Chapter

Green Roofs Influence on Stormwater Quantity and Quality: A Review

Cristina Santos and Cristina M. Monteiro

Abstract

This chapter intends to make an extensive review of the influence that Green Roofs (GR) have on the quality and quantity of stormwater. These aspects are very important to define the benefits and the disadvantages of this nature-based solution that is being implemented worldwide to improve the sustainability of urban areas. Previous studies show that the characteristics of GR (such as dimensions, the composition of the different layers and the type of plants) have a major influence on the quality and quantity of the GR runoff. Despite the proven benefits in urban stormwater management, in some reported cases, the quality resulted worst and for some GR conditions, the effect on rainwater retention was minimal. They are key elements to make resilient cities so a clear understanding of their functioning and development is fundamental to avoid and minimize potential impacts of malfunctioning of these nature-based structures.

Keywords: green roofs, stormwater, rainwater harvesting, rainwater quality

1. Introduction

1.1 Water issues and nature-based solutions

Nowadays, people are using water more efficiently due to environmental awareness, tariff policies and technological innovations. In Europe, for example, a decreasing trend in water abstraction is being observed in the last decades and water consumption is decoupling from economic growth, as water use efficiency has increased in the related water-dependent sectors, such as public water supply and tourism. However, as stated by the European Environment Report nr. 12/2021 [1] the issue of water stress continues to escalate as climate change exacerbates seasonal variations in water availability. The observed decreasing trend in water abstraction volumes has so far not translated into an improvement in the quantitative status of water bodies, and this may be partly due to the slow process of recovery and also to climate change, which can offset volumetric gains and aggravate local pressures. On the other hand, the urban population continues to grow, which leads to an increase in urban water demand. To continuously supply this demand, new storage systems, abstraction and networks are developed but with serious consequences to freshwater sources and ecosystems. Urbanization brings also soil sealing and flood situations, once the amount of naturally infiltrated stormwater is significantly reduced. The variability and pressure caused by climate change and seasonal variation in water supply tend to aggravate these problems. Thus, approaches focusing on valorizing unconventional resources (e.g., desalination, water reuse, rainwater harvesting) are already implemented in many Member states. Besides, several European Union policy initiatives support the use of Nature-based Solutions (NbS) to reduce Europe's vulnerability to water stress [1].

NbS are systems inspired and supported by Nature, implemented in urban areas to restore vegetation and natural ecosystems. The Federal Emergency Management Agency (FEMA) of the USA describes them as sustainable planning, design, environmental management, and engineering practices that weave natural features or processes into the built environment to build more resilient communities [2]. On a neighborhood or site scale, they are defined as distributed stormwater management practices that manage rainwater where it falls. These practices can often be built into a site, a corridor, or a block without requiring additional space.

The use of NbS infrastructure can reduce the cost of stormwater management for new development because material costs and land disturbance are lower than traditional drainage [2]. The use of Nbs can also help to control stormwater that enters combined sewer systems, resulting in important savings in the amount of water treated in wastewater treatment plants and the consequence of flood occurrences. As referred by FEMA [2], New York City developed a plan to reduce combined sewer overflows using green and gray infrastructure and they predict that the NbS component will capture runoff from 10% of the impervious areas with a cost of about $1.5 billion, while the gray infrastructure option would cost about $3.9 billion.

The European Commission [3] states that implementing NbS on a larger scale would increase climate resilience while contributing to multiple Green Deal objectives. Buildings can contribute to large-scale adaptation, for example through local water retention and urban heat island effect reduction when incorporating green infrastructure.

NbS include green infrastructure technologies such as Green Roofs (GR), which are being implemented as part of a combined sewer overflow abatement strategy and to develop co-benefits of diminished stormwater runoff, including decreased loading of contaminants to the wastewater system and surface waters [4]. The study made by Koc et al. [5] revealed the important contribution of GR to stormwater management in urban areas: among different solutions (bioretention cells, permeable pavement and infiltration trench, isolated or in combination), GR provided the highest improvement with approximately 40% in both peak discharge and volume reduction and has been found as the optimal practice among the stand-alone solutions. The main reason for those results is that GR provides the closest characteristic to a natural basin by capturing the rainfall and increasing the time that a water drop takes to reach the drainage system. The best-integrated evaluation showed that GR and bioretention cells can significantly reduce the impacts of urban flooding.

Transitions towards urban built environments that incorporate sustainable drainage systems encounter several barriers such as limited evidence on their performance or concerns about negative impacts that they might cause. Collective efforts from different stakeholders, are essential to highlight the important benefits provided by them [6].

1.2 Aims and scope

This chapter intends to present the effects of GR in stormwater management. This NbS is being implemented worldwide and its effects on stormwater quality and quantity are being intensively investigated. These structures have an important impact on stormwater control and reduction, but they change the quality of the drained water. On the other hand, their efficiency is highly influenced by their characteristics and therefore, the more relevant design aspects should be carefully assessed. Intense literature research was made to analyze these questions. GR are characterized in detail in sub-chapter 2, and their effects on stormwater quantity and quality are detailed in sub-chapter 3, based on the main conclusions of experimental activities developed around the world.

The bibliographic research was made in two steps. In the first one, the "science direct" database was used, with four keywords: "green roof" stormwater quantity; "green roof" stormwater quality; "green roof" rainwater quantity; "green roof" rainwater quality. The advanced search (including title, abstract or author-specified keywords) was used and a total of 91 articles were found, 24 of them were duplicated. In the second step, the abstracts of the remaining 67 articles were analyzed and 24 of them were categorized as out of scope. Besides, 3 articles were not considered because two were extended abstracts from conferences and one was not available. The final result of the bibliographic research was 40 articles, published from 2007 to 2021. They were fully read to sustain the values and ideas presented in this chapter.

2. Green roofs

GR (also known as vegetated roofs) are defined as any type of soil–vegetation system established on building floors or roofs excluding the cases of pot vegetation [7]. In constructive terms, they are implemented in the building structure with the following components, from bottom to top: a high-quality waterproof membrane, a root barrier to protect the membrane, a drainage layer, a growing substrate and finally, the plants (**Figure 1**).

The GR vegetation most commonly used worldwide is Sedum, which has attributes of succulent plants such as a low growth rate and drought resistance that leads to low maintenance requirements [9]. Besides, using different plant species and

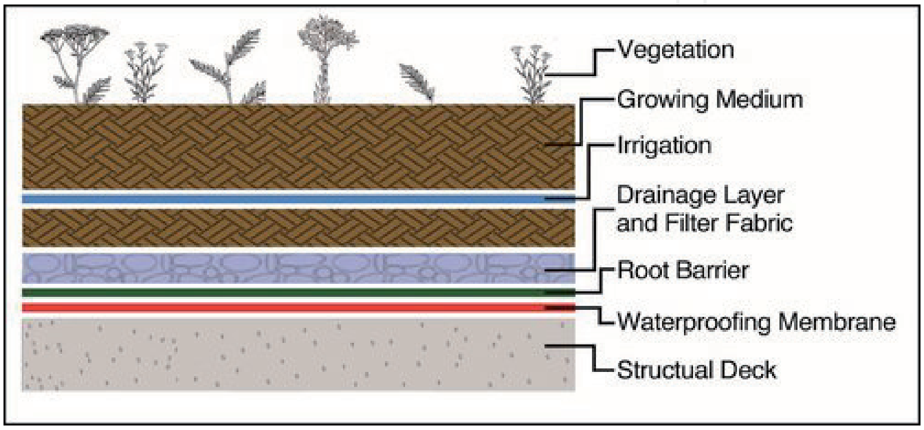

Figure 1.
GR section (the irrigation system is optional) [8].

creating diverse ecosystems, is generally more successful than planting single varieties of vegetation. Liu et al. [10] presented vegetation layers with three different plant species - Radix Ophiopogonis, Sedum Spectabile and Iris – with high resistance abilities to drought stress conditions and widely incorporated in local landscaping works and GR designs. Kuoppamäki [11] studied GR with two levels of establishment method: either by planting with seeds and plug plants or as pre-grown mats. The total thickness of the growing substrate of all meadow roofs was set to 10 cm. Meadow roofs established on-site with plantings are dynamic ecosystems, with wide temperature variation, which contribute to high evapotranspiration, resulting in lower moisture at the start of rain events. Although, this difference declined with time, as roof ecosystems evolved, the author considered plantings a better design than mats considering various factors. Guidelines were already developed by many countries to recommend the appropriate selection of plants to improve the benefits and to overcome difficult conditions prevailing on the rooftop, such as water scarcity and extreme climatic conditions [12].

Growing medium (also referred to as the substrate layer) is an essential component of GR that directly influences plant growth and also benefits GR regarding stormwater management, rainwater buffering, building energy savings, and sound insulation [12]. Substrates for GR are typically a mix of inorganic sand, organic soil, and fertilizers, which differ depending on the vegetation used. Sand, white charcoal debris mixed with sand, organic matter mixed with soil, and burned reservoir sludge mixed with rice hulls are examples of substrate constituents, that can also include the use of recycled materials [9]. Different ratios of organic and inorganic constituents result in GR substrate with distinct characteristics, appropriate for different applications.

The drainage layer maintains a non-water-logged and aerated condition for the substrate to support healthy plant growth. It plays a vital role in a GR, also by storing water between the substrate and the drainage material (or in the compartments of drainage plastic modules) that is used by plants in dry periods [12].

The root-barrier is optional for extensive GR but highly recommended in intensive ones once it protects the waterproof membrane from the roots of large plants. When necessary, an insulation layer might also be considered, as it prevents the water retained in the GR from extracting heat in the winter or cooling the air in the summer.

The waterproofing membrane will prevent the moisture of the substrate and drainage layer to pass into the structural deck, so its high quality and well execution are fundamental to keep the roof in good conditions and to avoid humidity problems inside the buildings.

GR systems may be modular, with drainage layers, filter cloth, growing medium, and plants already prepared in movable, often interlocking grids, or loose laid/built-up whereby each component of the system may be installed separately [8]. As referred, they present distinctive characteristics in terms of growing medium and plants but are usually categorized due to their intensive or extensive planting as stated by Berndtsson [7]:

- Intensive GR have deep soil layers and can support large plants and bushes. Typically, they require maintenance in the form of watering, fertilizing, and weeding;

- Extensive GR have thinner soil layers and smaller plants which in the final stage are expected to provide full coverage of the roof. These GR are more commonly used because they can be implemented in existing buildings and are generally maintenance-free. Some fertilization is often recommended especially in the first years.

It should be noted that distinct authors differ in the limits of substrate layer thickness defined for intensive and extensive systems, but the majority defines the 0.15 m as the frontier. **Table 1** resumes the main characteristics of both types of GR.

Existing full-scale GR, reported in the literature, present the following general characteristics:

- In Helsinki and Espoo, Finland: nine thin-layered (2–12 cm of the substrate) Sedum/moss roofs, and two meadow roofs with substrate depths of 21 and 23 cm [13];

- In New York, USA: a GR composed by six types of native sedum located over 10.2 cm of lightweight growth media. Above the growth, media is a drainage composite, with a water retention capacity of 7.9 mm of water, underlain by an adhered, waterproof, single-ply, thermoplastic polyolefin membrane. The membrane was installed over moisture-resistant gypsum board, tapered roof insulation, vapor barrier, and concrete deck [14];

- In Manchester, UK: a 43-year-old intensive GR with an average depth of 170 mm. It has standard construction with the vegetation and substrate layers divided from the 'egg box' design plastic drainage layer by a fibrous membrane. The roof itself is protected by a tough geotextile membrane. It has a mineral soil substrate rather than the more usual, prefabricated, lightweight aggregate (LWA) based substrate [15];

- In Alberta, Canada: an extensive GR planted with nine different vegetation species including three sedum varieties, two types of grass and four different flowering forbs. The GR growing medium are composed of recycled materials and minerals, and enhanced with compost, presenting a depth of 150 mm. On the bottom, the GR includes a Floradrain FD 25-E drainage board (with holes facing up) with a separate filter sheet [16].

In a conventional GR, such as the one represented in **Figure 1**, part of the rainfall is stored in the substrate layer and consumed by plants, another part returns to the atmosphere by evapotranspiration and the remaining rainfall is discharged as runoff. The amount of rainfall that is not released as runoff is affected interacts with the components of the GR and their physical environment and is defined as retention [11]. The dual-substrate-layer GR presented by Wang et al. [17], consisting of an upper organic nutrition layer for plant growth and a lower inorganic adsorption layer for water retention and pollutant reduction. This new generation of multilayer GR also present an additional layer to store rainwater which, if properly treated, can be reused for different purposes [18]. Cost analysis proved the practicability of dual-substrate-layer GR in retaining rainwater, but their long-term rainwater runoff quantity and quality performance in urban environments merit further investigation [17]. Xu et al. [19] studied a hydroponic GR system, developed to reduce urban stormwater runoff and to collect, treat and reuse greywater and rainwater onsite in green buildings. According to the authors, this system has a greater potential to reduce urban flooding relative to traditional GR and ensures the long-term effectiveness and stability of water reuse by intercepting rainwater and achieving long-term collection and treatment of greywater.

	Intensive GR	Extensive GR
Growing medium (substrate layer)	>15 cm	<15 cm
Weight	Heavy; require concrete support	Low; used with concrete, steel and/or timber support
Plants	Perennials, lawn, shrubs, small trees and rooftop farming	Grass, herbs, mosses, sedums and other succulents
Irrigation needs	Constant irrigation using an automated sprayer	Required only in dry periods
Maintenance	High	Low
Fertilization	Required trough the GR lifetime	Not required (except in the first years)
Waterproofing	High-end	Low-end
Root-barrier	Required	Not required
Overall costs	Higher	Lower

Table 1.
Characteristics of different GR (adapted from Vijayaraghavan et al. [12]).

The most relevant benefits associated with GR, are: (1) regulation of the urban thermal climate (minimizing urban heat island effect) and reduction of the energy consumption in buildings, (2) retention, reduction and quality improvement of stormwater, (3) enhancement of air quality, (4) creation of habitat for flora and fauna, (5) and supporting elements related to physical and mental well-being and (6) esthetic improvement of the urban environment [20, 21]. GR can also contribute to the food supply in urban areas, specifically the intensive ones, if they were used as rooftop farming. Apart from the great influence on the esthetics of the buildings, the study reported by Karteris et al. [22] showed that spices and aromatic plants achieve high CO_2 sequestration rates in extensive GR. They also showed their potential of reducing CO_2 emissions due to energy conservation and CO_2 absorption by GR. The energy conservation rates are strongly connected to the date of construction of the buildings, the available roof area and the number of floors and the use of the building. Large-scale implementation of GR can improve the mean rainwater retention rate in cities and thus contribute to the reduction of rainwater runoff and flood occurrence.

The survey made by Chen [9] in Taiwan revealed that the major concerns in selecting the type of GR, were the drainage performance and potential damages on the roof structure. People worried about litter clogging the drainage pipes and causing overflows on the roofs, and about water leakage on the ceilings due to the intrusion of the plant's roots into the roof construction materials. Thus, the most existing GR in Taiwan were the extensive type. The spatial distribution of GR benefits is dependent on the spatial distribution of suitable roof areas and environmental stressors. For example, the case study of the inner-city area of Braunschweig (Germany), presented by Grunwald, et al. [23], had great potential, with a higher percentage of benefits in comparison to residential areas. This is very relevant for this type of green infrastructure, that can be implemented on already existing roof areas (usually called as retrofit). GR is a highly sustainable and efficient solution to introduce additional vegetated areas within densely built cities where the impact of environmental stressors is usually high.

Despite the benefits of GR in managing urban stormwater quantity and quality, several studies have demonstrated that GR can pose negative impacts on the urban environment due to chemical leaching, in particular in their early age [16]. They are a living system with many components, so understanding its dynamics is necessary to predict potential environmental impacts. Also, a significant challenge in their widespread implementation is the execution costs, which are higher when compared to traditional roofs. However, the difference can be attenuated if the benefits are well investigated and documented. As referred above, besides the improvement in stormwater control and thermodynamic performance, the vegetative cover of GR also brings an extra source of CO_2 capture into the cities, and provides habitats for wildlife.

3. Impacts of green roofs on stormwater

As urban areas continue to expand, stormwater negative consequences are increasing, and climate change will worsen this situation. In this scope, particular focus should be given to cities with combined sewer systems where stormwater and wastewater are conveyed to the same pipes. In such cases, additional costs are allocated to the treatment plants and, when heavy rain events occur, the affluent volume can exceed the capacity of the system and raw untreated sewage might flow out of relief points into water resources.

A GR changes stormwater runoff, when compared with that from a traditional hard roof, through lowering and delaying the peak runoff. For the same rain event, the peak from the traditional hard roof occurs sooner because a certain water volume is detained in the GR multilayer system and a part of it is retained, as explained previously. The retained water is evaporated and transpired by the plants, and this explains the observed runoff volume reduction [7]. Besides, while flowing through the GR, the water interacts wilt the different organic and inorganic elements and changes its quality. Thus, GR have a direct influence on the stormwater runoff, mainly due to the characteristics of their components. The magnitude of this influence and the factors that contribute the most, both to the quantity and to the quality of the runoff, are described in the following subchapters.

3.1 Effects on stormwater quantity

For retaining water, the GR substrate texture and porosity act as a series of pipelines that store water and control the flow rate at which water runs through the growing medium. Before reaching its peak capacity, the runoff from a GR is lower than the runoff from a traditional roof. While water flows through the substrate, it is partially consumed by plants or retained in the substrate porous, so the total runoff volume at the end of rainfall events is also lower for GR than for traditional roofs. The retention capacity of a GR is the difference between the runoff volume of a conventional and GR and that difference is bigger in small-intensity rain events, considering that the substrate is not saturated. After reaching the peak capacity or if the antecedent dry weather days (ADWD) are not enough to restore the retaining capacity of the substrate, the benefits of the GR concerning stormwater control are minimized.

The reduction in GR runoff generally ranges from 50–100% depending on the distinct factors described below [24]. Once the runoff is released over a longer period of time, these structures decrease the flooding risk and improve the performance of the networks downstream.

Kuoppamaki [11] quantified the capacity of Meadow roofs to retain and detain runoff in a field experiment in southern Finland, with varying weather conditions over 4 years. The meadow roofs showed a 40–70% annual cumulative retention of rainfall. Three main factors influenced this retention: (1) the seasonal variability, as the highest retention was measured in the rainiest season, (2) the evapotranspiration, because the retention capacity declined for their study with the development of plant cover and (3) the establishment of root systems that may have created preferential flow paths that reduced storage capacity.

Vegetation plays an important role in the retention and detention capacity of a GR. Despite the 100% vegetation cover of the mat's treatment studied by Kuoppamaki [11], these roofs retained less rainfall annually (40–60%) than less densely vegetated plantings (50–70%). According to Liu et al. [25], trees and shrubs, when compared to grasses, have a higher capacity to retain stormwater, due to: (1) creation of a denser canopy and trunk layers, which increases the evaporation area and trunk flow; (2) establishment of a thicker litter layer on the substrate surface, with excellent water-holding capacity, that extends infiltration time and reduces surface runoff; and (3) more abundant roots with a higher water-retention capacity. Also, the nine-month GR pilot study performed by Harper et al. [26] showed an approx. 40% reduction in runoff from the unplanted growing medium and an approx. 60% reduction in runoff from the planted growing medium. They highlighted the seasonal impact of plant evapotranspiration as the reduction in runoff was dependent on the season. Plants were a statistically significant factor in fall and spring, but not in winter once in wet seasons a reduced overall impact of growing medium and planting on total flow was registered. Authors stated that plants had a 20% additional reduction in stormwater runoff in the fall, despite relatively recent establishment, and when the plants were dormant over winter, less variation between the planted and unplanted trays was observed, as would be expected under low evapotranspiration conditions.

Due to the dynamic of water flowing through the GR, the depth of the substrate and its initial moisture have a major influence on precipitation retention. Lee et al. [27] showed that a GR with a soil depth of 200 mm (intensive GR) reduced runoff by 42.8–60.8% compared to a 13.8–34.4% reduction of a GR with a soil depth of 150 mm. Viola et al. [28] also explored the retention performance of GR as a function of their depth and in different climate regimes, using both an intensive and an extensive GR. The amount of retained water increased in higher substrate depth, because more water was allowed to be stored in the active layer and consequently evaporate from the system. These results lead to the need to focus on real, intensive GR to characterize their benefits. In that scope, the aged intensive GR studied by Speak et al. [15] in Manchester, UK, achieved average retention of 65.7%. A comprehensive soil classification revealed that the growing substrate, a mineral soil used, was in good general conditions and also high in organic matter content which can increase the water-holding capacity of the soil.

Another factor that can influence the water retention and detention performance of GR is the irrigation. Perales-Momparler et al. [6] highlighted the importance of planting with vegetation with low water needs: during the start-up period of the green roof, irrigation was carried out to ensure the proper establishment and development of the plants, which significantly reduced its hydraulic efficiency to volumetric efficiencies of up to 50%. When irrigation operations were less frequent (in winter and spring seasons), the volumetric efficiency raise. In general, their study showed significantly different hydraulic behavior between GR and a conventional roof:

during a typical short torrential shower (total rainfall volume of 29 mm and the maximum 10-min intensity of 43 mm/h) showed only 26% of the rainfall volume detained by the conventional roof whereas 86% efficiency was achieved in the green roof. The peak flow reduction was also substantial: conventional runoff was seven times greater than that from the green roof.

The hydrological performance of the dual-substrate-layer referred above (with a lower inorganic adsorption layer for water retention and pollutant reduction, studied by Wang et al. [17]) was relatively good because of the porous structure and large specific surface area of the adsorption materials employed, which could help to absorb and hold the water in the GR structure. The rainfall retention values observed for the six dual-substrate layer GR in their study varied from 21.1% to 81.9% with an average of 48%. The different compositions of them explain the distinct retention values. The dual-substrate-layer GR, which used the mixture of activated charcoal with perlite and vermiculite as the adsorption substrate, possessed better rainfall retention performance.

Due to the limited retain capacity of GR, the size of the rain events also influences significantly the hydrological performance of all types of GR. Carpenter et al. [4] made a study based on rainfall events to evaluate annual retention during the growing and nongrowing seasons of an existing extensive GR, composed of six types of native sedum. No differences in water retention of the GR for the growing and nongrowing seasons were found but it was inversely dependent on the size of the rainfall. Under low rainfall inputs, the GR was partially saturated and retained high amounts of rainwater (between 98% and 100% of the incoming precipitation). Inversely, high-intensity rain events and a decrease in the antecedent dry period, promoted saturation of the roof, which decreased its retention capability to only 88%. The 150 mm of soil layer GR studied by Zhang et al. [29] (with retention capacities ranging from 35.5–100%) showed a significant negative relationship between the depths of rainfall and the runoff retention rates. However, there was no correlation between the runoff retention and the antecedent dry period. The size (or depth) of the rainfall is a major factor also reported by other authors, that presented lower retention for high rainfall events [11] and a high retention efficiency for small magnitude rainfall events [26, 27].

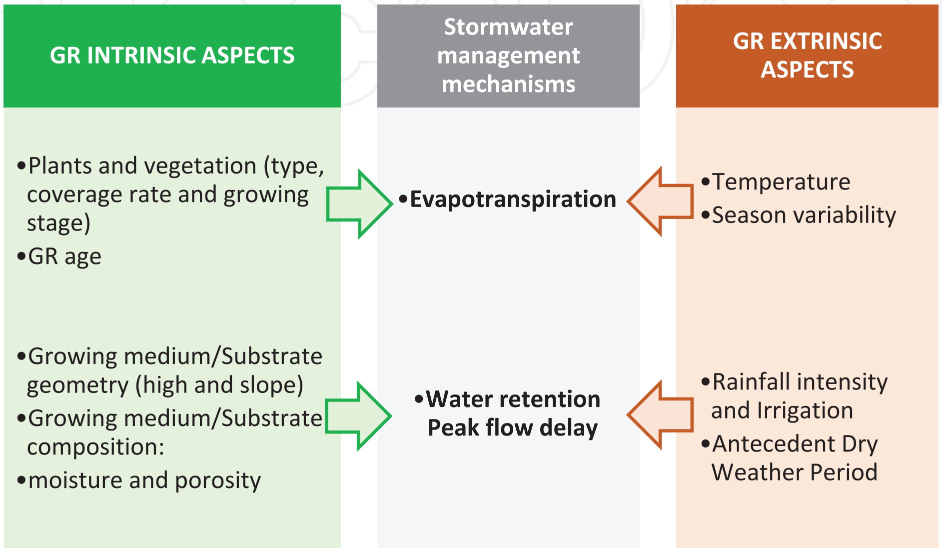

Figure 2.
Hydraulic performance of GR: intrinsic and extrinsic influencing factors.

Viola et al. [28] add that the performance of a GR increases when rainfall and potential evapotranspiration exhibit the same seasonality during the hydrological year happens, such as in humid subtropical climates. Conversely, the GR presents the minimum efficiency when rainfall and potential evapotranspiration are in counterphase, as is found in a Mediterranean climate.

Figure 2 resumes the main aspects that influence the hydraulic performance of GR, from internal and external point of view.

3.2 Effects on stormwater quality

GR also change the qualitative characteristics of stormwater runoff, due to the interaction between water and the different structural components. Both plants and substrate are expected to have a direct influence on the runoff quality, but it can be positive or negative, as they can filter or eventually be a source of contaminants. Besides, considering that rainwater is relatively pure (apart from being acidic and containing traces of nutrients and metals) the magnitude of the pollution caused by the GR can be very high [12]. The quality of the drained water flowing from GR has been carefully investigated in the last decade which is extremely important as cities are becoming greener. However, if the impacts on stormwater quality are not well known while GR are being promoted and spread over cities, there is a risk of providing contaminated water to the receiving watercourses.

It must be taken into account that GR vegetation may trap airborne particles and dust, thus eliminating them from the rainwater, which is beneficial. Also, the substrate material can act as an ion-exchange filter for pollutants, nutrients, and trace metals present in rainwater. If the ion concentration of the rainwater is high the GR components may act as a sink, decreasing the ion concentration in the GR runoff. Otherwise, if the concentration is significantly lower than the substrate one, some ions will seep into the rainwater from the substrate resulting in a higher ion concentration in the drained rainwater [12, 30].

Gregoire and Clausen [31] studied the runoff quantity and quality of a 248 m^2 extensive GR and a control roof in Connecticut, USA, using a paired watershed study. The mean concentrations of TP (total phosphorus) and PO_4–P (orthophosphate as phosphorus) in GR runoff were higher than in rainwater, but lower than in the runoff from the control roof. They concluded that the GR was a sink for NH_3–N (ammonia-nitrogen), Zn (zinc), and Pb (lead), but not for TP, PO_4–P, and total Cu (copper). The GR also reduced a load of Total Nitrogen (TN), Total Kjeldahl Nitrogen (TKN), nitrate and nitrite nitrogen (NO_3 + NO_2 –N), Mercury (Hg), and dissolved Cu due mainly to the reduction of the stormwater volume. The growing medium and slow-release fertilizer were the probable sources of P and Cu in GR runoff, pointed by the authors. Berndtsson et al. [32] also investigated the influence on runoff water quality from two full-scale GR located at two distinct climate regions (Japan and Sweden). Both had similar performance and were a sink of NO_3–N and NH_3–N. They also release dissolved organic carbon and potassium. The intensive GR was a sink of TN and Phosphorus was released from the extensive one. They were generally not a significant source of metal pollutants. In general, the concentrations of nitrogen and phosphorus compounds, as well as heavy metals, studied in the runoff from the GR were in a similar range or below the corresponding concentrations in the urban runoff. The authors concluded that GR did not provide the benefit of rainwater treatment (with exception to nitrate nitrogen) but neither would other urban impermeable surfaces.

The most common contaminants of urban stormwater runoff are heavy metals, petroleum hydrocarbons, pesticides, suspended solids, nutrients, and pathogenic microorganisms. Pollutants studied in GR runoff are most often some forms of phosphorus and nitrogen, and heavy metals. The factors that most influence GR runoff quality can be listed as follows [7] and described in the following paragraphs:

- type of material used (composition of the growing substrate, drainage material and/or underlying hard roof material, rain pipes material);
- type of vegetation, season (biomass using nutrients);
- soil high;
- type of drainage;
- maintenance/fertilizers used;
- dynamics of precipitation;
- wind direction;
- local pollution sources;
- physico-chemical properties of pollutants.

Liu et al. [30] studied GR with different substrate material compositions, substrate depths, vegetation types and slope gradients, and concluded that they acted as a source of most of the studied water quality parameters. Substrate materials and vegetation types contributed notably to water quality and the ones with the less organic materials in the substrate showed better water quality. The influences of substrate depths and slope gradients on runoff water quality were small. They noted that the mean electrical conductivity (EC) increased from 295.17 μs/cm in rainwater to 418.33 μs/cm in GR runoff, due to the increase in dissolved ion content. The substrate composition was the pointed cause of the elevated concentration of anions and cations in the runoff. Still, the majority of water quality parameters of GR outflows were partly considered to be good. Previously, the same authors had studied the influence of substrate and vegetation on the water quality of GR outflows, by designing a scale-based runoff plot of extensive GR with different substrate and vegetation types [10]. The results showed that the TSS (total suspended solids), TN (total nitrogen), and TP average concentrations of the GR runoff were all significantly higher than that of the conventional roof runoff. The TN and TP concentrations of 5 cm substrate depth were significantly lower than that in the 15 cm substrate depth. This result could be explained due not to the depth of substrate but the higher content of organic matter in its substrate, thus the nutrition was more prone to being leached out from the system. In this specific case, significant differences were observed in TN concentrations between the vegetation species Sedum Spectabile and Radix Ophiopogonis, but no significant differences were observed about TP concentrations. These results imply that the phosphorus in the substrate might not be used efficiently by plants and can be leached out by stormwater runoff. Beecham and Razzaghmanesh [33] also highlighted the importance of vegetation in enhancing pollutant removal in GR systems. In the study comprising sixteen, low-maintenance and unfertilized intensive and extensive GR testing beds (100 mm and 300 mm depth media, respectively), the intensive GR performed better than the extensive ones about outflow water quality, while in the non-vegetated beds, the extensive beds performed better than intensive systems. In addition, growing medium with less organic matter had better water quality performance. Generally, the pollutant concentrations were higher in runoff from non-vegetated beds. This was believed to be partly due to leaching from the growing medium and partly due to plant uptake in the vegetated beds.

However, the results reported by Akther et al. [34] pointed in the opposite direction, because vegetation played a secondary or minor role when compared to growing substrate in the nutrient leaching of the GR outflow. They characterized and modeled the temporal behavior of nutrient leaching from GR in both laboratory and field settings and concluded that the leaching behavior was very similar in both locations: the degree of nutrient leaching declined temporally, and the growing medium was proved to be the primary source for nutrients being gradually washed off by infiltrated water. In addition, they showed that nitrogen (N) leach quicker than phosphorus (P) from the GR, which is consistent with the higher mobility in the soil of N compared to P. The degree of nutrient leaching in their study was associated with the chemical properties (e.g., the nutrient content) of the growing medium.

Razzaghmanesh et al. [35] also studied the growing medium influence in the water quality of the outflow from intensive and extensive full-scale GR located on the roof top of a 22-storey building in the Adelaide CBD, South Australia. the values of the parameters such as pH, turbidity, nitrate, phosphate and potassium in intensive GR outflows were higher than in the outflows from the extensive GR, (except for some events and EC, TDS (total dissolved solids) and chloride). Generally, the performance of the extensive GR was better than the intensive systems in terms of pollutant removal, which may be related to the reduced volume of substrate that can leach pollutants. A very interesting aspect highlighted by the authors was that the contaminant concentrations in runoff from both intensive and extensive GR generally decreased during the study period: the concentrations at the start of the investigation were higher than towards the end of the nine months for most of the studied pollutants. This was an expected result once the systems settle down and the chemicals within the growing medium leach out over time. **Table 2** presents a resume of GR and traditional roofs runoff values.

To understand the influence of roof age and hydro-meteorological variables on the temporal evolution of chemical leaching in GR, Akther et al. [16] monitored in 2015–2018 a full-scale extensive GR and a reference roof located in a cold and semi-arid climate region. During the study period, their GR also leached nutrients (N and P) and constituents represented by EC, whereas it removed metals (Zn, Cu, and Pb). The degree of chemical leaching declined temporally: the leaching of N appeared to cease, whereas P leaching was still ongoing at the end of the study period. Also focusing on the GR age, Todorov et al. [37] presented a four-year study of water quality in runoff from an extensive vegetated roof, sedum covered, initiating with the first growing season. The GR also proved to be a sink of N, TP and chloride (Cl), and a source of phosphate and dissolved inorganic and organic carbon. Once the roof growing medium is designed to sustain plant growth, it is supposed to be rich in N and P. Both NO_3^- and NH_4^+ are essential nutrients for the plants and their retention in the vegetated roof was possibly a result of assimilation by the sedum species. In general, the water drained

Water quality parameter	**Experimental data**		
	Asphalt roof (average, mg/L)	**Aluminum roof (average, mg/L)**	**Green roofs range (mg/L)**
pH	7.13	7.58	6.72-8.45 [b]
Turbidity (NTU)[a]	2.98	1.26	4.0-300 [b]
EC (μS/cm)	75.00	23.00	<100 [b]
Chloride (mg/L)	1.25	1.03	<30 [b]
Total dissolved solids (mg/L)	37.00	31.00	385.77
Nitrate (mg/L)[a]	2.62	1.90	2.20-39.20
Phosphorous (mg/L)[a]	0.14	0.16	0.20-2.20
Potassium (mg/L)[a]	9.60	3.00	38.37

[a] *Pollutant level is above the potable standard level.*
[b] *USEPA. Guidelines for water reuse (2012) EPA/600/R-12/618.*

Table 2.
Water quality of outflows from green roofs and control roofs (adapted from Razzaghmanesh, et al. [35]).

from the vegetated and impermeable roofs presented good quality, meeting the United States Environmental Protection Agency freshwater standards for all parameters, except for TP.

The studies presented so far, might suggest that GR are bad solutions regarding stormwater quality, at first sight. The work presented by Perales-Mompaler et al. [6] is no exception, once the resulting values of chemical oxygen demand (COD), TSS, TN and TP were higher than the non-vegetated roof, except for TSS which was usually below 20 mg/L. Nutrients (TN and TP) and organic matter (COD) were notably higher in runoff from the GR showing the washing of dissolved substances. However, despite presenting higher concentrations of COD and nutrients, the total loads drained by the GR were lower than that drained by the non-vegetated roof, due to the higher volumetric efficiency of the green roof. Also in this study, the reported washing effect declined after some time: COD concentrations decreased from values higher than 350 mg/L to 50 mg/L and similar trends were observed for TN and TP. After 17 rainfall events (total volume drained 9.0 m^3), TN and TP concentrations were reduced by approximately one-half. Carpenter et al. [4] examined a GR in Syracuse, NY and also reported that overall, nutrient losses were low because of the strong retention of water. They reported seasonal variabilities, as runoff waters exhibited a high concentration of nutrients during the warm temperature growing season, particularly TN and dissolved organic carbon (DOC). There was marked variation in the retention of nutrients by season shown by the variation in roof runoff concentrations. The GR served as a sink for wet deposition inputs of TN and TP for the majority of rain events. In contrast, the roof was a source of DOC during the growing season and a sink of DOC during the non-growing season. Overall, the experiment also revealed that nutrient retention is dependent on water retention. Although, nutrient concentrations and fluxes in roof drainage were greater than in the incoming precipitation, the total loading of TN and TP was attenuated because precipitation quantity was strongly retained. According to the authors, the elevated concentrations of those nutrients in GR drainage are not an issue of concern as the strong retention of water results in limited mass loss of nutrients from the GR to the sewer system.

A direct correlation exists between the magnitude of the rain events and the number of solids in the GR runoff. During small rain events, nutrients and sediment that are washed off from traditional roofs are retained on the GR because there was no runoff. This would lead to misleading higher concentrations from the GR in future larger rain events. New GR tend to be a source of pollutants, due to the initial nutrient load that comes from the decomposition of organic matter that was incorporated into the original substrate mix. On the opposite perspective, established vegetation and substrates can improve the water quality of runoff by absorbing and filtering pollutants [24]. These findings lead to more diligent use of fertilizers to minimize the adverse impact on stormwater runoff. Even though, if nutrient loading remains a problem on implemented GR a possible solution is to couple them with other green infrastructures, such as rain gardens and bioswales.

Buffam et al. [38] analyzed the runoff from more than 80 rain events over 2 years, in the extensive GR in Cincinnati, USA referred previously. Strong seasonal patterns were observed in bioactive elements. Carbon, nitrogen, phosphorus, and base cation concentrations were highest in the summer, and were positively correlated with temperature. They concluded that temperature-mediated processes, rather than plant uptake or hydrologic variation among storms, were major controlling mechanisms for the GR runoff water quality. The seasonal variation in GR runoff water quality, according to the authors, might be due to:

- The plant-mediated nutrient cycling being altered during the growing season, either through direct plant uptake, or by the release of soil exudates;

- The chemical dissolution of minerals or ion desorption in the GR substrate, that are more rapid at higher temperatures;

- The increase of the microbial mineralization rates of the substrate organic matter with temperature, releasing dissolved inorganic nitrogen and phosphorous and solubilizing dissolved oxygen carbon;

- The season variability of GR hydrodynamics: evapotranspiration rates and rainfall event size and duration change with the season. Rapid drying occurs in the summer because of higher evapotranspiration rates, and short-duration high-intensity thunderstorms are more common in the warmer months, leading to a more rapid, episodic flow-through dynamic than in winter.

Zhang et al. [39] examined the effect on the quality of harvested rainwater of conventional roofing materials (concrete, asphalt and ceramic tile roofs) compared with a 15 cm substrate and plants GR and concluded that the ceramic tile roof was the most suitable for rainwater-harvesting applications because of the lower concentrations of leachable pollutants. The water quality of the roof runoff was closely related to the roofing material and the season when rainwater is harvested. Seasonal trends were verified in the water quality parameters of this study, which showed lower pollutants in roof runoff in summer and autumn, than those in winter and spring. The main pollutants of roof runoff from the four roofs studied, which exceeded the drinking water standard, were TN and COD. The effect of conventional roofing materials (asphalt fiberglass shingle, Galvalume-metal, and concrete tile) and alternative ones (cool and green) on harvested rainwater quality was also studied by Mendez et al. [36]. They demonstrated that if the consumer wanted to meet primary and secondary drinking water standards or non-potable water reuse guidelines, the rainwater harvested from any of these roofing materials would require treatment. The shingle roof and the GR drained water with very high concentrations of dissolved organic carbon, which might result in high concentrations of disinfection by-products after chlorination. Moreover, based on the concentrations of some metals (e.g., arsenic) in the harvested rainwater, the authors stated that the quality of the commercial growing medium should be carefully examined when the harvested rainwater is considered for domestic use.

As referred previously, the dual-substrate-layer extensive GR presented by Wang et al. [17] used porous inert materials (activated charcoal, zeolite, pumice, lava, vermiculite and expanded perlite) as the adsorption substrate, both to retain rainwater and to reduce pollutant leaching. Its performance, regarding runoff quality was assessed with six pilot-scale units (with different adsorption substrate) compared to a traditional single-substrate-layer extensive green roof. Results showed that dual-substrate-layer GR supported better natural vegetation growth, with coverage exceeding 90%, while the coverage in single substrate-layer GR was over 80%. All pilot-scale units acted as sinks for organics, heavy metals and all forms of nitrogen in all cases. They also showed that the dual-substrate-layer extensive GR performed better than the single-substrate-layer GR in retaining nitrogen, phosphorus, organics and turbidity.

When GR are enlarged to rooftop vegetable farms, the use of fertilizers might be a cause of concern. The example presented by Harada et al. [40] had atmospheric deposition of Pb and Mn exceeding the drainage output, which indicates that it is a net sink for these metals. Whittinghill et al. [14] also studied the impact of rooftop farming on stormwater runoff comparing a suite of extensive, sedum GR, located in New York City. Results indicate that the pH of runoff from the rooftop farm was slightly lower than that of the extensive GR, but the EC, apparent color, and TSS concentrations were higher, as well as the concentrations of nitrate-N, phosphorus, potassium, calcium, and magnesium. However, changes in nutrient management practices would help reduce these values.

The possible negative effects of fertilization o stormwater runoff have to be taken seriously in order not to damage the positive environmental image of GR. Emilsson et al. [41] investigated nutrient runoff, substrate nutrient storage and plant uptake following fertilization of vegetation mats, shoot-established vegetation systems and unvegetated substrate using three levels of fertilizer applied as either controlled-release fertilizer (CRF), or as a combination of CRF and conventional fertilizer. Their study clearly shows that conventional fertilizers should be avoided unless the water is either recycled or reused on the roofs or other vegetated surfaces in the first weeks following fertilization. Fertilization of old vegetation mats reduced the risk for nutrient leaching compared to fertilization of newly established roofs. They associated these results with temporary storage in the substrate and increased uptake by vegetation, however, the temporary storage of nutrients following fertilization indicated that there might be a risk for prolonged leaching. The aspects that influence the establishment of GR must be considered when designing a GR substrate and the vegetation cover. The maintenance requirements depend on the defined characteristics. Flowering and lush vegetation are not the most adequate types of plants, and fertilization might not be needed at all [41].

In summary, the runoff quality of GR is influenced by inherent and external factors of the GR, as presented in **Table 3**.

In terms of the potential for recycling of outflow water from GR, national and international standards indicate that such water can be reused for

	Pollutant source	Pollutant sinks
Inherent factors	The substrate, including component materials and depth, may contain heavy metals and nutrients that could contribute to leachate. Structural layers may contribute to heavy metal accumulation due to metal, plastic, and polymer materials used in construction. Plants are ambiguous. On one hand, they can act as an uptake of contaminants, on the other, they can be a pollutant source.	Plants behave as an uptake of contaminants by physiological metabolism of plant tissue and rhizospheric microorganisms Natural or artificial substrate added components that have the capacity of nutrient retention.
External factors	Irrigation, if supply water is contaminated (especially reclaimed water), with diverse nutrients such as N and P. Fertilizer and pesticides, including organic and chemical fertilizers and organic phosphor, chlorine, and nitrogen. Atmospheric deposition, including dry and wet deposition resulting from gravity and rainfall respectively. Age, as over time the plant biomass and ecological functions of the GR as well as levels of metal pollutants will increase, and substrate nutrients will decrease	The age of GR, can influence water conductivity and substrate pollutant retention. The age of the vegetation mat will affect the nutrient content of runoff. Newly-built GR have temporarily high nutrient levels that are steadily assimilated and degraded over time.

Table 3.
Potential of different factors, to be source or sink of pollutants (adapted from Vijayaraghavan, et al. [12]).

urban landscape irrigation and non-potable purposes such as toilet flushing. Nevertheless, treatment is required if the consumer wants to meet primary and secondary drinking water standards or demands requirement for non-potable water reuse guidelines [33, 35, 36, 39].

4. Final considerations

Stormwater control is critical to the continuous development and sustainability of urban areas, once the soil sealing caused by the increase of urbanization, together with the occurrence of more frequent extreme events due to climate change, will keep worsen the consequences of urban flood and the degeneration of water resources. GR are a type or NbS with several benefits that can help to minimize these problems.

Studies as the ones made by Karteris et al. [22] and by Hoeben and Posh [20] show the potential of implementing GR in cites (in new or existing buildings), making them more environmentally friendly, even with lack of available areas at the ground level. The majority of roof tops are unused spaces that might be transformed in a green space and a new ecosystem. The benefits of such transformation are well documented in the previous subchapters, being the most relevant the high potential of reducing CO_2 emissions (both due to the energy conservation and the CO_2

absorption), the increase of the rainwater retention rate and the delay of peak flow, which can reduce flood occurrence and negative environmental consequences to cities and its population.

Values resulting from the presented publications show GR retention rates of rainwater above 50%, reaching 100% in many cases, specifically when small-intensity rainfall events occur. Many factors were studied to understand the retention performance of GR, but it seems that the more relevant ones are the depth of substrates (intensive GR have higher retention rates than extensive ones) and the rainfalls characteristics. The retain capacity of the GR are limited and once the substrate becomes saturated, stormwater retention volume decreases significantly. However, even in those worst cases, the GR plants absorb part of the infiltrated water and extend the path taken by the water, leading to the decrease of the amount of runoff and the delay of the flood peak. Future investigations will continue to develop and search for more hydraulic-efficient GR and to understand the real effects of the large-scale implementation of GR. Long-term assessments must be made to consider variable weather conditions between years and seasons. There have been several attempts to create mathematical models to predict the runoff coefficient for distinct configurations of GR [16, 28], but the complex characteristics of these living systems, with specific dynamics and very dependent on the climatic conditions, make generalizations difficult.

Another important aspect that has been attracting the attention of investigators is the changes that GR cause on stormwater runoff quality. Plants, substrates, soil insects and microorganisms are expected to remove pollutants from rainwater in GR systems. However, the majority of the presented studies reveal that GR are a sink for heavy metals and all forms of nitrogen, but are generally a source of phosphate and dissolved inorganic and organic carbon in the growing seasons, as presented by Carpenter et al. [4], because the concentration of these parameters is higher in the runoff than in the precipitation water. This reveals significant concern about the effects of GR in urban water resources. Higher concentrations of pollutants were found in the deeper substrates and the performance of the extensive GR is, in most cases, better than the intensive systems. Intensive GR usually need fertilizers that remain in the substrates and are continuously leaching in the runoff. Since nutrients are essential for the plants especially in the first establishment years and in the growing seasons, it is not a surprise that the age of the GR has a beneficial effect in the chemical leaching of GR, as presented by the long-term studies [16, 37]. However, once that the runoff volume from GR is smaller than runoff from traditional roofs, the total discharged loads of these pollutants are smaller too. Most of the referred authors compared the GR runoff to the freshwater standards and concluded that, in general, it presents good quality and meets those standards, being also suitable for some non-potable uses. Another beneficial effect of GR reported by some authors [29, 32] is that acid deposition is neutralized by vegetation and the growing medium, revealing the potential of GR to mitigate acid rain runoff in densely populated urban areas.

Each GR is a unique system, thus differing from each other. Their nature-based characteristics make them develop and interact with the surrounding environment on their terms. The leaching problem is already defined, and solutions will be developed to minimize its consequences. First, the use of fertilizers must be very controlled and mostly avoided. Then, the implementation of layers that retain nutrients is also being considered. Also, the control of the discharged GR water may avoid the contamination of watercourses: first-flush systems might be considered, or drainage pipes can lead to gardens and/or to infiltration trenches to dispose of the nutrients in the soil. In that scope, combined solutions of GR with other LID structures must be considered when implementing GR in a neighborhood or site scale.

To pursuit circular economies, the adequacy of recycled materials in the GR substrate is also being studied which require new approaches in the study of the GR runoff quality and quantity. The use of alternative sources of water (such as greywater from the building) to irrigate might also be considered but their impacts on the runoff should be carefully assessed. Innovations will also focus on customizable low-cost and innovative GR designs, increasing the number of possible configurations, and hopefully leading to multi-perspective assessments.

Author details

Cristina Santos[1,2]* and Cristina M. Monteiro[3]

1 Faculdade de Engenharia da Universidade do Porto, Porto, Portugal

2 CIIMAR - Centro Interdisciplinar de Investigação Marinha e Ambiental, Matosinhos, Portugal

3 CBQF - Centro de Biotecnologia e Química Fina – Laboratório Associado, Universidade Católica Portuguesa, Escola Superior de Biotecnologia, Porto, Portugal

*Address all correspondence to: csantos@fe.up.pt

References

[1] EEA. Water resources across Europe — confronting water stress: An updated assessment. European Environmental Agency Report nº 12/2021. 2021

[2] FEMA. Building Community Resilience with Nature based Solutions - A Guide for Local Communities. Washington D.C., USA: Risk MAP - Increasing Resilience Together; 2021

[3] EC. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. In: Forging a Climate-Resilient Europe - The New EU Strategy on Adaptation to Climate. Brussels: European Commission; 2021

[4] Carpenter C, Todorov D, Driscoll C, Montesdeoca EM. Water quantity and quality response of a green roof to storm events: Experimental and monitoring observations. Environmental Pollution. 2016;**218**:664-672

[5] Koc K, Ekmekcioglu O, Ozger EM. An integrated framework for the comprehensive evaluation of low impact development strategies. Journal of Environmental Management. 2021;**294**:113023

[6] Perales-Momparler S, Andrés-Doménech I, Hernández-Crespo C, Vallés-Morán F, Martín M, Escuder-Bueno I, et al. The role of monitoring sustainable drainage systems for promoting transition towards regenerative urban built environments: a case study in the Valencian region, Spain. Journal of Cleaner Production. 2017;**163**:S113-S124

[7] Berndtsson J. Green roof performance towards management of runoff water quantity and quality: A review. Ecological Engineering. 2010;**36**:351-360

[8] greenroofs.org, “Green Roofs for Healthy Cities,” 2021. [Online]. Available: https://greenroofs.org/about-green-roofs. [Acedido em 30 11 2021]

[9] Chen CF. Performance evaluation and development strategies for green roofs in Taiwan: A review. Ecological Engineering. 2013;**52**:51-58

[10] Liu W, Wei W, Chen W, Deo C, Si J, Xi H, et al. The impacts of substrate and vegetation on stormwater runoff quality from extensive green roofs. Journal of Hydrology. 2019;**576**:575-582

[11] Kuoppamaki K. Vegetated roofs for managing stormwater quantity in cold climate. Ecological Engineering. 2021;**171**:106388

[12] Vijayaraghavan K, Reddy D, Yun YS. Improving the quality of runoff from green roofs through synergistic biosorption and phytoremediation techniques: A review. Sustainable Cities and Society. 2019;**46**:101381

[13] Kuoppamäkia K, Lehvävirta S. Mitigating nutrient leaching from green roofs with biochar. Landscape and Urban Planning. 2016;**152**:39-48

[14] Whittinghill L, Hsueh D, Culligan P, Plunz R. Stormwater performance of a full scale rooftop farm: Runoff water qualityLeigh. Ecological Engineering. 2016;**91**:195-206

[15] Speak A, Rothwell J, Lindley S, Smith C. Rainwater runoff retention on an aged intensive green roof. Science of the Total Environment. 2013;**461-462**:28-38

[16] Akther M, He J, Chu A, van Duin B. Chemical leaching behaviour of a full-scale green roof in a cold and semiarid climate. Ecological Engineering. 2020;**147**:105768

[17] Wang X, Tian Y, Zhao X. The influence of dual-substrate-layer extensive green roofs on rainwater runoff quantity and quality. Science of the Total Environment. 2017;**592**:465-476

[18] Cristiano E, Deidda R, Viola F. The role of green roofs in urbanWater-Energy-Food-Ecosystem nexus: A review. Science of the Total Environment. 2021;**756**:143876

[19] Xu L, Yang S, Zhang Y, Jin Z, Huang X, Bei K, et al. A hydroponic green roof system for rainwater collection and greywater treatment. Journal of Cleaner Production. 2020;**261**:121132

[20] Hoeben A, Posch A. Green roof ecosystem services in various urban development types: A case study in Graz, Austria. Urban Forestry & Urban Greening. 2021;**62**:127167

[21] Hashemi S, Mahmud H, Ashraf M. Performance of green roofs with respect to water quality and reduction of energy consumption in tropics: A review. Renewable and Sustainable Energy Reviews. 2015;**52**:669-679

[22] Karteris M, Theodoridou I, Mallinis G, Tsiros E, Karteris A. Towards a green sustainable strategy for Mediterranean cities: Assessing the benefits of large-scale green roofs implementation in Thessaloniki, Northern Greece, using environmental modelling, GIS and very high spatial resolution remote sensing data. Renewable and Sustainable Energy Reviews. 2016;**58**:510-525

[23] Grunwald L, Heusinger J, Weber S. A GIS-based mapping methodology of urban green roof ecosystem services applied to a Central European city. Urban Forestry & Urban Greening. 2017;**22**:54-63

[24] Rowe D. Green roofs as a means of pollution abatement. Environmental Pollution. 2011;**159**:2100-2110

[25] Liu H, Kong F, Yin H, Middel A, Zheng X, Huang J, et al. Impacts of green roofs on water, temperature, and air quality: A bibliometric review. Building and Environment. 2021;**196**:107794

[26] Harper G, Limmer M, Showalter W, Burken J. Nine-month evaluation of runoff quality and quantity from an experiential green roof in Missouri, USA. Ecological Engineering. 2015;**78**:127-133

[27] Lee J, Lee M, Han M. A pilot study to evaluate runoff quantity from green roofs. Journal of Environmental Management. 2015;**152**:171-176

[28] Viola F, Hellies M, Deidda R. Retention performance of green roofs in representative climates worlwide. Journal of Hydrology. 2017;**553**:763-772

[29] Zhang Q, Miao L, Wang X, Dandan L, Zhu L, Zhou B, et al. The capacity of greening roof to reduce stormwater runoff and pollution. Landscape and Urban Planning. 2015;**144**:142-150

[30] Liu W, Engel B, Chen W, Wei W, Wang Y, Feng Q. Quantifying the contributions of structural factors on runoff water quality from green roofs and optimizing assembled combinations using Taguchi method. Journal of Hydrology. 2021;**593**:125864

[31] Gregoire B, Clausen J. Effect of a modular extensive green roof on

stormwater runoff and water quality. Ecological Engineering. 2011;**37**:963-969

[32] Berndtsson J, Bengtsson L, Jinno K. Runoff water quality from intensive and extensive vegetated roofs. Ecological Engineering. 2009;**35**:369-380

[33] Beecham S, Razzaghmanesh M. Water quality and quantity investigation of green roofs in a dry climate. Water Research. 2015;**70**:370e384

[34] Akther M, He J, Chu A, van Duin B. Nutrient leaching behavior of green roofs: Laboratory and field investigations. Science of the Total Environment. 2021;**754**:141841

[35] Razzaghmanesh M, Beechama S, Kazemi F. Impact of green roofs on stormwater quality in a South Australian. Science of the Total Environment. 2014;**470-471**:651-659

[36] Mendez C, Klenzendorf J, Afshar B, Simmons M, Barrett M, Kinney K, et al. The effect of roofing material on the quality of harvested. Water Research. 2011;**45**:2049-2059

[37] Todorov D, Driscoll C, Todorova S, Montesdeoca M. Water quality function of an extensive vegetated roof. Science of the Total Environment. 2018;**625**: 928-939

[38] Buffam I, Mitchella M, Durtsch R. Environmental drivers of seasonal variation in green roof runoff water quality. Ecological Engineering. 2016;**91**:506-514

[39] Zhang Q, Wang X, Hou P, Wan W, Li R, Ren Y, et al. Quality and seasonal variation of rainwater harvested from concrete, asphalt, ceramic tile and green roofs in Chongqing, China. Journal of Environmental Management. 2014;**132**:178-187

[40] Harada Y, Whitlow T, Russell-Anelli J, Walter M, Bassuk N, Rutzke M. The heavy metal budget of an urban rooftop farm. Science of the Total Environment. 2019;**660**:115-125

[41] Emilsson T, Berndtsson J, Mattssona J, Rolfa K. Effect of using conventional and controlled release fertiliser on nutrient runoff from various vegetated roof systems. Ecological Engineering. 2007;**29**:260-271