in Newport, UK	GR Area, 1000 × 1000 mm were filled to a depth of 75 mm of soil.	December 2009-June 2010	7	Substrates with greater water-holding capacity resulted in increased water retention within the system.
[15]	Rain intensity	Subtropical climate. Auckland, New Zealand	GR. Full-scale rooftop in the field 50- and 70 mm substrate depths	October 2008–October 2009. Min 2 mm,	12	IMC's low evapotranspiration led to low retention and had the most significant influence on retention capacity.
[54]	Roof slope	Detroit, MI, USA	GR. 12 platforms sized 244 × 244 mm (8 × 8 ft) of extensive green roofs were examined. Slope 2%,7%,15%, and 25%	16 events <2 mm, 24 medium (2–10 mm) and 22 heavy > 10 mm	14	As the slope increased, the retention values decreased. This effect was particularly pronounced for slopes ranging from 2% to 15% and from 2% to 25%

4. Gap in Knowledge

A summary of gaps or limitations in knowledge is addressed below based on the literature review conducted (Tables 2–5).

4.1. *Limitations of Experimental Work*

Based on the reviewed experimental studies, the following gaps/limitations were found:

1. Many experiments may have a limited duration, providing insights into short-term hydrological behavior but not capturing the long-term dynamics and effects of green roofs over an extended period;
2. The scale of experimental plots was primarily small, which does not directly reflect real-world applications, affecting the accuracy of extrapolating results to larger areas or different configurations. Thus, it is necessary to establish a correlation between the length effect and runoff coefficient to relate experimental tests to real-life scenarios;
3. Existing experiments did not fully capture diverse rainfall patterns, including extreme rainfall events causing urban flash flooding, which are crucial for understanding the resilience of green roofs under different weather conditions;

4. The experimental setting did not fully replicate interactions between green roofs and surrounding structures, impeding a comprehensive understanding of their hydrological impact in complex urban environments;
5. The absence of standardized methodologies for assessing and reporting hydrological performance in green roof studies can make comparing results across different experiments challenging;
6. Green roofs evolve over time, and their hydrological performance may change with plant growth, substrate settlement, and aging. Short-term experiments may not capture the dynamic nature of these systems.

4.2. Limitation of Field Monitoring Studies

Despite the rising frequency and severity of extreme rainfall occurrences, monitoring these events comprehensively within a limited local observational timeframe remains challenging. Additionally, precipitation patterns exhibit significant variability from one geographic region to another. Existing studies are influenced by the specific characteristics of the green roof location, such as climate, soil type, and topography, limiting the generalizability of findings to other regions. While existing research primarily concentrates on case-specific investigations or historical datasets, they offer limited insights into the performance of roofs when considering future temperature projections.

Furthermore, field instrumentation often faces malfunctions, leading to the potential oversight of several rainfall events. Prolonged monitoring periods can encompass a broader range of rainfall intensities, facilitating a more robust correlation between system performance and climatic attributes. Insufficient or incomplete data, particularly in real-world scenarios, can hinder the comprehensive assessment of hydrological performance and limit the accuracy of model predictions.

Hence, it is crucial to assess the effectiveness of NBS-CR through extended field monitoring in diverse climatic regions. Furthermore, numerous influential factors interplay and affect the hydrological performance of a green roof. These interacting and fluctuating parameters are more manageable within a controlled laboratory setting. However, there is no standardized test protocol to adopt.

4.3. Lack of a Test Protocol

Based on a review of existing standards, guidelines, and codes, which is detailed in Section 1.1, the following findings are concluded:

1. Local authorities typically set codes that include requirements or recommendations for managing stormwater on green roofs. Regulations may cover aspects such as water retention performance, usually determined by local government bodies or relevant authorities. These standards are compliance standards and not performance standards;
2. There are no test protocols to regulate the design of green roof systems in the market. System regulations are significant in developing uniform design and testing requirements considering climate change while meeting structural requirements to mitigate urban flooding. Moreover, regulations will improve system quality, increase consumer availability, and accelerate mitigation efforts;
3. The existing ASTM standards (ASTM E2397/98/99) [9,10] do not address the whole system performance or quantification. Instead, these standards provide a methodology to test a single module;
4. NBCC [11] provides a reference for a guideline on the vegetative roofing system and the performance of protective materials to the German Landscape Research, Development and Construction Society (FLL) [7] and the National Roofing Contractors Association.

4.4. Lack of Knowledge in the Long-Term Performance

There is a lack of knowledge of the long-term performance of NBS-CR over an extended period. It is therefore necessary to assess the durability and long-term effectiveness of NBS-CR in managing stormwater.

5. Conclusions and Future Recommendations

Over time, various Canadian cities have experienced flash flooding, leading to substantial losses. The total insured losses attributed to flash flood events in Canada prompted the adoption of NBS-CR to manage urban stormwater runoff. This article offers a critical and systematically conducted literature review, analyzing existing research on the parameters influencing the hydrological performance of NBS-CR. The review aims to pinpoint gaps in the literature and pertinent findings.

While research extensively establishes the benefits of employing green roof systems to mitigate urban flooding and adapt to climate change for resilient city development, this review focuses explicitly on the methods or test protocol adopted to quantify NBS-CR performance through an analysis and synthesis of experimental and field research studies.

Research work identified several gaps in experimental testing, such as platform scale, test duration, and rainfall characteristics. Moreover, the short duration of field monitoring does not capture extreme rainfall events. Field instrumentations regularly suffer from malfunctioning instrumentations (Section 4.2). There is a lack of a standardized test protocol and durability of NBS-CR to quantify the hydrological performance of NBS-CR, as detailed in Section 4.3.

To address this missing link in the evaluation of NBS-CR, it is necessary to develop a multi-function work plan that will become a common platform among experts in the industry. This will enable experts to test their systems to meet local climate conditions, estimated climatic projections, structural requirements, and AHJ requirements. It is essential to establish an effective and viable testing methodology to investigate all influencing parameters affecting the retention performance of the GR system. The testing system have to be repeatable and with acceptable uniformity.

Addressing these limitations requires careful consideration in experimental design complemented by modeling, long-term monitoring, and collaboration between researchers, practitioners, and policymakers to develop comprehensive insights into the hydrological performance of green roofs in various contexts. Consequently, it is essential to develop a standardized test protocol that can become a common platform for the industry to test and quantify the hydrological performance of their systems.

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References

1. IPCC. *Climate Change 2022—Mitigation of Climate Change*; Full Report, no. 1.; Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Mitigation of Climate Change; IPCC: Geneva, Switzerland, 2022; ISBN 9789291691609.
2. City of Toronto, Combined Sewer Overflows. Available online: https://www.toronto.ca/services-payments/water-environment/managing-rain-melted-snow/what-is-stormwater-where-does-it-go/combined-sewer-overflows/ (accessed on 1 January 2024).

3. Statistics Canada. Municipal Wastewater Systems in Canada, 2013 to 2017. The daily, No.11, pp. 1–5. 2019. Available online: https://www150.statcan.gc.ca/n1/daily-quotidien/190625/dq190625c-eng.pdf (accessed on 1 January 2024).
4. Office of the Auditor General of Ontario. *Climate Change Adaptation: Reducing Urban Flood Risk*; Office of the Auditor General of Ontario: Toronto, ON, Canada, 2022.
5. Ferreira, C.S.S.; Potočki, K.; Kapović-Solomun, M.; Kalantari, Z. Nature-Based Solutions for Flood Mitigation and Resilience in Urban Areas. In *Handbook of Environmental Chemistry*; Springer: Cham, Switzerland, 2021; Volume 107, pp. 59–78. [CrossRef]
6. Lebeuf, P.A. *Cerner L'impact De La Végétalisation Du Bâtiment Comme Solution Durable Pour Les Organisations*; Essai présenté au Centre universitaire de formation en environnement et développement durable en vue de l'obtention du grade de maître en environnement (M. Env.); Université de Sherbrooke: Sherbrooke, QC, Canada, 2018.
7. FLL. *Guidelines for the Planning, Construction and Maintenance of Green Roofs*; Forschungsge-sellschaft Landschaftsentwicklung Landschaftsbau (FLL): Bonn, Germany, 2018; 150p.
8. City of Toronto. *Toronto Green Roof Construction Standard and the Supplementary Guidelines*; City of Toronto: Toronto, ON, Canada, 2017.
9. *ASTM E2398*; Standard Test Method for Water Capture and Media Retention of Geocomposite Drain Layers for Green Roof Systems. ASTM International: West Conshohocken, PA, USA, 2019; p. 3. [CrossRef]
10. *ASTM-2397*; Standard Practice for Determination of Dead Loads and Live Loads Associated with Green Roof Systems. ASTM International: West Conshohocken, PA, USA, 2019; p. 6. [CrossRef]
11. Canadian Commission on Building and Fire Codes. *National Building Code of Canada 2020*; National Research Council of Canada: Ottawa, ON, Canada, 2020.
12. Canadian Commission on Building and Fire Codes. *National Plumbing Code of Canada 2020*; National Research Council of Canada: Ottawa, ON, Canada, 2020.
13. Alim, M.A.; Jahan, S.; Rahman, A.; Rahman, M.A.; Liebman, M.; Garner, B.; Griffith, R.; Griffith, M.; Tao, Z. Experimental investigation of a multilayer detention roof for stormwater management. *J. Clean. Prod.* **2023**, *395*, 136413. [CrossRef]
14. Yao, A.Y. Agricultural potential estimated from the ratio of actual to potential evapotranspiration. *Agric. Meteorol.* **1974**, *13*, 405–417. [CrossRef]
15. Voyde, E.; Fassman, E.; Simcock, R. Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. *J. Hydrol.* **2010**, *394*, 384–395. [CrossRef]
16. Sims, A.W.; Robinson, C.E.; Smart, C.C.; Voogt, J.A.; Hay, G.J.; Lundholm, J.T.; Powers, B.; O'carroll, D.M. Retention performance of green roofs in three different climate regions. *J. Hydrol.* **2016**, *542*, 115–124. [CrossRef]
17. Shafique, M.; Lee, D.; Kim, R. A Field Study to Evaluate Runoff Quantity from Blue Roof and Green Blue Roof in an Urban Area. *Int. J. Control. Autom.* **2016**, *9*, 59–68. [CrossRef]
18. Squier-Babcock, M.; Davidson, C.I. Hydrologic Performance of an Extensive Green Roof in Syracuse, NY. *Water* **2020**, *12*, 1535. [CrossRef]
19. Hamouz, V.; Pons, V.; Sivertsen, E.; Raspati, G.S.; Bertrand-Krajewski, J.-L.; Muthanna, T.M. Detention-based green roofs for stormwater management under extreme precipitation due to climate change. *Blue-Green Syst.* **2020**, *2*, 250–266. [CrossRef]
20. Almaaitah, T.; Joksimovic, D. Hydrologic and Thermal Performance of a Full-Scale Farmed Blue–Green Roof. *Water* **2022**, *14*, 1700. [CrossRef]
21. Richter, M.; Dickhaut, W. Long-Term Performance of Blue-Green Roof Systems—Results of a Building-Scale Monitoring Study in Hamburg, Germany. *Water* **2023**, *15*, 2806. [CrossRef]
22. Wong, G.K.; Jim, C. Quantitative hydrologic performance of extensive green roof under humid-tropical rainfall regime. *Ecol. Eng.* **2014**, *70*, 366–378. [CrossRef]
23. Stovin, V.; Poë, S.; De-Ville, S.; Berretta, C. The influence of substrate and vegetation configuration on green roof hydrological performance. *Ecol. Eng.* **2015**, *85*, 159–172. [CrossRef]
24. Zhang, S.; Lin, Z.; Zhang, S.; Ge, D. Stormwater retention and detention performance of green roofs with different substrates: Observational data and hydrological simulations. *J. Environ. Manag.* **2021**, *291*, 112682. [CrossRef]
25. Park, S.-Y.; Oh, D.-K.; Lee, S.-Y.; Yeum, K.-J.; Yoon, Y.-H.; Ju, J.-H. Combined Effects of Substrate Depth and Vegetation of Green Roofs on Runoff and Phytoremediation under Heavy Rain. *Water* **2022**, *14*, 2792. [CrossRef]
26. Villarreal, E.L.; Bengtsson, L. Response of a Sedum green-roof to individual rain events. *Ecol. Eng.* **2005**, *25*, 1–7. [CrossRef]
27. Lee, J.; Moon, H.; Kim, T.; Kim, H.; Han, M. Quantitative analysis on the urban flood mitigation effect by the extensive green roof system. *Environ. Pollut.* **2013**, *181*, 257–261. [CrossRef]
28. Lee, J.Y.; Lee, M.J.; Han, M. A pilot study to evaluate runoff quantity from green roofs. *J. Environ. Manag.* **2015**, *152*, 171–176. [CrossRef] [PubMed]
29. Zhang, Z.; Szota, C.; Fletcher, T.D.; Williams, N.S.G.; Farrell, C. Green roof storage capacity can be more important than evapotranspiration for retention performance. *J. Environ. Manag.* **2019**, *232*, 404–412. [CrossRef] [PubMed]
30. da Silva, M.; Najjar, M.K.; Hammad, A.W.A.; Haddad, A.; Vazquez, E. Assessing the Retention Capacity of an Experimental Green Roof Prototype. *Water* **2019**, *12*, 90. [CrossRef]
31. Loiola, C.; Mary, W.; da Silva, L.P. Hydrological performance of modular-tray green roof systems for increasing the resilience of mega-cities to climate change. *J. Hydrol.* **2019**, *573*, 1057–1066. [CrossRef]

32. Razzaghmanesh, M.; Beecham, S. The hydrological behaviour of extensive and intensive green roofs in a dry climate. *Sci. Total Environ.* **2014**, *499*, 284–296. [CrossRef] [PubMed]
33. Giacomello, E.; Gaspari, J. Hydrologic Performance of an Extensive Green Roof under Intense Rain Events: Results from a Rain-Chamber Simulation. *Sustainability* **2021**, *13*, 3078. [CrossRef]
34. Liu, W.; Feng, Q.; Chen, W.; Wei, W.; Deo, R.C. The influence of structural factors on stormwater runoff retention of extensive green roofs: New evidence from scale-based models and real experiments. *J. Hydrol.* **2019**, *569*, 230–238. [CrossRef]
35. Kemp, S.; Hadley, P.; Blanuša, T. The influence of plant type on green roof rainfall retention. *Urban Ecosyst.* **2019**, *22*, 355–366. [CrossRef]
36. Graceson, A.; Hare, M.; Monaghan, J.; Hall, N. The water retention capabilities of growing media for green roofs. *Ecol. Eng.* **2013**, *61*, 328–334. [CrossRef]
37. Alfredo, K.; Montalto, F.; Goldstein, A. Observed and Modeled Performances of Prototype Green Roof Test Plots Subjected to Simulated Low- and High-Intensity Precipitations in a Laboratory Experiment. *J. Hydrol. Eng.* **2010**, *15*, 444–457. [CrossRef]
38. Johannessen, B.G.; Muthanna, T.M.; Braskerud, B.C. Detention and Retention Behavior of Four Extensive Green Roofs in Three Nordic Climate Zones. *Water* **2018**, *10*, 671. [CrossRef]
39. Todorov, D.; Driscoll, C.T.; Todorova, S. Long-term and seasonal hydrologic performance of an extensive green roof. *Hydrol. Process.* **2018**, *32*, 2471–2482. [CrossRef]
40. Rowe, D.B.; Getter, K.L. Improving stormwater retention on green roofs. *J. Living Archit.* **2022**, *9*, 20–36.
41. Pumo, D.; Francipane, A.; Alongi, F.; Noto, L.V. The potential of multilayer green roofs for stormwater management in urban area under semi-arid Mediterranean climate conditions. *J. Environ. Manag.* **2023**, *326*, 116643. [CrossRef]
42. Förster, K.; Westerholt, D.; Kraft, P.; Lösken, G. Unprecedented Retention Capabilities of Extensive Green Roofs—New Design Approaches and an Open-Source Model. *Front. Water* **2021**, *3*, 1–14. [CrossRef]
43. Jensen, R.G.; Burman, M.E.; Allen, R.D. *Evapotranspiration and Irrigation Water Requirements: A Manual*; ASCE: Reston, VA, USA, 1990.
44. Campisano, A.; Modica, C.; Gullotta, A. Long-term experiments for the evaluation of the potential for storm water control of modular blue roofs in Mediterranean climate. *Urban Water J.* **2020**, *18*, 33–42. [CrossRef]
45. Yin, H.; Kong, F.; Dronova, I. Hydrological performance of extensive green roofs in response to different rain events in a subtropical monsoon climate. *Landsc. Ecol. Eng.* **2019**, *15*, 297–313. [CrossRef]
46. Bengtsson, L.; Grahn, L.; Olsson, J. Hydrological function of a thin extensive green roof in southern Sweden. *Hydrol. Res.* **2005**, *36*, 259–268. [CrossRef]
47. Berretta, C.; Poë, S.; Stovin, V. Moisture content behaviour in extensive green roofs during dry periods: The influence of vegetation and substrate characteristics. *J. Hydrol.* **2014**, *511*, 374–386. [CrossRef]
48. Schultz, I.; Sailor, D.J.; Starry, O. Effects of substrate depth and precipitation characteristics on stormwater retention by two green roofs in Portland OR. *J. Hydrol. Reg. Stud.* **2018**, *18*, 110–118. [CrossRef]
49. Almaaitah, T.; Almaaitah, T.; Drake, J.; Drake, J.; Joksimovic, D.; Joksimovic, D. Impact of design variables on hydrologic and thermal performance of green, blue-green and blue roofs. *Blue-Green Syst.* **2022**, *4*, 135–155. [CrossRef]
50. Bortolini, L.; Bettella, F.; Zanin, G. Hydrological Behaviour of Extensive Green Roofs with Native Plants in the Humid Subtropical Climate Context. *Water* **2021**, *13*, 44. [CrossRef]
51. Berti, A.; Tardivo, G.; Chiaudani, A.; Rech, F.; Borin, M. Assessing reference evapotranspiration by the Hargreaves method in north-eastern Italy. *Agric. Water Manag.* **2014**, *140*, 20–25. [CrossRef]
52. Pereira, L.S. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56. 1998. Available online: https://www.researchgate.net/publication/235704197 (accessed on 1 January 2024).
53. Villarreal, E.L. Runoff detention effect of a sedum green-roof. *Hydrol. Res.* **2007**, *38*, 99–105. [CrossRef]
54. Getter, K.L.; Rowe, D.B.; Andresen, J.A. Quantifying the effect of slope on extensive green roof stormwater retention. *Ecol. Eng.* **2007**, *31*, 225–231. [CrossRef]
55. Carson, T.B.; Marasco, D.E.; Culligan, P.J.; McGillis, W.R. Hydrological performance of extensive green roofs in New York City: Observations and multi-year modeling of three full-scale systems. *Environ. Res. Lett.* **2013**, *8*, 024036. [CrossRef]
56. Montalto, F.; Behr, C.; Alfredo, K.; Wolf, M.; Arye, M.; Walsh, M. Rapid assessment of the cost-effectiveness of low impact development for CSO control. *Landsc. Urban Plan.* **2007**, *82*, 117–131. [CrossRef]
57. Carter, T.L.; Rasmussen, T.C. HYDROLOGIC BEHAVIOR OF VEGETATED ROOFS. *JAWRA J. Am. Water Resour. Assoc.* **2006**, *42*, 1261–1274. [CrossRef]
58. Silva, F.; Calheiros, C.S.C.; Valle, G.; Pinto, P.; Albuquerque, A.; Antão-Geraldes, A.M. Influence of Green Roofs on the Design of a Public Stormwater Drainage System: A Case Study. *Sustainability* **2023**, *15*, 5762. [CrossRef]