Chapter

Nature-Based Solutions Using LECA LWA to Increase Urban Sustainability and Support Stormwater Management

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Abstract

In recent decades, the increase of building systems and the consequent impermeabilization of the inner-city environment, poses several negative environmental risks, especially those regarding global warming and water management. Urban green infrastructure (GI) provides benefits to urban inhabitants, but their potential depends on their suitable implementation, under the responsibility of different stakeholders. Nature-based solutions (NbS) are an effective means to restore vegetation urban areas contributing to its sustainability and resilience. The use of NbS infrastructure helps to reduce flood incidences, furthermore contributing to the mitigation of the urban heat island effect and air pollution reduction. Several NbS such as green roofs and green walls, rain gardens, infiltration trenches and permeable pavements, are being implemented worldwide as an effective strategy to improve the environmental performance of densely populated urban cities. Lightweight Expanded Clay Aggregate (LECA®) has been widely incorporated in several innovative urban GI solutions due to their key characteristics (e.g. lightweight, porosity and good drainage), developing a crucial role in stormwater management and water runoff quality. This chapter aims to report the potential influence that several NbS have on urban stormwater management, considering several case studies using Leca® LWA—demonstrating their engineering benefits and innovative properties.

Keywords: nature-based solutions, urban green infrastructures, urban stormwater management, urban sustainability, lightweight expanded clay aggregate (LECA®), climate resilience

1. Introduction

The European Commission [1] states that collectively our people, our planet and our prosperity are vulnerable to climate change, and points out the need to prevent the un-adaptable and to adapt to the un-preventable. The increase in the frequency and severity of climate and extreme weather conditions has created a surge in the number of, and damages from, environmental disasters in recent decades. The implementation of the European Union (EU) Strategy on the Adaptation to Climate Change intends to put its countries in a better position to face climate impacts by 2030. This would mean (1) adaptation awareness and changes to every single local authority, company and household; (2) adaptation implementation is to be well underway for those most affected; and (3) global leadership is to immediately commence in areas such as climate services, climate proofing, or nature-based solutions. As climate change becomes more intense, the urgency of adaptive measures increases. The Strategy outlines a long-term vision for the EU to become a climate-resilient society and aims to reinforce the adaptive capacity of its countries and the rest of the world—thus minimising our vulnerability to the impacts of climate change, such as droughts, extreme weather events and flooding [2]. In this Strategy, ecosystem-based approaches are presented as a cross cutting priority. They focus on ecosystem restoration and on the enhancement of ecosystem services, being recognised as multipurpose solutions that are often more efficient than traditional technical measures.

Climate change adaptation and disaster risk reduction through the implementation of ecosystem-based approaches are widely applicable and hugely varied. They encompass several related concepts, such as Nature-based Solutions (NbS) and Green Infrastructure, that aim to enhance social and environmental resilience by restoring, maintaining, and improving ecosystems—thus enhancing their services to society, in areas such as water retention and prevention of soil erosion, floods and droughts. They answer to several environmental and sectoral policy objectives (e.g. regarding biodiversity, water quality or agricultural and forest management) and generate multiple socio-economic benefits that often go beyond technical solutions [2].

Nature-based Solutions are defined as solutions to societal challenges that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help to build resilience [3]. Such solutions bring nature and natural systems and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions. Despite the use of different terms referring to NbS used in international and European policies, the fundamental overarching idea is that nature can be used as a valuable tool to strengthen the resilience of ecosystems, protect biodiversity and reduce the risk of extreme weather and climate related disasters. Furthermore, NbS can help address broader societal challenges, including social and economic challenges within the paradigm of sustainable development.

For the effective design and successful implementation of NbS, it is critical to ensure that the measures are adequate for addressing the hazards while also delivering other societal benefits. If well designed, NbS can provide sustainable, cost-effective and multipurpose possibilities that can act as alternatives to or be applied to create synergy with established grey infrastructure [3]. Their benefits cover a large range of sectors, but specifically for water management and urban areas, the main ones are presented in **Figure 1**.

Nature-based solutions are essential for sustaining clean and healthy water resources. They help to address the risk of flooding and water scarcity (drought) by regulating water flows. Using NbS inland, including the restoration of the sponge-like function of soils, will boost the supply of clean and fresh water and furthermore reduce the risk of flooding. On the other hand, increasing green spaces can increase water infiltration into the soil, enhance evapotranspiration and provide storage areas for rainwater, which can alter the magnitude and timing of water runoff and flooding

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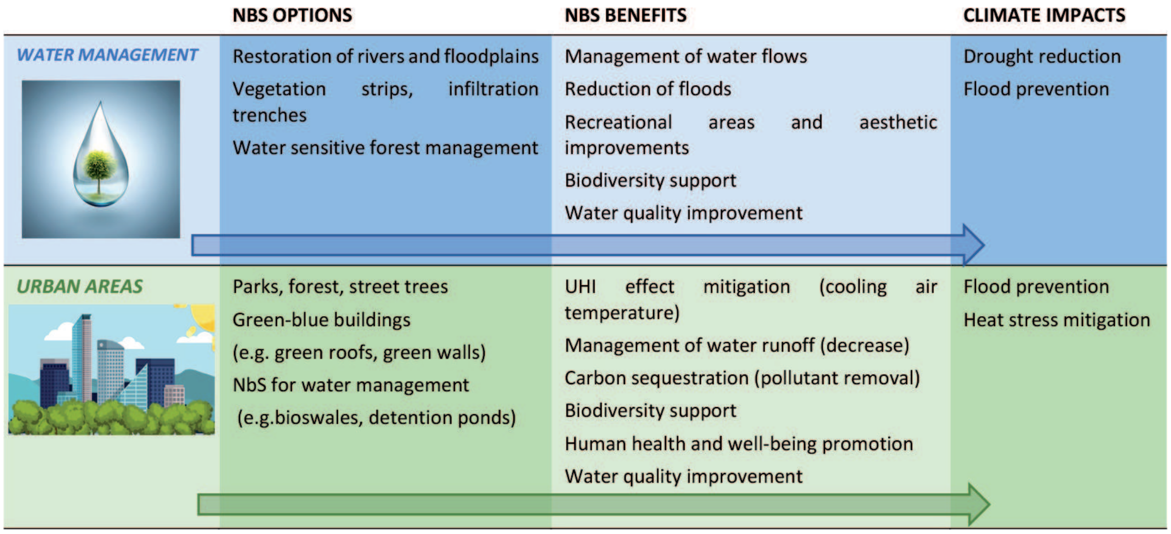


Figure 1.
Multiple benefits of nature-based solutions for addressing climate hazards in urban areas (adapted from EEA report n°01/2021 [3]).

during heavy precipitation events, while contributing to maintaining water flow during drought periods. Moreover, creating new green space for stormwater management (e.g. constructed wetlands, bioswales) has been shown to enhance flood protection while providing additional benefits such as biodiversity protection, recreational green urban space and water purification.

The porosity and hydraulic conductivity of lightweight aggregates (LWA) materials fulfil the hydraulic performances required for their use within hydraulic urban infrastructures. The application of LWA in urban drainage systems may guarantee an infiltration rate adequate for reducing different forms of stormwater runoff (e.g. rain gardens, infiltration basins, infiltration trenches). In addition, the sorbent capacities demonstrated by LWA complement their features in promoting both the infiltration of urban runoff stormwater and the recharging of groundwater, meeting the established quality requirements [4]. LECA® is the brand name that manufactures the LWA product, which is, an heterogeneous group of low-density material used for various civil engineering and construction applications [5]. LECA® LWA has been increasingly applied in stormwater management schemes and urban green infrastructure including green roofs and walls, permeable pavements and thermal insulation concretes [6–10].

This chapter aims to explore the application of LECA® LWA in NbS and to demonstrate how its application increases performance in terms of water management within urban areas. As discussed, NbS such as green roofs and green walls, rain gardens, infiltration trenches and permeable pavements, are being implemented worldwide as a solution to improve the environmental performance of densely populated urban cities. This performance can be enhanced by incorporating LECA® LWA, due to its natural characteristics (e.g. lightweight, porosity and good drainage) as presented in the following sections.

2. Urban nature-based solutions

Cities worldwide are facing challenges of resilience, as climate risks interact with urbanisation, loss of biodiversity and ecosystem services, poverty, and rising socioeconomic inequality [11]. Extreme events, especially flooding, heat waves and droughts, are causing significant economic losses and affecting the wellbeing of citizens and the rise of urbanisation will only magnify these challenges. Furthermore, cities host more than half of the global population, and more than 70% are expected to do so by 2050 [11]. This will lead to rapidly urbanised areas, most of which with lower-quality—unplanned settlements, vulnerable to climate impacts and with poorly maintained infrastructure—vulnerable to the magnitude of natural hazards.

Through this basis, it is fundamental to build adaptable cities and to create new spaces with resilient characteristics that, in a situation of extreme precipitation, for example, create a robust regeneration ability. This can be achieved, as referred above, by complementing traditional grey infrastructure with NbS. The World Bank group [11] defines grey infrastructure as built structures and mechanical equipment, such as reservoirs, embankments, pipes, pumps, water treatment plants, and canals. They can be considered as the opposite of NbS (actions to protect, sustainably manage, and to restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits, as presented) but, in fact, they are almost in-dissociable and function in a complementary way. The following subchapters present different types of NbS that can be implemented in urban areas.

2.1 Neighbourhood/site scale NbS

Nature-based solutions promote resilience and adaptation while being integrated into a community's-built environment or in its natural surrounding areas [12]. Nature-based stormwater systems, wetlands and green roofs, for example, can alleviate flooding from intense rainfall events, and also improve water and air quality, whilst reducing urban heat-island effects and creating ecological corridors for biodiversity. They are an effective means to restore vegetation in densely populated areas.

NbS can also be considered as environmentally-conscious approaches to stormwater management in urban areas, also known as Sustainable urban drainage systems (SUDS), low impact development (LID) or best management practices (BMP's) [12]. They help to control the stormwater runoff but also create a positive impact on its quality, minimising the effects of untreated stormwater, traditionally drained by grey infrastructure, on receiving water bodies. On the other hand, the implementation of NbS within urban areas, will promote the infiltration on stormwater, which will reduce the amount of water drained to Wastewater Treatment Plants (sewage networks, even when separative, have rainfall derived inflow and infiltrations that lead to the excessive entrance of rainwater into WWTP), resulting in important economic gains.

In conclusion, NbS can support surface water and groundwater water protection, and contribute to the qualitative and quantitative environmental and ecological status of water bodies. In a large scale, the extension of buffer zones and the establishment of water-sensitive forests and NbS for urban areas will reduce pollution and support habitat quality and biodiversity conservation, which can have positive effects for developing businesses and jobs, in particular those related to recreation and tourism. However, there are also some challenges related to the implementation of NbS, such as: (1) the associated construction/development works, which may negatively affect water quality and river ecosystems in the short-term; (2) enhanced green spaces connectivity triggers the dispersal of unwanted organisms (e.g. mosquitoes) with negative impacts on both local ecosystems and human health; (3) conflicts between different sectors, for example if agricultural areas are temporarily used as reservoirs for flood expansion; (4) in the case of heavily polluted surface waters, the reconnection of floodplains with rivers can contribute to the wide-scale diffusion of pollutants to soils, agricultural areas and groundwater [3]. Careful planning with a large-scale comprehensive analysis is thus essential when implementing a more natural and resilient configuration of cities. To initiate NbS, two main questions are fundamental: "What benefits can be obtained from the desired NbS?" and "Is it adequately suitable for the implementation onto site?"

According to FEMA [12], the implementation strategies for NbS are diverse, and a one size fits all strategy is not suitable. Choosing a solution depends on a several factors, including the level of natural hazard risk reduction, land use planning, economics and more [12]. This agency classifies NbS in three main categories, based on scale and location:

- Watershed or landscape scale: interconnected systems of natural areas and open space (large-scale practices that require long-term planning and coordination);

- Neighbourhood or site scale: distributed stormwater management practices that manage rainwater where it falls (they can often be built within a site, corridor, or neighbourhood without requiring additional space);

- Coastal areas: NbS that stabilise the shoreline, reducing erosion and buffering the coast from storm impacts. While many watershed and neighbourhood-scale solutions work in coastal areas, these systems are designed to support coastal resilience.

Watershed-scale NbS include land conservation (preserving interconnected systems of open space that sustain healthy communities), greenways (corridors of protected open space managed for both conservation and recreation), wetland restoration and protection, stormwater parks (recreational spaces designed to flood during extreme events and to effectively manage stormwater), floodplain restoration (keeping waterways healthy by storing floodwaters, reducing erosion, filtering water pollution, and creating a natural habitat).

Coastal-areas NbS include coastal wetlands, oyster reefs, dunes, waterfront parks (intentionally designed to flood during extreme events, reducing flooding elsewhere), living shorelines (combination of living components, such as plants, with structural elements, such as rock or sand).

The neighbourhood or site specific NbS are mainly found within cities and urban spaces. The most common ones are presented in the following sections.

2.1.1 Green roofs

A Green Roof (GR—also known as living roof or vegetative roof) is a vegetated system installed on a constructed roof structure consisting of several materials settled in a multilayer composition which must provide a suitable breeding ground for vegetation, respecting and promoting the physical integrity of the built structure (**Figure 2**). The multilayer system consists of the following layers (from top to bottom): a growing substrate layer, a separation filter, a drainage layer, a protection and absorption filter and a root barrier.

An effective GR system can absorb stormwater and temporarily store it to be used by the vegetation in their biological processes, reducing the amount of water running

Figure 2.
Example of Green roof [13].

off into the stormwater drainage system and furthermore improve its quality. A GR is a highly appreciated water management solution through its ability to decrease stress on the sewer systems at peak flow in urban areas. According to Augustenborg Botanical Roof Garden (Malmo, Sweden) research paper, a GR retains 50% of the rainwater on yearly basis, allowing only for the 50% of the rainwater to runoff into the drainage system. However, the retention capacity of a GR is highly dependent on the climate conditions, so a significant variability on the runoff retention capacity can be expected throughout a year in different locations.

2.1.2 Vegetated swales

Vegetated swales are an open channel system holding plants or mulch to treat and infiltrate stormwater (**Figure 3**). Grassed channels, dry and wet swales and biofilters are included in this type of NbS. Though there are differences in their design, they are all an upgraded form of a traditional drainage ditch. According to Jotte et al. [13], the swale technique cannot be applied to large drainage areas, but their small slope makes them a good choice for treating runoff from highway or residential areas.

Vegetated swales are designed to slow runoff, promote infiltration, and filter pollutants and sediments in the process of the transmission of water runoff, through the use of endemic vegetation species, capable of growing in water environments and with the capacity to remove pollutants [15]. Pollutants are removed by sedimentation and the filtering processes, both promoted by vegetation and by the different layers of the soil.

2.1.3 Soakaways

Soakaways are small infiltration devices built close to the receiving stormwater production areas. Their walls and bottom are permeable and allow water to flow into the surrounding soils (**Figure 4**), thus their main design considerations are the permeable area and the infiltration rate. The performance of these structures is highly dependent on the soil characteristics and high levels of groundwater can make this NbS inadequate.

Figure 3.
Example of vegetated swale [14].

Figure 4.
Example of a soakaway [15].

Usually, soakaways serve only one household and are constructed in the private grounds surrounding a property, allowing for rainwater management to be handled at the source. Their main benefits are related to runoff volume reduction, hydraulic control and groundwater recharge, but can furthermore through the possibility of complementing other NbS (rain barrels or other rainwater harvesting systems); they also have a very positive effect on stormwater quality, due to the removal of total suspended solids, heavy metals, phosphorous and nitrogen removal [13].

2.1.4 Filter/buffer strips

Unlike swales, buffer strips are set on flat areas with very low slopes. They may be located along streets and highways in order to receive the lateral runoff to block suspended solids and associated pollutants (**Figure 5**) [13].

Grass or other dense vegetation are planted in buffer strips to treat the runoff through vegetative filtering, sedimentation, and to promote water retention and infiltration when possible. Local wild grass and flower species can also be introduced for visual interest and to provide a wildlife habitat [15]. This NbS can serve as a buffer between incompatible land uses and can provide locations for groundwater recharge in areas with pervious soils.

Figure 5.
Example of a vegetated filter strip [15].

2.1.5 Infiltration trenches and basins

Infiltration trenches and infiltration basins (**Figure 6**) have the same operating principle. Similarly, to soakaways, they are designed to receive the surrounding stormwater and to infiltrate it to the surrounding soils through the walls and the base. However, they have an open configuration which leads to the necessity of designing and creating an effective pre-treatment unit to remove coarse solids and hydrocarbons.

Groundwater contamination and soil saturation are concerns associated with these NbS, hose performance is dependent, amongst other factor, on the characteristics of the soil [13]. However, many benefits are linked to these NbS, especially related to the reduction of stormwater runoff, groundwater recharge and treatment capacity (filtration and bio filtration through the substrate in the trench and subsequently through soil).

2.1.6 Wetlands

Wetlands are artificial ponds, conceived with emerged, submerged and/or floating plants, that have a significant role in the removal of a significant part of the influent pollutants (**Figure 7**). They are made up with a substrate layer (except for floating

Figure 6.
Examples of an infiltration trench (left) and an infiltration basin (right) [15, 16].

Figure 7.
Example of an urban wetland [17].

vegetation) and water appropriate plants, being separate from the surrounding soil by an impermeable membrane. This configuration allows stormwater to be detained in the pond and benefits from the natural depuration processes. Part of the water is consumed by the plants and the remaining one leaves the wetland with its quality significantly improved.

Properly designed wetlands can remove significant amounts of nitrogen and phosphorus, suspended solids, and other pollutants from urban environments [13]. When properly designed, wetlands can also provide landscape enhancement and harvest the discharged water for non-potable purposes.

2.1.7 Raingardens

Raingardens (also known as bioretention, bioswales or biofilters) are shallow excavated surface depressions containing mulch and a prepared soil mix, planted with specially selected native vegetation that captures and treats runoff (**Figure 8**), through filtration, which then can either infiltrate to the natural soil or be collected into a sublayer returning to the stormwater sewer system. They remove pollutants from runoff through filtration in the soil and uptake by plant roots and can help to reduce runoff volume through evapotranspiration and full or partial infiltration [13].

The main function of these gardens is to receive, treat and infiltrate low-intensity but frequent precipitation, so they can be complemented with other NbS or even with

Figure 8.
Example of a rain garden [15].

grey-infrastructure to manage excess flows. The use of native vegetation is essential to keep a well maintained and sustainable structure.

2.1.8 Permeable pavements

Pavements with high infiltration capacity are considered permeable. Nowadays, considering the significant area that streets and highways encompass in urban spaces, the transformation of such surfaces into permeable ones are fundamental to reduce the negative impacts of soil sealing. Infiltrating water can thus flow directly into the underlying layers (soils and aquifers) or be stored below ground and released at a controlled rate to surface water.

Examples of permeable pavements are permeable asphalt, permeable concrete, permeable interlocking concrete pavers, concrete grid pavers (**Figure 9**), and plastic grid pavers where opening are filled with pea gravel, sand or top soil and grass [13].

Figure 9.
Example of a permeable pavement [18].

Urban NBS	Advantages	Disadvantages
Green Roofs	Stormwater runoff retention and large detention capacity. Aesthetically pleasing. Good insulation properties. Reduction in impervious area of the property. Suitable for high density developments.	Maintenance of roof vegetation. Expensive design and construction when compared to traditional tile roofs. Necessity of drainage systems and, in some cases, irrigation also. Limited plant species. Potential fire hazard.
Vegetated Swales	Less expensive than conventional conveyance practices. Enhances infiltration. Reduces runoff rates and volumes.	Water treatment is limited to a confined area. There are risks of blockage in connecting pipe networks.
Soakaways	Minimal area space is required. Easy construction and operation. Groundwater recharge.	Not suitable for poor drainage soils. Not suitable for polluted runoff. Performance is reduced during wet periods.
Infiltration trenches	Significant reduction of runoff rates and volumes. Effective reduction of many pollutants, including suspended solids, bacteria and trace metals.	High clogging potential without effective pre-treatment.

Urban NBS	Advantages	Disadvantages
Infiltration basin	Reduction of peak flow rate, erosion and scouring. Effective pollutant removal and local flooding reduction. Groundwater recharge. Base flow of nearby streams is maintained. Simple and cost-effective solution.	High potential for failure rates. Potential for pollution if high TSS (solid materials, including organic and inorganic, that are suspended in the water) in the runoff. Not appropriate for large drainage areas (above 10 acres).
Wetlands	Effective pollutant removal. Enhance wildlife. Good aesthetic and high ecological potential. Positive community acceptance. May increase value of property.	Need to be lined and applied where there is a risk of groundwater contamination. Not appropriate for steep groundwork sites. Nutrients release. No significant runoff volume reduction Space restrictions. May require maintenance and approval from safety authorities. Risk of invasive species development.
Rain gardens	Aesthetic enhancement. Minimal land consumption. Runoff rates and volumes reduction.	Risk of clogging if there is a poor maintenance of the surrounding landscape. Requires proper plant selection and maintenance. Treats relatively small drainage areas.
Permeable pavements	Significant reduction of the runoff rates and volumes. Impervious surface area reduction. Provides pollutant filtering.	Not suitable for high sediment loads.

Table 1.
Advantages and disadvantages of source control systems (adapted from [13]).

2.2 Brief summary

Other NbS can also be classified (e.g. detention ponds or rainwater harvesting systems), but are considered beyond the scope of this chapter because their benefits cannot be improved by using LECA® LWA. The following table presents a comparative analysis of the urban NbS described previously. For each technique, a small description and some advantages and disadvantages are included (**Table 1**).

3. Use of LECA® LWA IN nature-based solutions

3.1 General considerations

The main advantage of NbS in relation to urban stormwater management, is the reduction of the urban surface water runoff that goes into drainage networks (and sometimes to wastewater treatment plants (WWTPs) through the sewer systems), and the delay of the peak flow, when compared to traditional systems without detention mechanisms, as seen in **Figure 10**.

However, NbS efficiency can be enhanced through the application of LECA® lightweight aggregate (LWA) in its different layers, by itself or mixed with other components. LECA® LWA in a sublayer of a NbS, increases the temporary storage

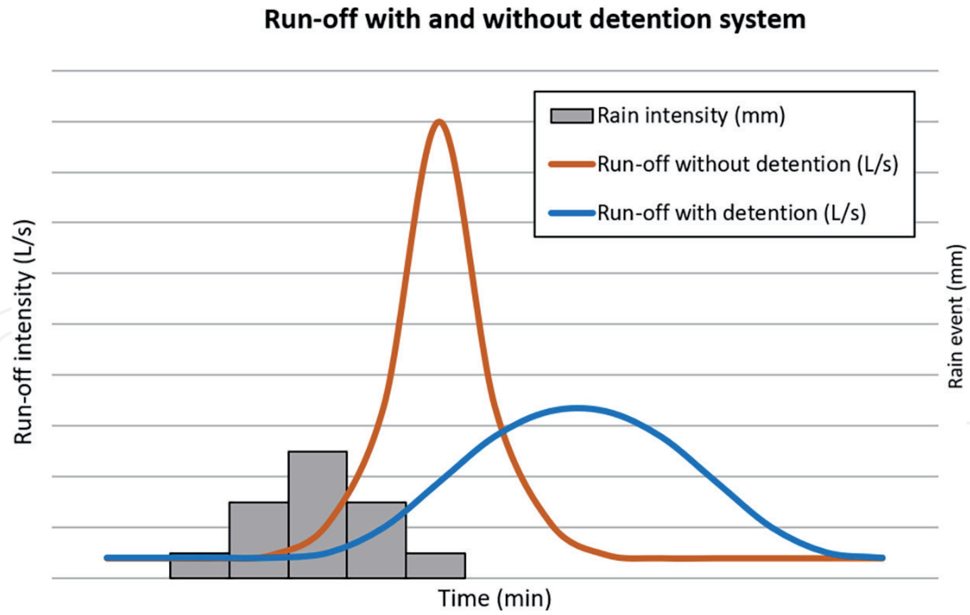


Figure 10.
Typical curve of runoff from a drainage system, with and without a detention layer [19].

capacity for water, reducing the average runoff intensity and decreasing the peak flow intensity. As such, the use of LECA® LWA maximises the advantages and functions of a NbS, as well as the local water resilience.

LECA® LWA is a natural product made by heating natural clay and can be used as a construction material in local water management infrastructure, due to its high mechanical strength, robustness, easy installation and sustainable longevity. LECA® LWA competes with other materials on the market for water management such as plastic boxes, textile mats, pumice, foam-glass and crushed brick [20]. This aggregate has an inherent ability to retain, detain and drain water runoff due to its natural characteristics: lightweight highly porous grains, high specific surface area and large volume of voids between the grains. The geometry allows LECA® LWA to temporarily detain moderate amounts of flowing water and thereby reduce peak intensity runoff for small catchments.

Furthermore, due to its highly porous structure and large surface area of crushed grains, LECA® LWA is also suitable to improve rainwater runoff quality. Through physical, biological and chemical processes, LECA® LWA can act as a filter, removing dissolved and suspended particles, nutrients (e.g. phosphates) and heavy metals in its porous grains that would otherwise end up downstream within the water cycle. Its greater resistance to clogging enhances its use in stormwater treatment and is furthermore supported by its typically low operating costs and a long life-span [19].

The capacity of a NbS to manage stormwater, is determined through the runoff coefficient or coefficient of discharge (C), a dimensionless value which varies between 0 and 1 that indicates the surface runoff from a catchment. The runoff coefficient is expressed as the rational between the total amount of water running onto the surface and the amount of received precipitation during a rainfall. **Figure 11** presents runoff coefficients for different surfaces with increasing precipitation.

The application of a subsurface layer of LECA® LWA into an already existing permeable surface (**Figure 11**) allows for lower runoff coefficients, achieved even at high rain intensities, when compared to other surfaces. Highly porous crushed LECA® LWA

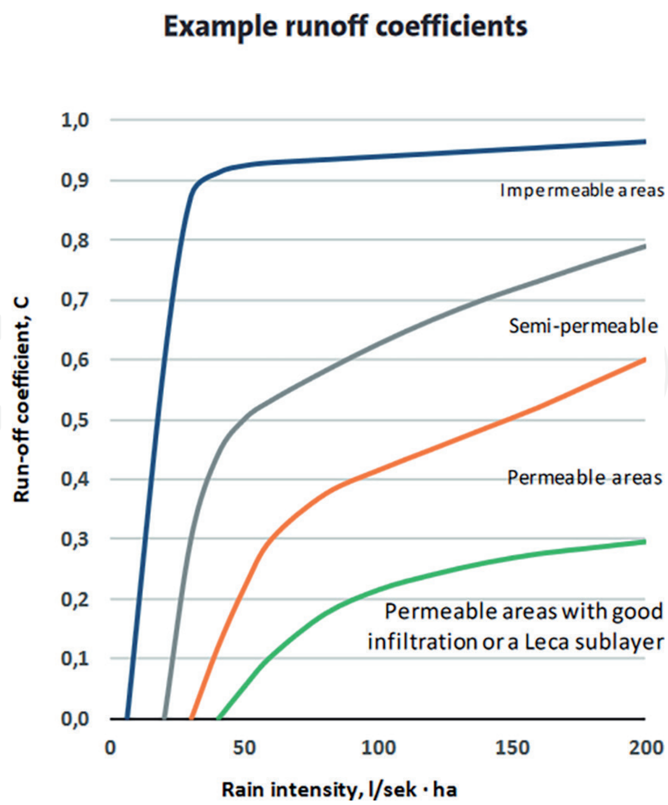


Figure 11.
Examples of runoff coefficient (C) for different surfaces with increasing rain intensity [19].

integration in a given water management solution, substantially decreases the runoff coefficient of the surface, through retention and detention of rainwater, thus improving the capacity to manage water runoff in extreme events, delaying water runoff and preventing floods. LECA® LWA will operate in synergy with the surface components, and the runoff reduction will increase with the thickness of LECA® LWA layer.

3.2 Hydrological performance of LECA® LWA with different granulometry

LECA® LWA can be presented with different granulometry: finely crushed (0–6 mm); coarsely crushed (4–10 mm) and uncrushed or round LECA® LWA (10–20 mm). In order to assess LECA® LWA hydrological characteristics, technical water retention tests simulating an intense rainfall, have been performed, in trial tests of 100 mm and 200 mm layer thickness, 2% slope and compared to a reference impermeable area without detention measures. The achieved results are shown in **Figure 12** and the corresponding values presented in **Table 2** [20].

The results have shown that finely crushed LECA® LWA in both layer thickness tests, presented higher peak runoff intensity reduction and a higher amount of detained water, when compared to the coarsely and round LECA® LWA. This result solves the gap identified by Pradhan et al. [21] when studying the hydraulic performance of several plant growth media in a greywater treatment NbS, including one with LECA® LWA. The low performance of this aggregate when comparing to perlite, coco coir and sand, was due to the largest size particles and high porosity. On the other hand, the runoff reduction resulting from the finely and the coarsely crushed LECA® LWA, and showed in **Table 2**, is with accordance with the reduction expected from an intensive green roof, as the one reported by Lee et al. [22] with 200 mm substrate layer thickness and a runoff reduction between 42.8–68%.

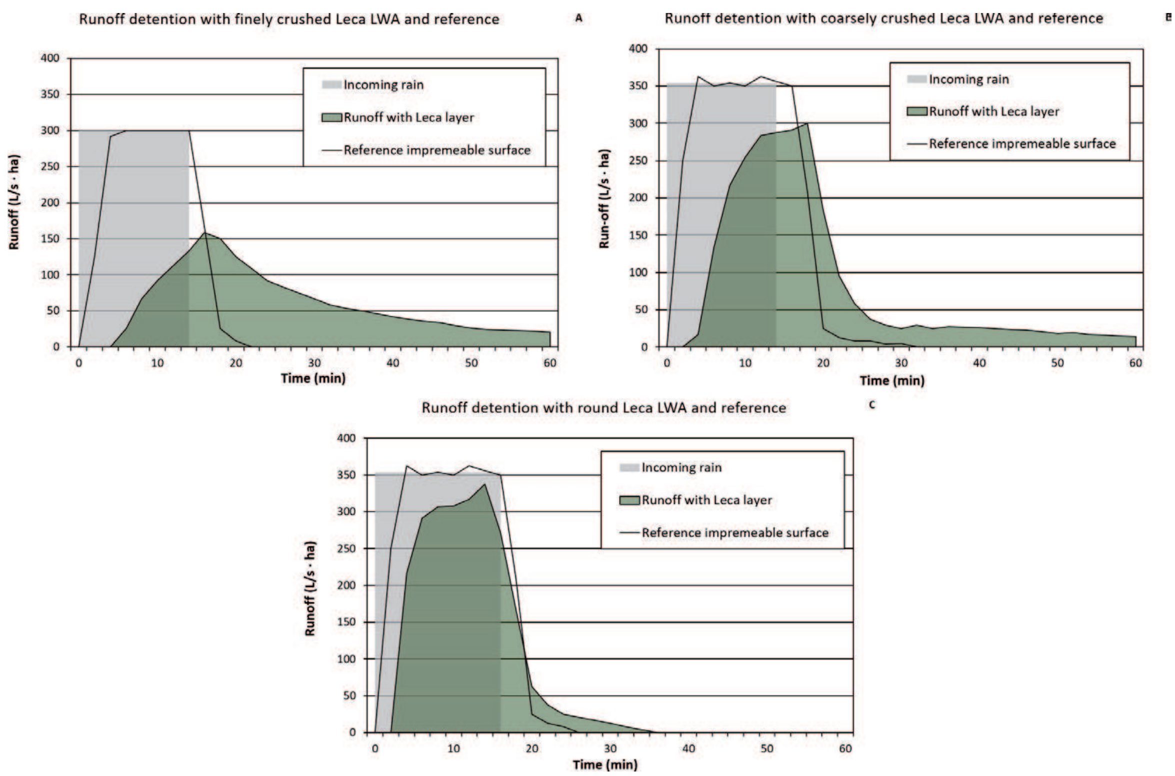


Figure 12.
Runoff behaviour for LECA® LWA (A: Finely crushed; B: Coarsely crushed; C: Round).

LECA® type	Finely crushed LECA®		Coarsely crushed LECA®		Round LECA®	
Rainfall event conditions simulation	27 L/m^2 for 15 min		36 L/m^2 for 15 min		36 L/m^2 for 15 min	
Rain intensity	300 L/(s.ha)		350 L/(s.ha)		350 L/(s.ha)	
Thickness of LECA®-layer	200 mm	100 mm	200 mm	100 mm	200 mm	100 mm
Peak runoff intensity reduction	53%	45%	35%	18%	17%	6%
Amount of delayed water, approx.	70%	55%	40%	30%	20%	15%

Table 2.
Peak runoff intensity (%) and the total amount of water detained (%) for different LECA® LWA granulometry.

Tests for runoff coefficient determination of the three LECA® LWA granulometry showed that finely crushed LECA® LWA presents the best runoff coefficients: values between 0.15–0.4 in a 200 mm thickness of LECA® LWA layer (with rain intensity varying from 200 to 400 L/(s.ha)) when compared to coarsely and round LECA® LWA with values between 0.2–0.5 and 0.3–0.7, respectively. The lower runoff coefficients achieved by finely crushed LECA® LWA are explained due to their higher surface area and porosity that can retain water [20].

	Pollutant removal (%) by filter material			
	Cu	Pb	P	Zn
LECA® round 2–4 mm	99	99	>90	98
LECA® crushed 0–3 mm	99	99	>90	98
LECA® crushed 3–8 mm	86	85	>90	80

Table 3.
Stormwater pollutant removal (%) in laboratory column tests (initial pollutants concentration: Cu = 10 mg/L; Pb = 20 mg/L; P = 10 mg/L; Zn = 40 mg/L).

Therefore, based on the technical tests performed and depending on the intended purpose when installing a LECA® LWA layer coupled with a NbS, it can be claimed that finely crushed LECA® LWA is optimal when maximum water detention is intended; coarsely crushed LECA® LWA when higher hydraulic permeability must be achieved; and round LECA® LWA when increased drainage and water storage are needed.

LECA® LWA can also act as a stormwater filter material—improving water runoff quality. By incorporating LECA® LWA into biofilters or as filter strips, a wide range of dissolved and suspended pollutants and heavy metals can be removed from water runoff. Holt et al. [23] reported removals of several pollutants using different granulometry of LECA® LWA as presented in the following **Table 3**, based on the results achieved on the VTT Stormfilter research program.

3.3 Runoff coefficient for different layered detention-based roofs with LECA® LWA

The work developed by Schärer [24] to investigate runoff coefficients for different layered detention-based roofs, included a comparison of different roof configurations with commonly used layers of typical combinations of green or LECA® LWA—based roof solutions. Results confirm the beneficial effect of LECA® LWA on the performance of green roofs and permeable pavements.

From the five configurations studied for single layer roofs, the 10 cm LECA® medium layer presented the best performance with a lower and later peak flow. It had a considerably lower runoff coefficient than the other four individually tested layers (two with two types of felt mat and two with drainage mat with and without holes on the bottom).

Three green roofs were also tested: one with sedum and felt mat, another with sedum, felt mat over-the-drainage mat with extra drainage holes and the last one with sedum, felt mat, drainage board and LECA® medium (**Figure 13**). This last one resulted in the lowest runoff coefficient and also gave a substantially lower runoff coefficient than the 10 cm LECA® medium layer referred above.

LECA® LWA also had a very significant effect in the performance of the studied non-vegetated roofs (**Figure 14**). The runoff coefficient of a LECA® LWA based roof system with permeable pavement (C = 0.33) was significantly lower than the test of the pavement alone (C = 0.89).

Of all the experimental measurements (ten roofs, plus one reference), the LECA® medium based systems gave the lowest runoff coefficients. Those were the most complex systems, with the main drainage in the LECA® LWA layer. The event-based detention hydraulic performance was found to be higher for vegetated roofs, instead of the non-vegetated ones. LECA® medium clearly made a significant difference on

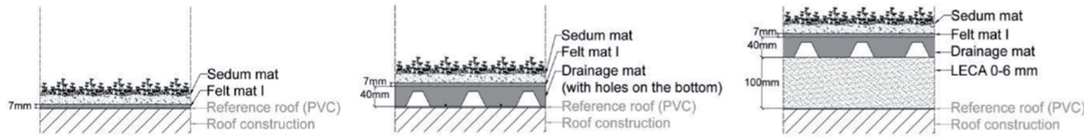


Figure 13.
Green roofs configuration [24].

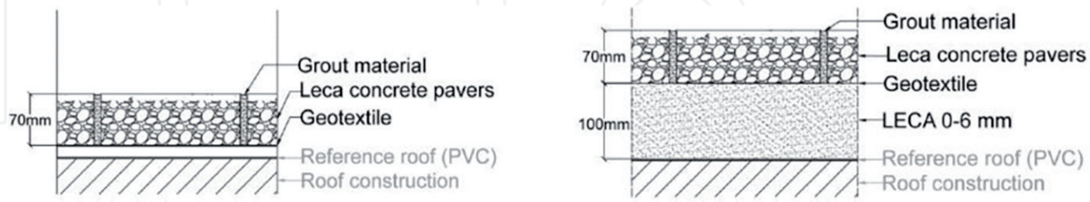


Figure 14.
Non-vegetated roofs configuration [24].

the results with lowest measured runoff coefficients on the corresponding roofs that achieved runoff coefficients of around 0.3 instead of around 0.8 in the corresponding roofs without it.

Koc et al. [25] reported the capacity of four different NbS for stormwater management presenting a runoff reduction of 41.67% for green roofs, 37.83% for bioretention cells, 27.99% for infiltration trench and 29.04% for permeable pavement. Another study reported by Harper et al. [26] presented ca. 60% runoff reduction of a vegetated substrate compared and only 40% runoff reduction when the same substrate was unplanted. Although this shows a good stormwater management performance, according to the findings of Schärer [24] here presented, these NbS could improve their runoff retention values by introducing LECA® LWA in their layers.

3.4 LECA® LWA field test at Høvringen in Trondheim and the Oslo project

For a long time, the traditional way of guiding rainwater off a roof has been with gutters and downspouts to the ground, which nowadays faces two major challenges: (1) more precipitation and more frequent short periods of torrential rain (resulting in large quantities of water overloading stormwater sewage networks); (2) densification of urban areas and fewer natural areas for absorbing and infiltrating water. As such, in 2016 under the project Klima 2050 (developed at Høvringen in Trondheim, Norway), researchers started focusing on new solutions for delaying water runoff when it rains while at the same time converting the sewage treatment plant roof into an attractive terrace. As such, a field test for detention and retention based roofs was installed and instrumented at Høvringen RA in Trondheim, Norway (**Figure 15**) [13].

The detaining and retaining runoff properties of the pilot GR system have shown that both mean and peak intensity (5 min) of runoff may be reduced. The LECA® LWA based configuration provided a detention performance for a peak runoff reduction of 95% (median) and for a peak delay of 1 h 15 min (median). The peak detention and peak reduction from reference vs. blue grey roof achieved 1 h 47 min and 75%, respectively. The high permeability characteristic of LECA® LWA contributed

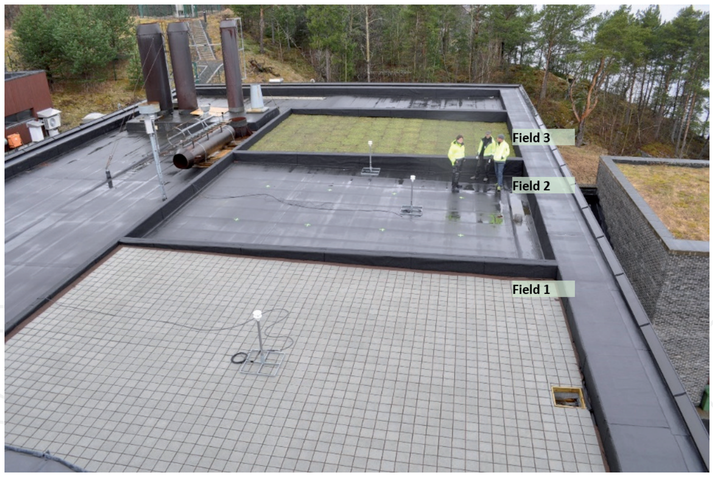


Figure 15.
KLIMA 2050 project field test at Høvringen using LECA® LWA in Trondheim, Norway (field 1—LECA® LWA below permeable paving blocks; field 2—Black empty reference roof; field 3—LECA® LWA under a traditional sedum green roof) (Photo: Tore Kvande, NTNU—Norwegian University of Science and Technology).

to a steady, but restricted flow of water through the medium. Therefore, it could be concluded that LECA® LWA can be used as an alternative to natural detention and infiltration of rainwater, to reduce local runoff coefficients, by simulating the same mechanisms found in natural environments [13, 27].

Blue-grey and green roofs were also installed at Oslo with the suggested LECA® LWA build-up, based on recommendations from Andenæs et al. and Thodesen et al. [28, 29] that addresses the performance of blue-grey and green roofs in cold climates.

Oslo municipality has developed a 3-step-strategy against all rainwater (not only the extreme events), to maintain a healthy water cycle and increase water resilience of the city (**Figure 16**). The advantage of using LECA® LWA was due to their potential benefits in all steps of this water management strategy (catchment, infiltration, delay, detention, drainage and protection).

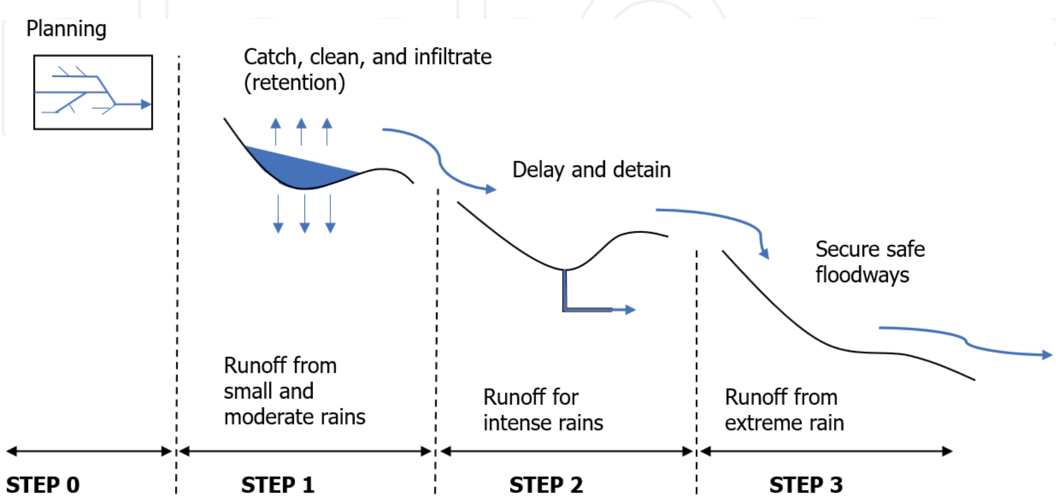


Figure 16.
Oslo 3-step strategy city planning and urban water management.

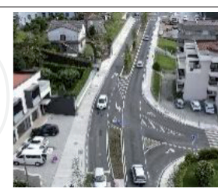
Project name	Location	Usage/Area	Purpose of LECA® LWA	LECA® LWA type (Volume)	Project photography
Lilleborg Terasse	Stokke, Norway	Rooftop recreational area (450 m^2)	Water detention	Finely crushed LECA® (59 m^3)	
Makrillen	Goteborg, Sweden	Courtyard (2500 m^2)	Sublayer water storage	Round LECA® 10–20 mm (700 m^3)	
Valkyriegata	Oslo, Norway	Rooftop recreational area (320 m^2)	Water detention	Finely crushed LECA® LWA (105 m3)	
Budolfi Plads	Aalborg, Denmark	Public Town square and park (7200 m^2)	Lightweight drainage material	Round LECA® LWA 10–20 (3000 m^3)	
REDI shopping center green deck	Helsinki, Finland	Rooftop recreational area (13.000 m^2)	Terrain shapes, drainage and soil mix	LECA® LWA 4–10 mm and crushed LECA® LWA 3–8 mm (1200 m^3)	
Emporia shopping center	Malmo, Sweden	Rooftop recreational area (27.000 m^2)	Terrain shapes, drainage, insulation	LECA® LWA 10–20 mm (10.000 m^3)	
Drainage ditch, Guimarães national highway	Guimarães, Portugal	Re-profiling of a national highway section	Lightweight drainage material	LECA®(S), LECA®(L) (192 m^3)	
Zielony Nugat II Housing Estate	Warsaw, Poland	Buffer water drainage	Drainage, thermal insulation and substructure	LECA®(L) (300 m^3)	
Laureate Gardens, Henley on Thames	United Kingdom	Rooftop recreational area above a residential car park	Lightweight drainage material	LECA® LWA 10–20 mm (120 m^3)	

Table 4.
LECA® LWA water management reference projects.

3.5 Reference projects for LECA® LWA applications

Stormwater management strategies in a specific location contribute to runoff decrease and lessen water accumulation preventing drainage sewer systems overflow. As such, several other water management reference projects have been constructed taking advantage of LECA® LWA properties and their water management capacity. **Table 4** presents a few examples of such projects.

4. Conclusion

Rainwater management in urban areas is a major concern in the present climate change scenario, with more frequent and intense precipitation events and the consequent urban floods and water resources degradation. NbS have been increasingly implemented within cities, due to their operational benefits in minimising stormwater management problems by catching, retaining, detaining and infiltrating the excess water when intense precipitation events occur. However, NbS performance can be enhanced by adding a natural material—LECA® LWA, as a layer. This lightweight material is applicable to all traditional NbS solutions, and increases the simulation of nature's own water infiltration mechanisms due to its high water retention capacity—thus being ideal for local water management in all types of infrastructures. Experimental studies show that by using LECA® LWA in a green roof sublayer, a reduction on the runoff volume of about 95% has been achieved and a delay in the peak flow at around 1 h 15 min. Permeable pavements with LECA® LWA can also significantly increase their runoff coefficient from 33–89% when compared to the pavement alone. On the other hand, the LECA® LWA granulometry has a significant influence on the NbS. Finely crushed LECA® LWA presents the lower runoff coefficient values then coarsely or round LECA® LWA (0.2–0.5 and 0.3–0.7, respectively), revealing a better retention performance.

Several reference projects have been implemented in Europe specifying LECA® LWA in their sublayers to increase the performance of those structures. Laboratory and field tests have shown that by using a layer of LECA® LWA, a peak runoff intensity reduction has been achieved as well as a peak delay, and also higher amounts of detained water when compared to systems without LECA® LWA layer. However, the water retention capacity of LECA® LWA is limited and when it reaches saturation level, stormwater retention capacity of the system incorporating LWA ceases and the runoff starts flowing to drainage systems. Further investigations are thus necessary to continue scientific research and development of NbS with higher hydraulic efficiency using LECA® LWA with different granulometry in their composition, considering their inherent operating differences and their distinct interaction with the surrounding environment. Additionally, NbS combination with other LID or BMP's solutions must be considered, since it can enhance its stormwater retention capacity and water quality improvement to a level where it can become an alternative water source to urban consumption.

Furthermore, the good planning and development of such NbS as the one implemented in Oslo, can combine recreational areas and stormwater water management measures, thus improving the standard of living in densely populated urban cities, creating at the same time, more pleasant and accessible places. The development of such blue-grey/green solutions are imperative, and will challenge the construction industry norms when planning local water management measures, contributing at the same time to urban areas resilience and climate change mitigation.

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Conflict of interest

No conflict of interest.

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