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*Review*

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

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

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

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## 1. Introduction

### *Urban Nature-Based Solutions*

Urban development and the consequent increase in impermeable areas have changed the hydrological cycle of highly densely populated cities [1,2], with significant negative environmental consequences for urban ecosystems. These landscape changes have affected the corresponding need for water management, in terms of both quantity and quality, since replacement of vegetation and natural infiltration areas have decreased the amount of rainwater that naturally infiltrates groundwater systems, thereby increasing runoff into traditional drainage systems [1]. Additionally, the modification of the landscape has influenced water quality, as stormwater originating from impermeable surfaces tends to accumulate pollutants [2]. All these changes in the urban tissue, coupled with the present climate change scenario, makes city centers more vulnerable to floods and droughts [2]. Current climate change predictions point out that increased precipitation events will occur more frequently and with more intensity, placing more pressure on urban populations and stormwater management infrastructure [3], thus increasing the need to adapt urban areas to those scenarios using biotechnological solutions to achieve more sustainable and resilient cities.

Traditional water management systems focus on transportation and detention at the end of the sewage systems. There are several traditional urban drainage systems that can be used and implemented for stormwater management and drainage in cities, such as cemented surfaces (streets, parking lots, walkways) [4]. However, all these traditional urban drainage systems are not sufficient to deal with stormwater runoff when intense precipitation events occur that exceed the drainage capacity, causing urban floods and the consequent economic losses and environmental degradation. In addition, traditional drainage systems have already proven to be highly expensive in highly populated cities [4]. As such, a change is needed towards a more effective management of rainwater at the development site level, which will help groundwater recharge and water quality management with the aim of decreasing urban flooding and contributing to a more pleasant, sustainable and resilient environment [5].

In this way, urban green infrastructure, also called nature-based solutions (NbS), is identified as “activities to protect, sustainably manage, and restore ecosystems that face social challenges in an effective and adaptative way, serving both human well-being and biodiversity profits” [6]. Green infrastructure or NbS techniques are being developed and implemented with the major goal of keeping natural areas functioning (with regard to water quality and quantity), in addition to allowing the use of rainwater as an alternative resource for potable water, contributing to the improvement of stormwater management in the post-development era [7]. As such, NbS denote more efficient and sustainable responses than traditional water management procedures, concerning disaster risk decrease, water safety and urban resilience [8].

NbS techniques mimic the natural hydrological cycle since they intercept rainfall, enhance infiltration-recharging groundwater, enhance evapotranspiration and reduce surface runoff and peak flow [1,9,10] in an effort to mitigate floods [11]. Furthermore, NbS in built-up areas can reduce pressure on aging stormwater infrastructure, reducing the size of stormwater conveyance systems and the associated costs [1]. In general, all these NbS are designed to control stormwater locally in an attempt to reduce the imperviousness of urbanized areas. Although NbS are not totally effective on flood mitigation when extreme precipitation events occur, coupling them to traditional gray systems might alleviate floods that happen when low- to moderate-intensity rainfall events occur [12]. It has been described that connecting green infrastructures to traditional and transportation surfaces have helped to substantially reduce stormflow volume from a higher surface area [13].

The implementation of NbS follows the EU Water Framework Directive [14] that requires water precipitation management as close as possible to the source, where rainwater must be retained, through water infiltration into the ground [15,16]. Furthermore, NbS also contribute to the UN 2030 Agenda Sustainable Development Goals 11 and 13, which intend to make cities more resilient and sustainable and take actions toward climate change mitigation, respectively.

Thus, the significance of implementing NbS for water management can be condensed into the following four key points:

(1) rainwater retention, allowing it to be used locally where it falls;
(2) reduction of surface runoff into the drainage system;
(3) contribution to water evaporation, decreasing the urban heat island (UHI) effect;
(4) improvement of stormwater quality.

FEMA (Federal Emergency Management Agency) [17] states that the implementation approaches for NbS are varied, and a “one size fits all” is not appropriate. As such, various factors should be taken into account (e.g., local climate, available space or maintenance needs) when designing an NbS typology. Also, differences in design and construction are important factors that will affect the level of the intended benefit(s) [13].

FEMA [17] organizes NbS based on their scale of implementation and place of settlement:

1-Landscape scale: large-scale practices of natural areas requiring extended time for development and management;

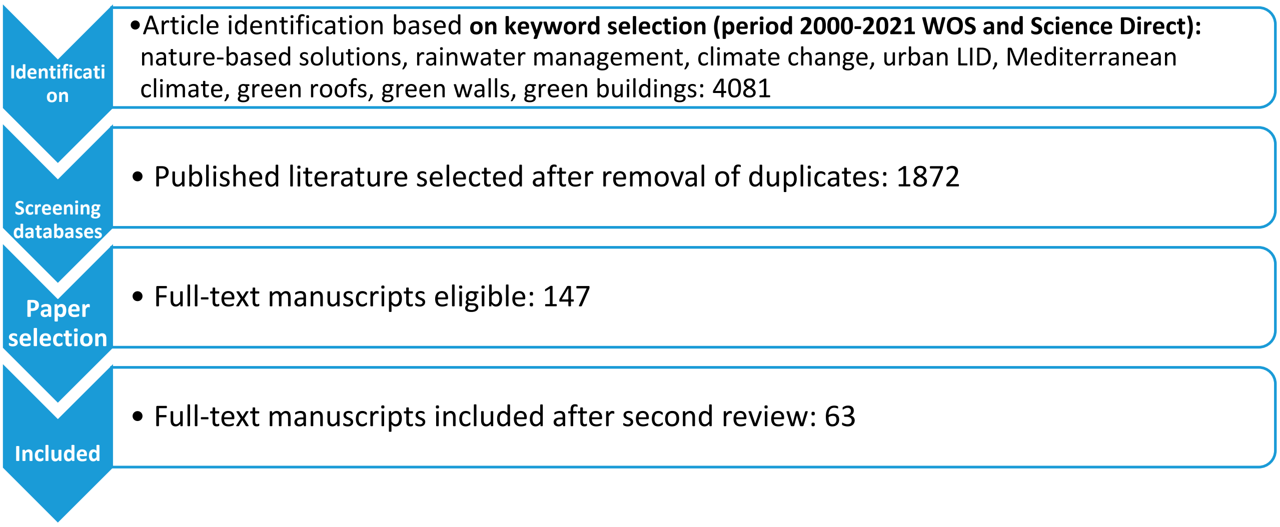
2-Neighborhood or site-scale: practices that manage rainfall at the location of precipitation;

3-Coastal areas: systems that intend to stabilize the coastline, reducing storm impacts and promoting coastal resilience.

Urban NbS are usually settled at the neighborhood scale, where resilience challenges are addressed at a local level (e.g., measures in buildings, streets and open public spaces) [8]. Besides mitigating impacts of air pollution and reducing heat levels in cities by providing shade (urban heat island effect reduction), these NbS can be very effective for local rainwater collection and for increasing stormwater retention capacity, relieving the pressure on existing local infrastructure such as stormwater drains [7]. However, in order to achieve highly functional and effective systems, neighborhood NbS implementation must involve the collaboration between the different stakeholders—governments, private sector, property owners and communities.

## 2. Methodology and Data Collection

The present survey was performed following these steps: (1) definition of the scope and study subjects; (2) selection and exclusion of duplicate research papers; (3) organization of selected papers using an accomplished approach; (4) assessment of the final selected scientific papers (Figure 1). Specific keywords, such as nature-based solutions (NbS), rainwater management, climate change, urban LID (low-impact development), Mediterranean climate, green roofs, green walls, green buildings, plus their combinations were used to search, in both the Science Direct and Web of Science databases, publications from 2000 to 2021, achieving a total of 4081 scientific manuscripts. Limiting the published literature through removal of duplicates, a total of 1872 remained. Furthermore, a more detailed selection was performed based on title analysis, accessibility of full papers and research papers (excluding conference papers) that focused NbS and water quantity data, reducing the number of articles to 105. During the review preparation and after reading the full papers, only 63 completely fulfilled the goal of the present review paper and thus were cited.



- Article identification based **on keyword selection (period 2000-2021 WOS and Science Direct):** nature-based solutions, rainwater management, climate change, urban LID, Mediterranean climate, green roofs, green walls, green buildings: 4081
- Published literature selected after removal of duplicates: 1872
- Full-text manuscripts eligible: 147
- Full-text manuscripts included after second review: 63

**Figure 1.** Diagram of manuscript search approach.

From the conducted selection process, the 63 resulting articles referred to several relevant aspects, such as NbS's support of sustainable development goals' achievement and effectiveness, the influence of their components on the improvement of water retention and the combination with grey infrastructures and with rainwater harvesting and greywater reuse systems. Other important aspects presented by several authors were the need to develop and use adequate design guidelines and to share the benefits of integrating NbS in a clear way with the stakeholders and the population in general. Nowadays, NbS are categorized according to their implementation area (neighborhood, watershed or coastal scales), and diverse pilot studies and modeling studies are being conducted in order to address their effectiveness and the effect of different combinations.

Given the shift of populations from rural to urban areas, thereby resulting in the enlargement of urban areas, and an increase in the number of man-made structures and buildings, a decrease in the accessibility to green spaces has occurred, and therefore an exacerbation of issues related to flooding and water quality (stormwater management) as well as air quality have been observed in urban areas. Therefore, the effectiveness of these solutions in rural areas are not so determinant since the impermeability of roofs combined with a reduction in green areas is more noticeable in cities, due to their densification in recent years [18].

The fast increase in NbS studies shows the relevance that the scientific community sees in these structures, and many efforts are being made to minimize their disadvantages and maximize their benefits. In terms of urban water management, the benefits on stormwater quality are evident (despite the need to improve some configurations with the opposite effect) as are the provided source control of stormwater as presented in the following sections. According to the studies, despite being a worldwide theme, the implementation of NbS in cities is still very scarce and limited to small areas. It is clear that NbS are only 100% effective when exposed to light precipitation events, and the present climate change scenario will exacerbate the intensity of rainfall in urban areas; therefore, a combination of several measures with distinct implementation areas will be crucial. Furthermore, the need to develop stormwater management studies in other climates than temperate ones has been highlighted.

Figure 2 reveals that the first publication on NbS was in 2003 and that there has been an exponential increase in scientific publications on NbS mainly since 2015–2016. Green roofs are undoubtedly the NbS that have been scientifically studied the most (Figure 3). Given the present climate change (with extreme climate events) and the imposed goal of achieving carbon neutrality on the European continent by 2030, scientific research is expected to continue to develop and grow on this topic. Reported studies on NbS will provide significant information towards investigations contributing to the commitment to find efficient and sustainable technological solutions to achieve that goal in the present urban scenario.

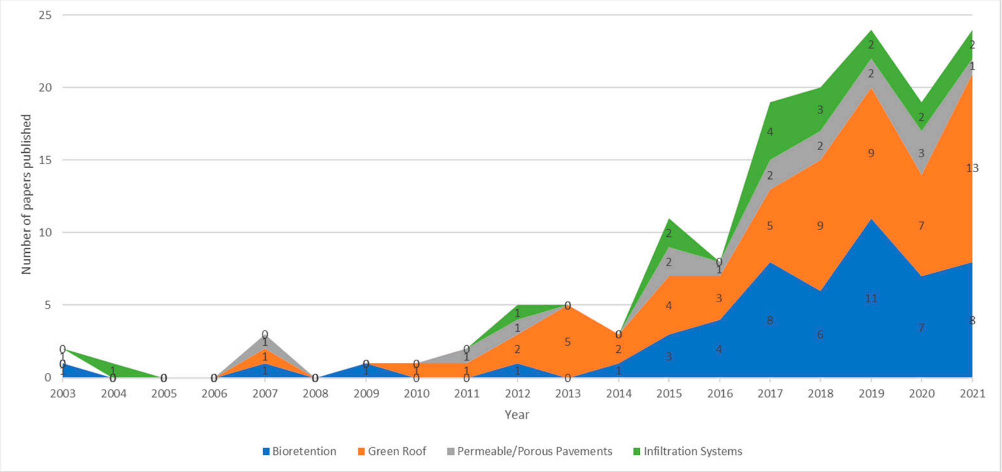


**Figure 2.** Number of papers published per year ($n$ = 147) organized based on their NbS focus (bioretention, green roofs, permeable/porous pavements and infiltration systems). Note that some studies ($n$ = 23) cover more than one type of NbS.

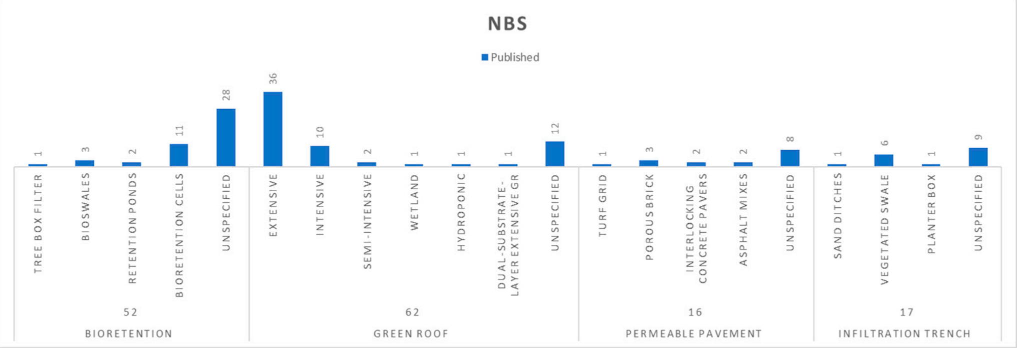


**Figure 3.** Nature-based solutions covered in the studies (*n* = 147, corresponding to the total eligible manuscripts before the second selection).

The current review delivers a summary of published scientific manuscripts that focus on NbS in general, and GR in particular, as sustainable measures for improving stormwater management in urban areas, while contributing to climate change mitigation, aiming to encourage these practices to achieve an environmentally friendly and resilient urban setting. The novelty of the present review paper falls within the conclusions regarding the crucial role that NbS play in urban water management and the main features that must be tested and technically advanced to improve their functioning. The present paper also suggests that green infrastructure design must be adjusted to each region and to the intended goal, emphasizing the need for long-term scientific research to validate the achieved results and to show its long-term efficiency.

## 3. Nature-Based Solutions for Urban Rainwater Management

Urban NbS engineering techniques encompass several biotechnological systems such as bioretention systems (also called rain gardens), bioswales, permeable pavements, infiltration trenches/basins, green roofs and green facades [4,7,19], which are designed to accomplish the following:

- improve stormwater management through natural infiltration;
- develop technological solutions for rainwater harvesting and use of precipitation water in buildings (a practice recommended by the European Commission);
- reduce rainwater runoff from impervious pavements into drainage systems;
- decrease consumption of potable water (e.g., for car washing, garden watering, toilet flushing), which is a topic of high significance due to the decrease in global water availability [15].

However, in order to achieve higher urban stormwater management performance, a combination of techniques is needed to maximize the intended goal, and also to be more effective for urban flood control [1,4]. As an example, the use of vegetated sustainable drainage systems (SUDS) in the UK is encouraged (e.g., green roofs, vegetated swales, rain gardens), for surface water runoff management due to their similarity to natural processes (i.e., infiltrating and attenuating), constituting thus a further sustainable and resilient measure for stormwater management [20]. Furthermore, and due to the structural constraints and high maintenance costs of the current grey infrastructures, Song et al. 2023 [18] emphasize the significance of NbS in overcoming coastal flooding, describing that a maximum of 30% of the green infrastructure area (that may respond to climate change and the recovery of natural ecological processes away from the artificial area) offered the best flood protection and resilience. Infiltration storage facilities, followed by green roofs, are the most effective kind of land cover, while porous pavement has the lowest impact.

Tables 1 and 2 sums up the limitations and advantages of NbS.

### *3.1. Porous Pavements/Permeable Pavements*

Permeable pavements are considered a SUDS infrastructure offering surface urban runoff and peak flow reduction, and therefore drainage system overflow reduction [21]. Porous pavements provide storage (detention and infiltration) of a large proportion of the rainwater precipitation that falls on their surface, functioning as a reservoir that temporarily stores water during the time needed to infiltrate the underlying soil or under-drains, which will then transfer infiltrated water to the conveyance system.

Several research studies have reported permeable pavements' potential for surface runoff reduction, pointing out that differences in infiltration capacities of NbS arise from the materials' diversity [20]. Valinski and Chandler 2015 [22] tested the infiltration capacity of porous pavements' common materials and found that engineered porous pavements performed better than natural silt loam soils.

However, research in the area points out that infiltration capacity is mainly related to location design and environmental issues instead of the material used. Qin et al. 2013 [4] achieved results indicating that the permeable pavement tested achieved a higher flood reduction when intense but shorter precipitation events happened, rather than small and longer precipitation events. Furthermore, the place of peak intensity significantly affected their performance (the best performance was achieved with a middle peak). Lin et al. 2021 [23] reported a pervious pavement water retention rate of ≈50% with cumulative precipitation below 20 mm; with higher precipitation (60 mm rainfall), the rate decreased to 40%. This result shows that when precipitation increases, water retention capacity decreases given the system's saturation threshold. Another author reported significant differences between rainwater volume retention by permeable and impermeable pavements, achieving stormwater retention volumes varying from 16 to 66% [21].

### *3.2. Bioretention*

Bioretention, also called "rain gardens or bioswales", is defined as a practice that allows infiltration with the main goal of decreasing total runoff, storing part of the water, contributing thus to subsurface flow recharge [10,24]. Bioretention systems are usually superficial surface depressions with mulch and an engineered growing substrate, which will host selected autochthonous plants (e.g., shrubs, perennials and flowers) [2,25,26].

Various studies have reported bioretention performance in improving watershed hydrology. Bioretention systems typically holds water only during and following a rainfall event, being dry most of the time. Compared to a conventional lawn, bioretention systems allow for 30% more water infiltration into the ground [1]. Batalini de Macedo et al. 2019 [27] reported average efficiencies of 70% for a bioretention system. A lower retention capacity of 40% for a bioswale system was reported by Shetty et al. 2019 [28]. Batalini de Macedo et al. 2019 [10] also reported 65% average runoff retention efficiency for a bioretention basin structure, over an entire hydrological year, reaching higher values during the dry season (73%). These results made it possible to conclude that bioretention performance (infiltration and retention functions) is crucial when bioretention systems are in the project phase [2] and is highly dependent on the structure and climate conditions [26]. Qin et al. 2013 [4] reported higher flood reduction in early peak storm events when testing bioretention swales. It has been described that the hydrological performance of a vegetated swale to increased storm events is similar to the grey catchment system, reaching thus a limit above which the bioretention swale was unsuccessful. This response shows that for rain events of a high intensity and magnitude, several solutions (green and grey) should work together to accomplish the defined hydrology goals for the management system [29].

Peak flow delay and reduction and a decrease in runoff volume are other important hydrological benefits reported in bioretention systems' performance, depending mainly on the system design. It has been reported that higher substrate depth provides larger runoff storage capacity, and consequently volume and flow peak reduction and peak delay, appearing thus to be the main feature contributing to achieving a better performance [2]. Batalini de Macedo et al. 2019 [10] reported a peak flow attenuation of 80% (that could reach a 96% reduction) by bioretention systems. The experimental study described by Chai et al. 2014 [30] presented a peak flow reduction of 50% from a rain garden and an 83.7% control rate of total annual rainfall runoff volume.

However, quantifying bioretention facilities hydrological benefits in field situations is still little understood due to its complexity regarding technical considerations and is limited due to differences in design and precipitation variability [2,24,25]. Nevertheless, it has been stated that the system can effectively decrease both peak flow and runoff volume, mainly due to the infiltration process [31].

Therefore, it has been identified that additional scientific research to add knowledge about bioretention systems in different climate regions besides the temperate one is required. Nevertheless, bioretention facilities in general provide proven hydrological advantages in runoff management by decreasing runoff and promoting storage, infiltration and groundwater recharge, and thus contributing to flood control [2,32] in urbanized areas and sustainable hydrological cycles [33].

### *3.3. Infiltration Systems*

Infiltration systems (trenches and basins) are shallow excavations filled with filter material, projected to temporarily collect stormwater runoff from the surroundings and to allow its infiltration into the ground through the implemented system [34]. However, since they have an open configuration, the design must be adapted, and a pre-treatment must be performed to eliminate some contaminants. The research presented by Flores et al. 2015 [35] regarding the hydrological assessment of an infiltration trench demonstrated that runoff and peak flow volume relies on the land-use features (e.g., imperviousness, slope) but most significantly on the amount and intensity of the rainfall events. A maximum peak flow reduction of 61% was achieved when the rainfall amount was 40 mm [35].

From the searched literature, only two accessible papers have been found, allowing for the conclusion that little research has been published regarding these types of NbS. It is conceivable to hypothesize that the lack of research experiments conducted using infiltration trenches/basin systems could be due to their complexity to implement and test in real conditions (e.g., installation cost, maintenance) and to follow their performance in situ, and maybe the system and its performance are not widely disseminated among city planners and designers.

### *3.4. Green Roofs*

#### 3.4.1. Green Roof Benefits

Green Roofs (GRs—engineered rooftops that sustain vegetation over a multilayer structure), a type of NbS [5,12,18], contribute to improving urban environments' sustainability and resilience when implemented on a large scale. Among the multiple benefits that GRs provide, we can point out (1) multiple ecosystem services and biodiversity improvement; (2) a decrease in UHI; (3) air pollution reduction ($CO_2$ sequestration) and climate change mitigation; (4) building energy needs decrease; (5) improvement of cities' aesthetic value; (6) stormwater management and runoff reduction [20,36].

Taking into account the present climate change scenario, the last described benefit related to stormwater management and runoff reduction is the main and the most relevant one in urban areas, which could potentially help to increase and disseminate GR implementation throughout cities [4] and is therefore the focus of the present section.

**Table 1.** Urban nature-based solutions—implementation advantages and disadvantages.

| NbS Type | Location | Summary of Results | Advantages | Disadvantages/Limitations | References |
|---|---|---|---|---|---|
| Permeable pavements | China | Flood reduction gradually increases with increasing rainfall amount. | LID designs coupled with conventional flood control techniques reduce urban flooding from heavier and longer storms. | Permeable pavement has the lowest storage capacity among LID designs. | Qin et al., 2013 [4] |
| | Taiwan | Water retention rates ranged from 9.1% to 61.0% (from three studied sites). | Permeable pavement can minimize stormwater drainage system load. | Retention and infiltration are constrained by a prompt runoff outflow at high rainfall intensity. | Lin et al., 2021 [23] |
| | Spain | Permeable pavements retain more rainwater volume (16–66%) than impervious pavement. | After six months of functioning, the NbS is still capable of infiltrating the full water volume at low rainfall intensity. | Drained water releases non-negligible load nutrients (e.g., nitrates). | Crespo et al., 2010 [21] |
| Bioretention | Brazil | Average runoff retention efficiency of 70%.<br>Outflow water with low pollutant concentration reduction. | Runoff may be used for non-potable applications, lowering the catchment's water demand during the dry season.<br>Flood risks and pollutant contamination reduction. | Pollutant removal with low efficiency (concentrations of Fe, Pb, Ni and Cd above the water guideline limits). | Batalini de Macedo et al., 2019 [27] |
| | Brazil | Bioretention system retained 9–100% of runoff.<br>Dry vs. wet seasons: runoff retention efficiency averaged 73% vs. 61%. | Bioretention system delays by 10 min and reduce peak flow by 4–100%. | Bioretention device's storage was constantly below its maximum capacity, demonstrating the system's performance. | Batalini de Macedo et al., 2019 [10] |
| Infiltration systems | South Korea | As rainfall progressed, runoff and flow peaks decreased in magnitude, frequency and duration. Maximum peak flow reduction achieved of 61% (rainfall amount = 40 mm). | Runoff infiltrates into the soil, providing groundwater recharge.<br>Runoff can be temporarily stored or used by the plants. | Volume decrease and peak flow reduction were limited by rainfall intensity and volume.<br>Land use imperviousness, slope, and runoff interceptors also limit the runoff and peak flows. | Flores et al., 2015 [35] |

GRs help with heavy rainfall events, reducing the risk of peak water flow and flood events that arise in urban areas through water harvesting and retention in their structure [4,20], thus reducing the pressure on the city water management systems [37]. Unlike many ground-level sustainable drainage strategies, the great advantage of GRs is that they do not require additional land besides that of the building where they will be implemented [38,39]. In highly urbanized areas, rooftops cover almost 40–50% of impermeable surface area, which is an area not used and could thus be taken advantage of to improve on-site source reduction stormwater management and to increase the permeable surface area [20]. The reported study by Brandão et al. 2017 [40] described that if 75% of Lisbon's city roofs were covered by vegetation, then a maximum of 224,000 m$^3$ of rainwater could be stored, helping the sewage systems deal with intense precipitation events and thus preventing floods.

### 3.4.2. Green Roof Retention Capacity

Rainwater retention capacity by GR systems is affected by several elements:

A. Climate variables: characteristics of the rainfall event—precipitation intensity, antecedent dry weather period (ADWP), season;
B. GR physical features/design variables: system layers and used materials, substrate layer height, substrate hydraulic features, vegetation and roof coverage percentage, geometry, slope and GR age.

A. Climate Variables

- Event Intensity/Duration

Full-scale GR studies have reported that mean rainwater retention is dependent on multiple aspects such as local climatic situations (air temperature, days of antecedent dry weather and precipitation events' pattern and intensity). Usually, a higher retention of precipitation volume is observed in low-intensity rainfall events of moderate duration, which is opposed to a lower precipitation retention volume for heavy events [1,41–43]. Lee et al. 2013 [44] demonstrated a significant retention capacity of an extensive GR system when precipitation events occurred with an intensity inferior to 20 mm/h, once more corroborating the published scientific results that in higher precipitation intensity events, a decrease in the capacity to retain the precipitated water is observed. Following this trend, Wong and Jim 2014 [39] have reported retention capacities varying from 72.6 to 83.9%, 35.9 to 46.7%, and 15.7 to 18.9% for light, medium and heavy events, respectively. The results have also shown outstanding reduction and delay in the precipitation peaks even when the GRs reached their saturation level. Along the same line, Rosatto et al. 2015 [45] described a decrease in storage capacity of the studied extensive GRs (15 cm media depth) (from 68% to 16%) with increasing precipitation intensity (ranging from 21 mm to over 90 mm precipitation events). Results presented by Bortolini et al. 2021 [46] once again corroborated that GR systems present a high capacity to retain precipitation, with retained rainfall volumes varying depending on the intensity of the events: ≈100% for light precipitation (<10 mm); 48–95% for medium precipitation (≥10 and <25 mm) and 20–88% for heavy precipitation (≥25 mm). This differences in retention capacity not only depends on the amount of precipitation (rainfall depth) but also on the weather conditions before the event occurs. The study reported by Stovin et al. 2012 [20] described a total retention of 949.4 mm by the GRs from an amount of 1892.2 mm of precipitation, corresponding to an annual retention rate of 50.2%, and the reported flood reduction performance of GRs by Qin et al. 2013 [4] indicate that GRs are more effective during heavier and shorter storm events with a late peak. Once again, the best rainwater retention results for GR systems regarding the variable of rainfall characteristics have been reported for rainfall events of small length instead of those of high intensity, with the worst retention capacity for high-intensity and extended rain events [40].

Growing substrate humidity is largely affected by precipitation intensity (which is related to the precipitation event's magnitude) and therefore by stormwater holding capacity and runoff. Furthermore, the weather conditions before the precipitation event also affect growing substrate humidity—with higher environmental humidity conditions, retention capacity by the growing substrate is low, thereby increasing the runoff from the system [5]. As such, GR retention capacity is particularly effective for short-duration storm events [39]. Nawaz et al. 2015 [47] demonstrated an extensive GR capacity to effectively hold and delay rainwater from isolated precipitation events in Leeds, UK, significantly correlating its holding capacity with precipitation characteristics (depth, duration, intensity and previous days without rain). On the other hand, extensive GR systems have demonstrated the capacity to efficiently store precipitation in the beginning of the event, highly decreasing the runoff and peak flow compared to roofs without vegetation [43].

- Antecedent dry weather conditions/season

Also, GR water retention performance is seasonally dependent—a higher retention capacity is observed in months with a mild air temperature (spring and early summer), which is related to the substrate's moisture conditions and the antecedent dry weather conditions [1,38,47]. During the winter season, associated high rainfall with low evapotranspiration reduces GR efficiency with regard to water retention: it has been shown, during the rainy season, that GR runoff equals or even exceeds rainfall amounts since the GR system was already saturated at the start of the experiment [38].

A study developed in Italy, a country with a typical Mediterranean climate, showed that the GR systems tested were able to retain 57.5% of the total precipitation, allowing the authors to also conclude that the hydraulic response of the GR system was significantly affected both by the weather conditions before a precipitation event and the characteristics of the precipitation event itself [48].

While GRs' capacity to store precipitation from intense events is restricted, their capacity to store precipitation from light events is crucial for stormwater and urban runoff management, contributing to achieving the goals traced by the Water Framework Directive [47]. Since human beings are not able to change weather conditions, a system's physical characteristics (composition of layers and materials) are the main influencing characteristics that could be changed and adapted to local environmental and climate conditions.

B. GR Physical features/Design variables

During a precipitation event, GR systems intercept rainwater, which allows its infiltration into the growing substrate, promoting its storage in the drainage layer [20,41,42]. After reaching saturation capacity, the excess water that precipitated into the system will run off into the urban drainage systems, or evaporate due to vegetation evapotranspiration [1,20]. As such, GR system design is extremely important and must pay attention to the climate characteristics of the region. This will limit the vegetation species that can be installed and reach healthy development, as well as the materials used for the growing substrate and drainage layer disposal, giving preference for materials with high water-retention capacity [49].

- GR system design (extensive, semi-intensive or intensive)

Water retention of GR systems has been widely studied, and the reported literature points toward a considerable ability to retain rainfall with extensive GR [43] systems, with a 15 cm substrate depth presenting high rates of stormwater retention and peak runoff attenuation [50]. Nevertheless, a reduction percentage between 34.0% and 83%, depending on the GR system implemented, has been observed (extensive, semi-intensive or intensive) [47].

Following FLL guidelines from Germany [51], the key factor affecting retention capacity by GRs is the substrate depth. Extensive and semi-intensive GRs (substrate depth < 200 mm) have been pointed out to retain 60% maximum annual precipitation. The advantage of installing extensive or semi-intensive GR systems is that the load capacity for the building's structure is reduced to [51]. Figure 4 exemplifies the different types of green roofs (not to scale).

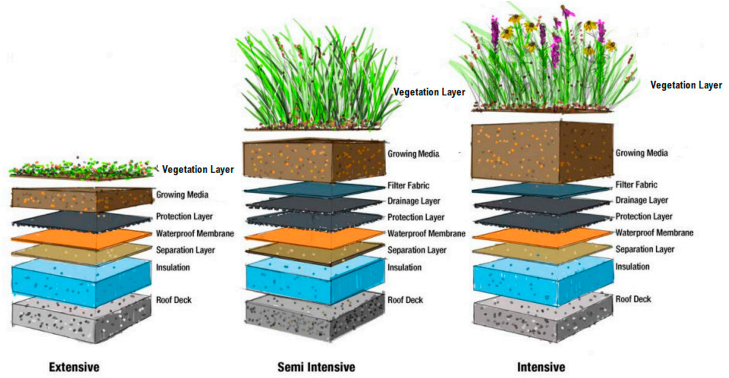


**Figure 4.** Different types of green roofs and their layers (adapted from [52]).

Several authors have reported that substrate chemical formulation and depth influence the capacity for rainwater retention [1,38]. Bradford and Denich 2007 [1] reported that the annual rainfall that can be retained by GRs depends upon the thickness and type of growth medium, contributing to reduction in peak flow. The study presented by Buccola and Spolek 2011 [53] showed that increased GR growing substrate depth (5 cm and 14 cm) improved water retention (36–64%, respectively) and runoff lag-time (5.3–8.1 min, respectively) for medium-intensity rainfall. This study concluded that runoff storage was influenced not only by the precipitation event intensity but also by the substrate depth: rainwater storage was high for low precipitation and higher substrate depth. Zhang 2021 [50] in turn showed that extensive GR (10 cm substrate depth) precipitation retention and detention rates were in the range of 81–87% and 83–87%, respectively. Growing substrate height is thus a feature that demands attention in the design decision step, which largely influences GR performance [53]. However, it has been described that there is a limit to substrate depth to achieve its maximum storage capacity and that an increase in substrate height does not enhance GR system retention capacity [50].

- GR substrate composition/vegetation species

Substrate properties and composition are some of the major influencing factors that affect GR stormwater retention (or water-holding capacity) [54]. Baryla et al. 2018 [55] concluded that GR substrates with a mixture of mineral and organic materials in their composition showed higher retention abilities compared to growing substrates composed of only mineral materials. On the other hand, Bortolini et al. 2021 [46] described a GR holding capacity between 46.2% and 62.9% against 15.4% retention by gravel. Another study reported that a substrate layer composed of fine tile duplicated the capacity to retain rainwater compared to the same substrate layer composed of coarse tile [38]. A developed study where hydrological attributes of individual extensive GR substrate components were evaluated concluded that substrate mixtures with higher perlite amounts showed higher performance regarding rainwater retention (volume and time). Nevertheless, perlite is a manufactured material that uses a high amount of energy to be produced, and its selection must be made carefully so as not to run the risk of nullifying the advantages of the NbS in terms of sustainability [56]. Monteiro et al. 2016 [49] reported a maximum of 20% rainwater runoff from an extensive GR from a total precipitation of 389.7 mm.

As reported by Rocha 2021 [57], runoff volume was significantly dependent on the media composition, with substrate humidity being the key factor influencing rainwater retention capacity and therefore the amount of rainwater drained from the system. Furthermore, Yin et al. 2019 [43] published that precipitation event characteristics (total rainfall depth and duration, and media humidity) induce both intrinsic storage capacity and the runoff volume amount, calling attention to the impact that growing media characteristics coupled with rainfall features have on extensive GR hydrological performance.

Regarding the plant type used in GR systems, the study reported by Bucola and Spolek 2011 [53] concluded that vegetation species are not a key element affecting the runoff amount. Bortolini et al. 2021 [46] reported the opposite tendency in extensive GR pilot systems, concluding that the vegetation layer was the main component of the system that influenced rainwater storage followed by drainage layer and substrate layer. More wide-ranging experimental research developed by Nagase and Dunnet 2012 [58] sought to analyze the influence of plant species and diversity on GR runoff decrease by using vegetation in monocultures and in mixtures, to allow for a wise choice of plant species if the maximizing of rainwater retention (and reduced water runoff) is the intended goal of GRs. The authors described a significant difference in discharge volume when comparing plant species due to their differences in size and structure: grasslands presented the highest reduction (due to their taller height) whereas sedum the lowest (due to its shorter height and reduced root biomass). Besides vegetation species, total GR coverage is also advisable for effective water management [58]. The study described by Liu et al. 2019 [59] concluded that GRs successfully store rainwater, with the delay in the onset of water discharge being mainly affected by the following factors: media composition > media depth > inclination gradient > plant species. This result denotes that media composition and the implemented system media height are the two main layers affecting GR storage capacity.

Several scientific studies have been performed analyzing GR performance when subjected to precipitation events. There are a variety of conditions (environmental and design-/structure-related) that will affect GRs' capacity to store rainwater until reaching their saturation capacity, which makes the results obtained from scientific research hard to compare. Nevertheless, some aspects are universal:

(1) GRs demonstrate a high potential to store rainwater for low-intensity precipitation events;
(2) An antecedent dry weather period (ADWP) is a condition that significantly influences a substrate's ability to retain and delay stormwater drainage;
(3) Higher media height expands GR storage capacity;
(4) Plant density (and its individual metabolism characteristics) affect GRs' capacity to store precipitation, thereby decreasing water drainage.

Studies focused on GR systems' efficiency operating under field conditions are limited. As such, the long-term performance data of GR components are scarce. Furthermore, the outcomes described in the literature highlight the need for GR studies on less explored climate regions (e.g., tropical) [25] to lead to optimal operational performance and to support municipalities' decisions.

### 3.4.3. Hydrological Parameters Evaluated on GR Stormwater Retention

#### A. Volumetric Moisture Content (VMC)

As described previously, the amount of stored water in GR media alters water balance, thus influencing all the related benefits provided by GR systems. There are several means by which GR media can increase the capacity (and time) to reach their saturation capacity subsequent to a precipitation event. After a precipitation event, the maximum substrate water content (or volumetric moisture content) relies on substrate properties (e.g., media layer height), which in turn influences the maximum rainwater retention capacity. A positive correlation has been found between media depth and moisture retention up to a threshold, where further substrate height increments will only retain insignificant water amounts. This situation is particularly important since water retention capacity could be increased with small increments in substate height, avoiding an excess load to the building structure [5].

#### B. Evapotranspiration (ET)

Evapotranspiration (ET) is an important vegetation mechanism in green stormwater infrastructure (GSI), affecting systems' water retention capacity. ET depends on several environmental weather characteristics (precipitation pattern, air temperature and humidity, wind) and vegetated system properties (such as substrate composition and vegetation species used) [41,60]. Plant species used in GRs affect runoff volume according to each plant's specific characteristics (water retention capacity and evapotranspiration rate) [58].

Thus, increasing ET improves all the related benefits regarding stormwater management of the implemented GR. ET is intimately associated with vegetation's stomatal resistance (that changes daily) and leaf area index (LAI) (that changes seasonally) [5]. Leaf area index varies among plant species and indicates the surface area available to release water—the higher the LAI, the higher the vegetation surface area contributing to evapotranspiration. However, ET could also be higher when vegetation coverage is reduced, and therefore sparsely covered substrate loses more water to ET than well covered GRs [5].

#### C. Drainage Reduction/Peak Attenuation/Peak Delay/Runoff Coefficient

GRs also have a preponderant role regarding peak attenuation and therefore the related runoff coefficient of the vegetated system, decreasing the total runoff that is forwarded to the traditional sewer system [5,38]. The runoff coefficient represents a value of the water retention capacity of the GR [49]. Monteiro et al. 2016 [49] developed a user-friendly mathematical expression for the determination of a monthly runoff coefficient for an extensive GR, achieving a runoff coefficient of 0.81, a result of extreme significance since, in the reported literature for runoff coefficient determination, only annual values can be found. Gioaomello et al. 2021 [61] reported a runoff coefficient of 0.68 for a non-vegetated roof for an intense rain event (9 mm/5 min during 15 min), while the GR retained 20% of the rainwater in simulated events. Also, a decrease in outflow (decrease in drained rainwater) of 13% was achieved. We must keep in mind that all these hydrological parameters are interconnected with GR characteristics and climate conditions. As such, it has been reported that the antecedent humidity content of GRs' growing media negatively affects runoff reduction (runoff coefficient) and the period that water starts to drain (peak delay) [59]. As such, GR substrates with an initial lower humidity are pointed out to have a higher capacity of precipitation storage and an extended period to start the drainage process [62].

Discharge rate (or flow) is related to the volumetric amount of water drained by the GR structure per unit time, commonly expressed in L/s. As such, if the discharge rate is low, rainwater retention by the GR system is increased. Peak discharge is influenced by GR system characteristics, namely substrate depth, composition and sometimes the species of the vegetation used [5]. It has been reported that peak discharge attenuation is higher on GRs with vegetation rather than bare soil or unvegetated roofs [5]. As reported by Zhang 2021 [50], the time delay until runoff started and peak release followed in the range of 82–210 min and 63–131 min, respectively, for an extensive GR with 15 cm growing substrate depth. Loiola et al. 2019 [42] reported 58% retention on average, and a delay of 12 min, when testing modular extensive GR systems. On the other hand, 72% runoff was reported by Jeon et al. 2019 [63], achieving an outflow reduction six times higher compared to a traditional concrete material rooftop.

### 3.4.4. Green Roof Disadvantages

Each multilayer GR is a unique living system also presenting some limitations. Especially in the early years of the vegetation's development in intensive GR systems, a leaching problem might exist due to the use of fertilizers, which must be avoided or at least decreased. Furthermore, and in order to avoid water course contamination, control of the first-flush GR discharge might be considered, for example, coupling the GR system drainage system to other NbS urban structures (e.g., rain gardens and/or vegetated swales) to allow nutrients' infiltration into the ground soil [36]. Another example is that the installation of this vegetated system in old buildings might be not suitable due to the excessive load needs. As such, a carefully engineered examination must be performed before retrofitting the building; an adequate choice of the intended type of GR, and subsequently the growing substrate's depth, must be made in the design phase if the intended benefit is stormwater management and rainwater harvesting and retention [37]. Nevertheless, GR systems are a valuable strategy for improving urban sustainability and resilience in the present climate change scenario.

**Table 2.** Green roofs as urban nature-based solutions—implementation advantages and disadvantages.

| NbS Type | Location | Summary of Results | Advantages | Disadvantages/Limitations | References |
|---|---|---|---|---|---|
| Green Roofs (GRs) | Lisbon, Portugal | GR decreased and delayed stormwater runoff and peak flow.<br>Out of 184 tests, 69 did not create runoff. | 224,000 $m^3$ of rainwater is estimated to be retained (if 75% of Lisbon's rooftops were covered with vegetation). | Mediterranean region has extra need for watering systems throughout the summer drought.<br>Colder/rainy season brings heavy rainfall in short periods. | Brandão et al., 2017 [40] |
| | Italy | Retained rainfall volumes varied with rainfall depth and the previous meteorological period: ≈100% for light precipitation (<10 mm); 48–95% for medium precipitation (≥10 and <25 mm) and 20–88% for heavy precipitation (≥25 mm).<br>Vegetation retained the most stormwater volume, followed by drainage/storage and substrate layers. | Tested GR systems retained 46.2% to 62.9% of precipitation, vs. 15.4% retention by gravel. | Substrates' capacity to control rainfall depends on their combination with the drainage/storage layer. | Bortolini et al., 2021 [46] |
| | Hong Kong | Retention capacities varied depending on the event's intensity: 72.6–83.9% for light events, 35.9–46.7% for medium events and 15.7–18.9% for heavy events. | Precipitation peaks are significantly reduced and delayed. | Since GR retention is finite, it may not be able to mitigate stormwater during severe precipitation events. | Wong and Jim 2014 [39] |
| | USA | GR soil depth enhanced water retention and runoff lag time. | Vegetated roofs have lower runoff conductivity than bare soil. | Soil depth affects GR performance.<br>Additional soil depth increases retention but also solution conductivity, which may indicate suspended particles (degrading water quality). | Buccola and Spolek 2011 [52] |
| | China | Factors affecting extensive GR storage capacity: substrate composition > substrate depth > inclination gradient > plant species. | GR can efficiently delay runoff and retain stormwater. | Antecedent moisture contents of the substrate have a negative effect on runoff retention. | Liu et al., 2019 [58] |

## 4. Research Gaps and Future Directions

This review examines the role of NbS in mitigating the effects of urbanization and consequent high impermeabilization and its ability to increase urban resilience to climate change, according to studies published within the last two decades.

Current studies are focused on finding NbS solutions in original ways to maintain the functions of urban natural areas (in terms of water quality and quantity), in addition to enabling the use of rainwater as an alternative resource to potable water and stormwater management improvement in the post-development era. NbS also represent a sustainable action to enhance urban resilience by reducing disaster risk and ensuring the safety of the water supply. However, there are some obstacles due to unpredictability in the functionality, performance and implementation of NbS. Consequently, it is essential to take an integrated approach, assigning the critical role of NbS practices to the environment and mitigating the effects of climate change.

In the context of environmental and water management strategies, NbS are acknowledged as a very effective method. In the urban setting, initiatives like porous and permeable pavements, bioretention, infiltration systems, and green roofs have been put into place offering integrated benefits, such as water flow management and runoff mitigation, flood control and the implementation of natural water retention measures, enhancing the connections and operations of green infrastructure.

The benefits of stormwater quality and quantity in urban water management are evident, although there is room for improvement to avoid adverse effects. Empirical research shows that urban adoption of NbS is still very limited and geographically constrained. Moreover, there has been an emphasis on the necessity of conducting stormwater management research in climates beyond temperate regions. The findings of this review lead to the conclusion that the performance of bioretention systems, specifically in terms of infiltration and retention functions, plays a critical role during the project phase. Furthermore, the effectiveness of these systems is influenced by their structural characteristics and the prevailing climate conditions.

It has been determined that only two papers were identified regarding infiltration trenches and basin systems, indicating a limited amount of published research pertaining to these NbS. This may be attributed to the inherent challenges associated with their implementation and testing in situ, such as high installation costs and maintenance requirements.

Green roofs are the most studied NbS implemented in urban areas. There are several benefits associated with GRs, many of which have been extensively researched. One of the main benefits of GRs is that, in contrast to many ground-level sustainable drainage techniques, they do not need any more land beyond the building where they will be used. Recent studies have revealed that GRs can be seamlessly integrated with other NbS, thereby making a valuable contribution to the promotion of environmental sustainability. However, there is a notable knowledge deficit that delays the widespread adoption of GRs beyond their current level of popularity. One of the primary justifications is that most of the advantages associated with GRs remain theoretical. Additionally, it should be noted that the scope of research pertaining to GRs is currently limited to some countries in Europe, America and Asia. According to full-scale GR research, factors such as local climate conditions and GR physical design components affect mean rainfall retention. Regarding the variable of rainfall characteristics, the best rainwater retention outcomes for GR systems have been recorded for short-duration rain events rather than long-duration rain events, with high intensity and lengthy rain episodes having the poorest retention capacity. However, there is a limit to substrate depth in achieving its maximum storage capacity.

The implementation of NbS in urban contexts requires the cooperation of different stakeholders, such as governments, the private sector, property owners and communities, in order to produce highly functioning and successful systems. Policymakers have the potential to ease the adoption of GRs by offering incentives, addressing common concerns and establishing regulatory frameworks. To help the end-consumer and stakeholders better understand the actual circumstances, life-cycle and cost analyses should also be carried out in each geographic region.

## 5. Conclusions

A diversity of evident benefits arise from the implementation of NbS in urban ecosystems, mainly water management efficiency given the technological development guarantee and cost-effectiveness. In that way, governments worldwide have promoted their installation to gain their benefits, following guidelines that have been developed by taking into account the established research. Nevertheless, some limitations still exist. More research is needed to quantify benefits with easily measurable outcomes that are easily understood, to contribute to a real understanding of the positive influences of NbS for both the short and long term that will help widen policy adaptation.

The excellent performance of NbS (particularly GR) could be attained following the recommendations below:

1. Rainfall patterns in the Mediterranean region are changing due to climate change. As such, NbS selection and design criteria need to be adapted to each region, local weather conditions (based on the rainfall and runoff pattern) and the intended target, in order to increase the successful achievement and cost-effectiveness of NbS implementation with higher water resilience.
2. Engineered growing substrate and drainage layer materials are the key elements in NbS stormwater management, to enhance hydraulic performance (water infiltration, retention, runoff) of the technological system.
3. Further NbS must be implemented in urban Mediterranean regions, combining them with traditional drainage systems to achieve higher efficient NbS that are more adapted to the installed location and intended goal. This process of integrating NbS into existing traditional local stormwater control systems has a long way to go in the investigation of NbS. In addition, combining rainwater retention measures for later use will be of higher significance for academic investigation and real-world implementation of NbS applications.

Further research over extended time periods must be performed to surpass the current limits in NbS technologies.

The high number of research studies published over the last decade suggests that NbS can be implemented at scales with a high degree of influence in watershed hydrology, therefore enhancing overall urban resilience to climate change. In that way, it is highly recommended that urban designers start to include stormwater management design in their projects to decrease the vulnerability of those areas to floods, especially in those cities that still mainly use the conventional method of drain and pipe. This review paper serves as an encouragement for urban designers and hydrological engineers to apply NbS practices at the neighborhood or site scale as a tool to improve urban stormwater management, also contributing to mitigating the consequences of the climate crisis and furthering current knowledge of the actual topic.

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## Abbreviations

| | |
|---|---|
| NbS | Nature-based solutions |
| LID | Low-impact development |
| SUDS | Sustainable drainage systems |
| GR | Green roofs |
| FEMA | Federal Emergency Management Agency |
| VMC | Volumetric moisture content |
| ET | Evapotranspiration |
| GSI | Green stormwater infrastructure |
| LAI | Leaf area index |
| UHI | Urban heat island |

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