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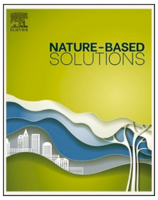

Urban stormwater retention capacity of nature-based solutions at different climatic conditions

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ABSTRACT

Climate change and the continuing increase in human population creates a growing need to tackle urban stormwater problems. One promising mitigation option is by using nature-based solutions (NBS) – especially sustainable urban stormwater management technologies that are key elements of NBS action. We used a synthesis approach to compile available information about urban stormwater retention capacity of the most common sustainable urban drainage systems (SUDS) in different climatic conditions. Those SUDS targeting stormwater management through water retention and removal solutions (mainly by infiltration, overland flow and evapotranspiration), were addressed in this study. Selected SUDS were green roofs, bioretention systems (i.e. rain gardens), buffer and filter strips, vegetated swales, constructed wetlands, and water-pervious pavements. We found that despite a vast amount of data available from real-life applications and research results, there is a lack of decisive information about stormwater retention and removal capacity of selected SUDS. The available data show large variability in performance across different climatic conditions. It is therefore a challenge to set conclusive widely applicable guidelines for SUDS implementation based on available water retention data. Adequate data were available only to evaluate the water retention capacity of green roofs (average 56±20%) and we provide a comprehensive review on this function. However, as with other SUDS, still the same problem of high variability in the performance (min 11% and max 99% of retention) remains. This limits our ability to determine the capacity of green roofs to support better planning and wider implementation across climate zones. The further development of SUDS to support urban stormwater retention should be informed by and developed concurrently with the adaptation strategies to cope with climate change, especially with increasing frequency of extreme precipitation events that lead to high volumes of stormwater runoff.

1. Introduction

The last two decades have been the warmest on record, and the frequency and intensity of extreme weather events has constantly increased [33]. Climate models predict further increases in periods with unpredictable and intensive rainfalls and droughts worldwide in the near future [49]. The European Commission [33] has accepted a long-term strategic vision to achieve climate neutrality by 2050 and, among other directives targeting climate-related issues, to find solutions to prevent water-related disasters. There is a rapid increase in urbanization worldwide that has both increased the demand for high-quality potable water resources, and profoundly disrupted the natural water

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cycle and surface water quality [78]. In the urban environment, impervious surfaces have profound impacts on hydrology, reducing infiltration and thus dramatically increasing the amount of surface runoff and flooding [5,37]. These changes are greatly augmented by the increases in extreme storm events, storm surges, and severe floods, that have become more frequent due to climate change.

One of the greatest challenges cities face is to find optimal, sustainable and economical solutions for stormwater management in highly developed urban areas [69]. This is a critically important challenge, because of the negative impacts that urban stormwater has on aquatic and terrestrial ecosystems and on humans through water pollution and floods [20,37,38]. These problems have been recognized for many years, inspiring the development of more environment-friendly stormwater management solutions that utilize nature-based structures and functions (e.g., wetlands that retain and infiltrate stormwater) rather than gray infrastructures made solely from anthropogenic materials (e.g., storm sewers that rapidly reroute stormwater away from the landscape) [38]. However, these nature-based management tools have not yet been widely applied, and most of the new stormwater management solutions implemented in cities remain in the form of conventional storm sewers with occasional and limited treatment by associated detention or retention basins [85]. The management of urban stormwater has seen significant change from single goal of reducing flooding [111] toward integrated sustainable management approaches like nature-based solutions (NBS), where multiple aims lead the design and decision-making processes including improved water quality, enhanced biodiversity, recreational and other social co-benefits, better groundwater recharge, reduction of energy consumption [78], reduced heat island effect and improvement of urban microclimate [6,20].

NBS are different types of blue-green infrastructure that are "*inspired by, supported by, or copied from nature*", and they use or mimic natural processes [103]. The NBS located in urban areas are largely designed to enhance sustainable urbanization, aiding in the development of climate change adaptation and mitigation [94]. The main aim of NBS for urban stormwater management is to control surface runoff volumes and timing and, hence, they reduce the risk of flooding during heavy rainfall events [35]. However, because by definition NBS are resource-efficient, they can be adapted to diverse spatial areas, and can in many ways assist cities in addressing various social and environmental challenges in a more cost-effective manner than grey infrastructure [94]. In a review by Seddon et al. [89], the values and limits of NBS to climate change and other global challenges have been addressed.

NBS related to urban stormwater management are considered sustainable solutions that enhance water availability, improve water quality and reduce risks associated with water-related disasters and climate change [89,103]. The terms associated with blue-green infrastructure and urban drainage can differ widely on a global scale [38]. Examples of blue-green infrastructure with general aim to manage stormwater include sustainable urban drainage systems (SUDS), best management practices (BMP), stormwater control measures (SCM), low impact developments (LID) and water sensitive urban designs (WSUD) [38]. In this overview we decided to use the term SUDS.

The SUDS, that are key elements in NBS actions to manage stormwater in urban environments, include stormwater retention, infiltration and buffering structures such as bioretention cells/filters (i.e. rain gardens), swales, buffer and filter strips, constructed (treatment) wetlands, ponds, basins, green roofs and walls as well as permeable pavements. SUDS, such as swales, street tree pits or rain gardens can improve the interception, evaporation, and infiltration of stormwater before it reaches sewage systems, thus decreasing the volume of water needing to be treated [34]. The effectiveness of SUDS for urban water management depends on the type and design of the systems and the local conditions. Small-scale systems have been found to decrease runoff by 30-65% for porous pavements, up to 100% for rain gardens or up to 56% for infiltration trenches [87]. Green roofs can retain greater amounts of rainwater than conventional roofs and delay stormwater runoff [77,79]. A heavy rain event of short duration (e.g. 30 min) could be completely retained by a dry green roof [84] and in general reduce runoff volume by up to 70 % and peak flow volume by up to 96% [87].

Most NBS have not achieved wide-spread implementation worldwide due to the gaps in knowledge regarding designing, implementing, and maintaining NBS or quantifying the benefits and co-benefits of their ecosystem services [94]. The most common barriers to implementing SUDS are the cost of establishment and maintenance of these systems [85], and the availability of space in urban areas [115]. Most of all, a lack of confidence in SUDS among decision-makers is one of the greatest challenges to implementation, as there is still lack of awareness and compiled information about successful experiences with SUDS; this is especially the case when it comes to their role in flood control and water-related disaster prevention [87]. Thorne et al. [100] has concluded that the limited use of blue-green infrastructures like SUDS is due to lack of confidence in public preferences for SUDS over conventional stormwater infrastructure, as well as the uncertainty regarding scientific evidence related to efficiency of physical processes in SUDS. There is still, surprisingly, a shortage of concise information about rainwater and runoff retention and volume reduction capacity of many existing SUDS. Further there is particularly limited evidence related to the applicability of SUDS in cold climate and in urban landscape that is already highly developed. A comprehensive critical overview of research on NBS for hydro-meteorological risk reduction has been done by Ruangpan et al. [87] where current knowledge gaps and future research prospects are also provided.

The barriers preventing wider use of in SUDS in cities due to the uncertainties and public attitudes detailed above require a comprehensive evaluation of available information from practitioners and from the scientific world.

Therefore, the main goals of our literature review were to determine and compare the average urban stormwater retention capacity of most widely used SUDS and to explore how much the climatic conditions, based on annual temperature and precipitation differences, affects the water retention capacity of different SUDS. With this analysis, we aim to provide information that can improve the implementation of SUDS on a global scale, uncover potential shortcomings in using them for stormwater management based on biome, and future research needs associated with sustainable stormwater management.

2. Methodology of search, selection process and data analyses

The primary purpose of this literature review and analysis was to focus on water retention capacity of the most widely spread and implemented SUDS in the world. These solutions include green roofs (GR), constructed wetlands (CW), bioretention systems (BR), buffer and filter strips (BS), permeable pavements (PP), and swales (S). The following comprehensive databases of published, peer-reviewed scientific literatures were used to identify and locate scientific articles and books: ISI Web of Science, Science Direct, Scopus and Google Scholar. Additional searches were performed in the Google search engine for governmental and highly recommended guidelines, reports and related area-specific databases. After an initial search we reviewed all findings and finally selected 170 different sources (scientific articles, guidelines, reports, thesis and databases).

The terms '*green roof(s)*', '*constructed wetland(s)*', '*treatment wetland (s)*', '*bioretention (cell(s)/system(s))*', '*rain garden(s)*', '*buffer strip(s)*', '*filter strips*', '*permeable (pervious/porous) pavement(s)/(layer(s))*', and '*swale(s)*' in combination with the one or many of the following terms '*urban*', '*stormwater*', '*water*', '*rain*', '*retention*', '*volume reduction*', '*runoff*', '*removal*' were searched in combinations.

From collected articles, reports, guidelines, and databases, we identified both function of the SUDS in terms of stormwater mitigation (% of water retention capacity) and aspects of SUDS design that may affect water retention capacity, namely depth of the substrate layer (cm) and size (m^2) of the SUDS. A data table with total 327 individual SUDS or studies, and corresponding references that addressed and/or evaluated water retention capacity are available in the Supplementary Table S1.

In order to accurately categorize climate setting of each SUDS study, we obtained the annual average temperature and precipitation [4,117]; and the major climate zones (subtropical, tropical, temperate, boreal) [71] for each study/solution in our database. In cases, when data ranges were provided, we calculated average values for our analyses. Major climate zones were also used to classify the conditions at each SUDS location as '*warm, wet*', '*warm, dry*', '*cold, wet*' and '*cold, dry*'.

We applied R version 4.1.2 [80] to explore, analyze and visualize the data. Missing data (Fig. 1) were identified and explored using the packages "naniar" version 0.6.1 [101], and "VIM" version 6.1.1 [59]. The packages "lme4" version 1.1-27.1 [10] and "ggeffects" version 1.1.1 [68] were applied to model and predict the relationships between average water retention capacity and the SUDS characteristics of size, media depth (in the case of green roofs), and the random effect of each study in our database was included for different climatic conditions.

3. Overview of definitions and main characteristics of selected NBS

For NBS, the most commonly used definitions are from the European Union and the International Union for Conservation of Nature (IUCN). The European Commission [32] defines Nature-Based Solutions as: "*Solutions that aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by, or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions. Nature-based solutions use the features and complex system processes of nature, such as its ability to store carbon and regulate water flows, to achieve desired outcomes, such as reduced disaster risk and an environment that improves human well-being and socially inclusive green growth*". The definition by IUCN [50] states: "*Nature-based Solutions are actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.*"

Blue-Green Infrastructure is an "*interconnected network of natural and designed landscape components, including water bodies and green and open spaces, which provide multiple functions such as: (i) water storage for irrigation and industry use, (ii) flood control, (iii) wetland areas for wildlife habitat or water purification, and many others*" [43] and are crucial part of NBS.

Mostly nature-based sustainable urban drainage systems (i.e. sustainable urban stormwater management systems; SUDS) are blue-green infrastructures that mimic natural ecosystems in stormwater drainage and treatment, enabling stormwater to be managed efficiently and in an environmentally friendly manner [115]. SUDS are a set of water management practices aimed at adapting modern drainage systems to natural water processes, while considering challenges associated with climate change conditions [115]. The objective of SUDS is to reduce the amount and flow of stormwater runoff by dispersion, infiltration and by re-using rainwater as much as possible at the source [22]. In the following sub-sections, the main concepts and characteristics of selected SUDS are presented.

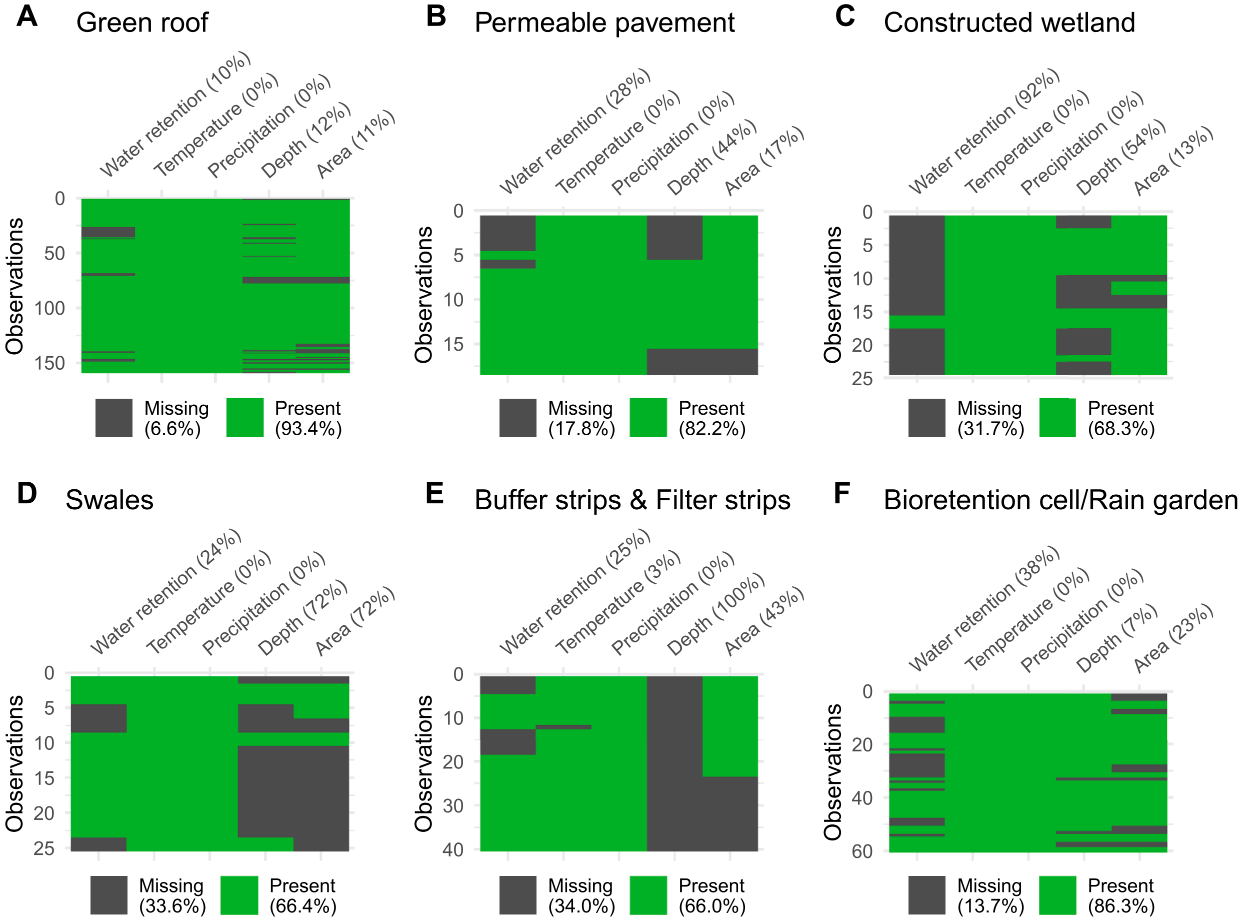

Fig. 1. Missing data in the gathered database of total 327 SUDS.

3.1. Green roofs

In city centers, where a large area of land is occupied by buildings, the best solution to control stormwater runoff is to use green roofs [104]. A comprehensive review about applications of green roofs for managing urban stormwater in different climatic zones has been published by Akther et al. [2]. A green roof is a multi-layered composition on the roof main structure with a planted upper surface. Green roofs can be classified as extensive and intensive types. Extensive GRs are composed of a thin substrate layer (<150 mm) with grasses and herbs (mainly *Sedum* genus). Intensive vegetated roofs have deeper topsoil layers (>150 mm) and more choices of usable plant species. However, at the same time, they require more maintenance. There are numerous environmental and economic benefits of green roofs [60]. They can help to sequester carbon, conserve energy, reduce heat island effects, evapotranspiration from green roofs cools the buildings, improve air quality, extend the life of base roof materials, improve biodiversity, raise aesthetic value of the building, improve water quality and manage stormwater [1]. There is a vast volume of review papers about the hydrological performances of green roofs published in last 20 years [2,23,92,119]. The ability to hold stormwater depends mostly on the substrate layer thickness and components, roof slope and vegetation type. Weather conditions, which influence the water retention capacity, are season/climate, rainfall event characteristics and length of the antecedent dry weather period. Efficacy in stormwater management by green roofs is determined by two factors [1]: (a) rainfall amount, which is partly retained by a substrate layer and taken up by plants, returned back to the atmosphere by evapotranspiration, and (b) runoff after peak flow attenuation time, that is influenced by rainfall intensity and roof saturation. In view of the above-mentioned factors, when rainfall intensity is low and the roof substrate is dry, there is almost no runoff and the retention rate is consequently 100%. When rainfall is intensive and the substrate is already saturated with water – runoff will be instantaneous, and the runoff retention rate will be therefore very small.

3.2. Bioretention systems

Bioretention systems have become one of the most widely used and versatile SuDS [24,72], certainly in the USA, but also in other parts of the world. A good overview of targeted bioretention design has been published by Hunt et al. [48]. A typical bioretention system consists of relatively small areas in urban settings that are excavated and backfilled with special substrate [86]. The substrate (0.7 to 1 m deep) is usually a mixture of high-permeability soil, sand and organic matter that is covered with a mulch layer [24]. The design of bioretention systems should maximize the infiltration and support vegetation growth. Therefore, native terrestrial vegetation resistant to environmental stresses is typically used in these systems. Selected vegetation may vary in size and species depending on the size of the bioretention system and climatic conditions [86]. Bioretention systems are designed to allow for about 15–30 cm of runoff pooling/ponding on top of the substrate. Influent structures (designed according to climatic conditions) allow runoff to enter the system. Usual features are also underdrain and overflow pipelines (both connected to storm sewers). Overflow systems bypass the flows above the ponding capacity. When soil infiltration must be avoided, bioretention cells can be built with impermeable bottom liners and connections to storm sewers. Bioretention systems are meant to drain within hours [30], so the vegetation in these installations must be selected to tolerate changing hydrologic regimes [86]

Bioretention systems are effective in peak discharge control, as different studies have reported the peak discharge reduction to be on average 40 to 99% [24]. Bioretention is also designed as effective measure to reduce stormwater volumes and pollutants through natural treatment processes [24,28,86]. However, there is still deficit of information about the real-life runoff retention capacity in these systems, especially in cold climate, as flow measurements in most of the stormwater infiltration systems are technically complicated.

The ability to reduce peak flow volumes through infiltration and evapotranspiration depends on soil infiltration capacity and capture volume. Thus, bioretention systems could be used effectively in different locations including urban areas to mitigate an increase in stormwater volume from impermeable surfaces that otherwise would overload traditional drainpipes and stormwater control systems [24,86].

3.3. Buffer and vegetated filter strips

Buffer and vegetated filter strips are gently sloped land adjacent to water-courses (e.g., stream and ditch) to minimize non-point source pollution [14,72]. They provide green links in urban developments, next to roads or parking lots to buffer stormwater runoff from these impermeable surfaces [8,26,48,64,112].

Urban vegetated filter strips (also called “vegetated filter strips” and “grass filter strips”) are designed to receive stormwater from adjacent impervious surfaces, such as parking lots [72] and roads [14], and are mostly located between hard-surfaced areas and a receiving water-courses. They are uniformly graded, gently sloping and should be vegetated with smaller plants, covered by a grass mixture. They are designed to receive runoff as overland sheet flow from upstream developments. Their main goal is to buffer the stormwater, reduce its velocity and improve water quality before it reaches a conveyance system. They help to increase infiltration and remove sediments and other pollutants through sedimentation and filtration as well as biological and chemical activity [8]. Filter strips are often used together with other SUDS (e.g. swales) as they usually are designed to treat runoff from rather smaller drainage areas such as roads or parking lots [114]. However, when only filter strips are used for stormwater runoff reduction, previous studies have reported 20 to 85% of inflow runoff volume reduction [26,48,56,66]. For better performance, Woods Ballard et al., [115] indicated some key design criteria for filter strips. For example, the longitudinal slope should be 1 to 5%, runoff should be evenly distributed and the minimum width should be 6 m to obtain good performance values for filter strips.

3.4. Vegetated swales

Swales are usually linear, wide and shallow depressions (or open channels) that are vegetated and convey stormwater runoff from impervious areas [27] and allow water to infiltrate into permeable soils [82]. The minimum base width should be 0.5 m and maximum depth around 400–600 mm. The longitudinal slope should not exceed 6%. The length of the swale should be equal or greater than the road its adjacent to [115]. In addition to their main purpose of conveying stormwater, they also treat and attenuate storm water through sedimentation and filtration by vegetation and plant material as well as infiltration through soil [40]. The vegetation must be selected from native plant species (grasses and herbaceous species) that should be maintained at a height of 75–150 mm [115]. By promoting infiltration, swales help to reduce runoff volumes and delay runoff peaks and flow velocity [27].

There are several types of swales: standard, dry and with check-berms [82,115]. In dry swales, infiltration and drainage is maximized by a special filter media bed and an under-drain pipe at the bottom [82]. If more infiltration is targeted, check-berms could be added at regular intervals and combine the swale with filter strips [25]. Swales could be used separately or together with buffer strips or other SUDS. Best areas where to establish swales are low density housing areas with wide roadway verges or open spaces where overland flows might occur [27].

The performance of swales is related to the size of it and the intensity of rainfall events. With smaller rainfall events, the swale generally produces no runoff. However, during intensive rain events, the swale acts as a conveyance system that helps to delay runoff peaks [82]. Different studies have reported runoff volume reductions to be 23 to 48% [7,9,56,82].

3.5. Constructed wetlands

Constructed wetlands (CWs; especially treatment wetlands) are permanently wet areas that provide runoff water attenuation and treatment through natural treatment processes [115]. There are several CW classifications, which are, most commonly, based on the hydrology and vegetation type. By flow, CWs are categorized as to horizontal sub-surface flow, vertical sub-surface flow, free water surface (i.e. surface flow) or hybrid CWs (different types that are combined with each other) [29,39]. The free water surface CWs are more commonly used for stormwater management in urban developments, as they create green areas and have a better recreational value. The shallow areas of free water surface CWs are usually vegetated with emergent and submerged aquatic plants that provide habitat for amphibians, birds and enhance treatment processes. Common plants in wetlands are common reed (*Phragmites spp.*), cattail (*Typha spp.*), rush (*Juncus spp.*) and bulrush (*Scirpus spp.*) [62]. Vegetation in wetlands should preferably be selected from native species. Most CWs could be located in various landscapes and developments: However, for their beneficial aesthetic value, they should not be hidden in a development area. CWs can be established within existing natural depressions or by excavating new ones. The CW should be designed with smooth edges to avoid dead zones and algae growth that could inhibit removal processes [107]. Baffles or islands could be added to increase diverse water flow paths [53]. The maximum depth should not exceed two m. However, too shallow areas should be also avoided, as they can be source of greenhouse gases [54]. Most CWs effectively reduce peak flows, as their discharge is usually controlled [51,65] as the main purpose is to store the urban runoff for a longer period and improve stormwater quality. Previous studies have indicated widely varying water treatment efficiencies for nutrients, suspended solids [107] and heavy metals [99]. Some CWs could also be used for educational purposes and as recreational areas [51,115].

3.6. Permeable pavements

There are two types of pervious pavements: porous pavements and permeable pavements. Both constructions allow rainwater to infiltrate through the surface, but are still suitable for pedestrians or vehicles in parking lot, and on less-trafficked streets. The rainwater will infiltrate into underlying soils or could be discharged into the rainwater collection system with a delay. The porous pavement material enables rainwater to infiltrate across its surface. The permeable pavements have impervious surfaces, but the material is laid on the underlying media with some void space, so the water can infiltrate through the joints or voids between the material [115]. They can be used in many combinations and locations. Grass reinforcement grids that are infilled with gravel or grass can only be used for lightly- trafficked locations such as pedestrian walks, schools, private driveways, hotels, and office car parks.

There are many permeable materials to use: the most appropriate one should be chosen based on the expected traffic load, infiltration need and visual appearance. There are several factors that affect the performance of a permeable pavement such as pavement type and its thickness and the porosity of the underlying bedding material [3]. The use of permeable pavements should be avoided if there is a high risk of clogging by silt loads on the surface. Permeable pavements provide attenuation storage, and therefore, effectively help to reduce storm water flow rates and peak flows [17,115]. In addition to flow rate reduction, they also help to reduce pollutants from the water, such as heavy metals, oil, grease, sediments, and some nutrients [17,18].

4. Data interpretation and discussion

In Table 1, the total number of different SUDS types are presented. Highest number of studies and NBS applications were available for green roofs, followed by bioretention cells and buffer and filter strips. The missing data analysis shows (Fig. 1) that except for green roofs, all other SUDS have a lot of gaps in the database. Data are mainly absent concerning water retention and removal efficiency of different stormwater SUDS. This can be explained by the differences between the SUDS in water runoff data collection simplicity. For example, it is easy to analyze retention in green roofs where there is easily measurable influent with portable onsite weather stations and effluent from down-spouts. It is more challenging to analyze retention in SUDS with infiltration to the ground or with design of the inflow area and drainage pipelines that do not allow flow measurements. All this is making it difficult to evaluate the overall potential of various SUDS in urban environments to retain and remove rainwater.

Table 1
The number of studies per SUDS type and average water retention capacities. Abbreviations: BR – bioretention cell; BS – buffer strip; CW – constructed wetland; GR – green roof; PP – permeable pavement; S – swale.

SUDS type	Number of studies	Average water retention (%)	Standard deviation	Minimum (%)	Maximum (%)
BR	37	58	24	13	99
BS	30	51	24	0	88
CW	2	59	41	30	88
GR	144	56	20	11	99
PP	13	78	23	30	100
S	19	48	18	19	85

4.1. Location of selected SUDS in the world

According to information gathered in our overview, the main locations of SUDS were, as expected, mostly in North America, Europe, East-Asia and Australia (Fig. 2) where implementation of SUDS has been most reported. The most wide-spread SUDS type with the highest number of available information (Table 1) about water retention capacity was green roofs, followed by bioretention cells, buffers and vegetated filter strips (Fig. 2).

4.2. Relationship between water retention capacity and climatic conditions

In Fig. 3, the median water retention capacity of selected SUDS according to the climatic conditions in the world are presented. When comparing the water retention capacity (%) of selected SUDS (Fig. 5; Table 1), we can see that there is no straightforward clear pattern between the climatic conditions and the SUDS type. However, the largest number of quantifiable data on SUDS are in the 'warm, wet' regions, whereas for the 'cold, dry' regions, the data are limited (Fig. 4) This probably also indicates that in general, SUDS are more commonly implemented and studied in warmer regions with higher amount of precipitation and, therefore, a higher need for such a solution (Fig. 4). In cold climate conditions, there is a lack of available information, however, SUDS have gained more popularity in these conditions, recently. Therefore, more information linked to research and development of SUDS for cold climate conditions is expected to be published in the future [73].

The water retention efficiency and annual precipitation were highly variable for all solutions, as seen in Figs. 4 and 5. Average water retention with standard deviation, minimum and maximum values are provided in Table 1 (across all sites) and Supplementary Tables S2 (full-scale and experimental studies separately), S3 (four defined climatic conditions separately) and S4 (climatic conditions and study types separately).

For most of the selected SUDS (except green roofs), the amount of data is much scarcer, and therefore, it is difficult to model the relationships between different parameters of these SUDS and state what is the real average retention efficiency for different boundary conditions. The reliable amount of data (see Fig. 1) for further analyses of the results

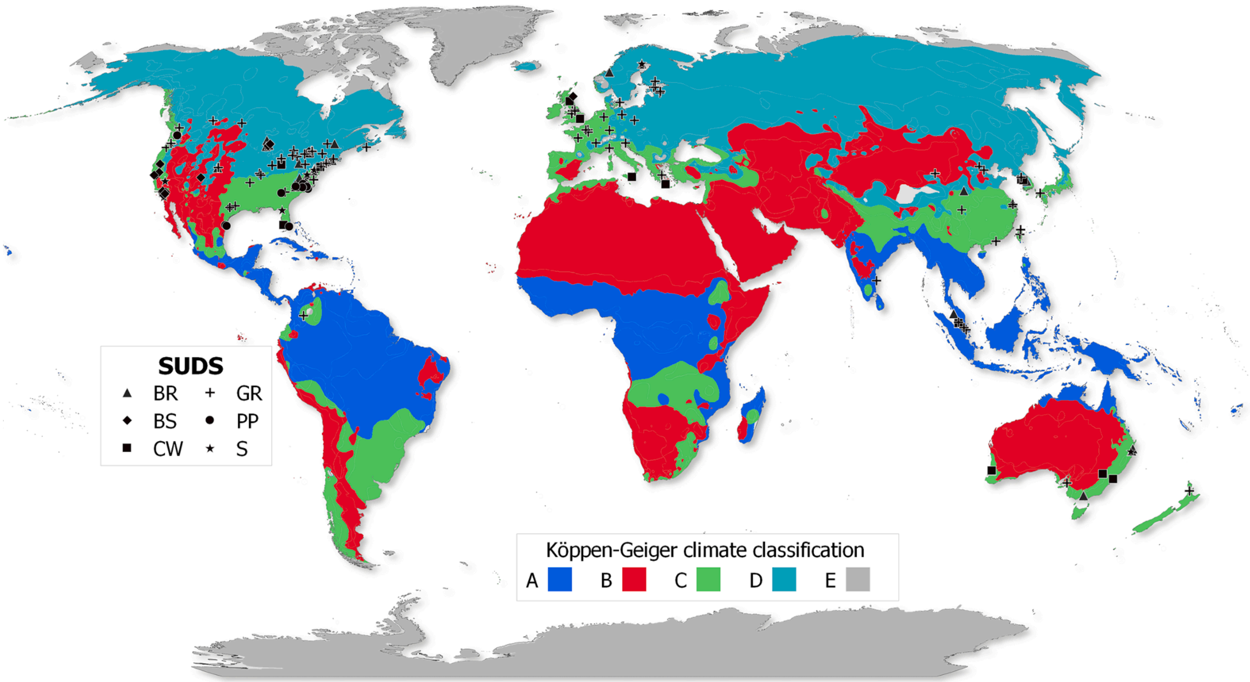

Fig. 2. Location of selected SUDS gathered in our database. Abbreviations: BR – bioretention cell; BS – buffer and filter strip; CW – constructed wetland; GR – green roof; PP – permeable pavement; S – swale. Köppen-Geiger climate classification: A (tropical), B (arid), C (temperate), D (continental) and E (polar).

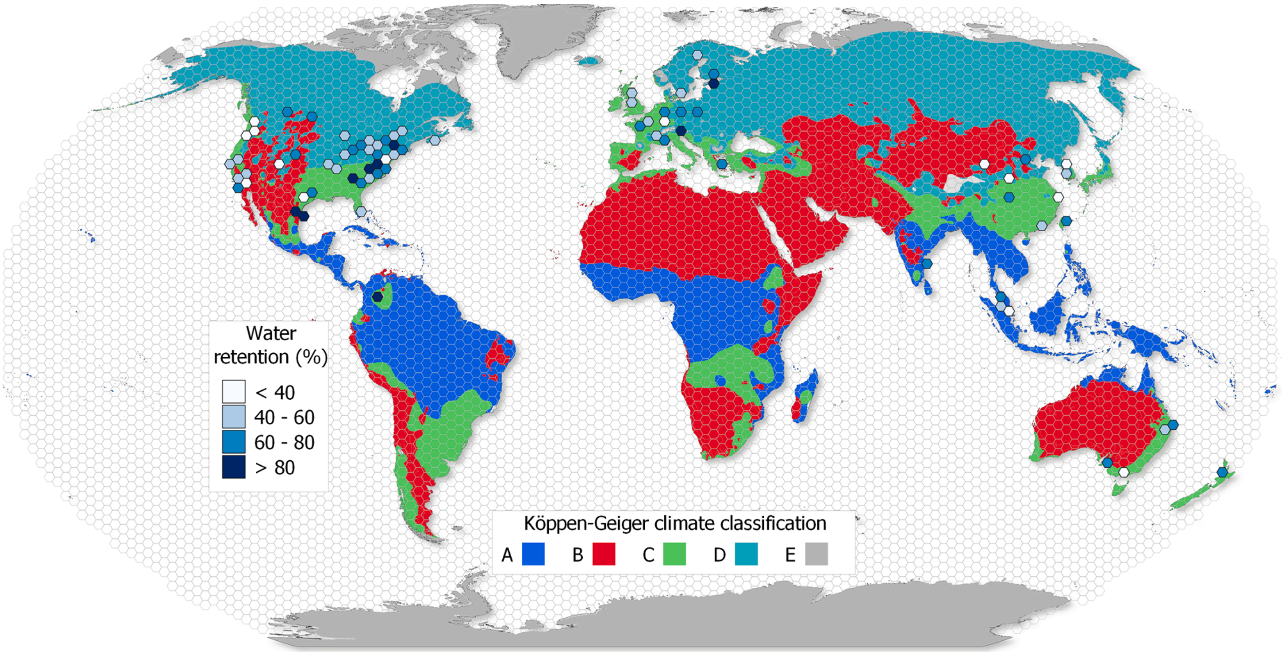

Fig. 3. Median water retention capacity (%) of different SUDS. Median water retention is calculated for hexagonal grid where all SUDS that fall into each hexagon are considered in the calculation for that respective hexagon. Köppen-Geiger climate classification: A (tropical), B (arid), C (temperate), D (continental) and E (polar).

and for making any decisive conclusions is only available for all climatic conditions concerning green roofs. Therefore, we present in sub-chapter 4.2.1 relationships between average water retention capacity (%), size (m^2) and media depth (cm) of the green roofs predicted by modeling (Fig. 6).

In general, the highest water retention efficiency was in 'warm, dry' climate, while in 'cold, wet' climate, it was low. Surprisingly, in 'warm, wet' and in 'cold, wet' climatic conditions the water retention capacity reached a plateau at about 65%, while for 'warm, dry' conditions, the retention capacity was remarkably higher. For green roofs, the average water retention efficiency was 56% with a maximum value of 99%. The average water retention for other measures was slightly higher or in the same range, but due to the low amount of data, there is still a lot of uncertainty (Fig. 4).

As expected, Fig. 5 indicates that the stormwater management-focused SUDS are more studied and used in wet climatic conditions with the highest amount of annual precipitation. However, as shown in part 1 of the IPCC 6th assessment report [49], as a consequence of

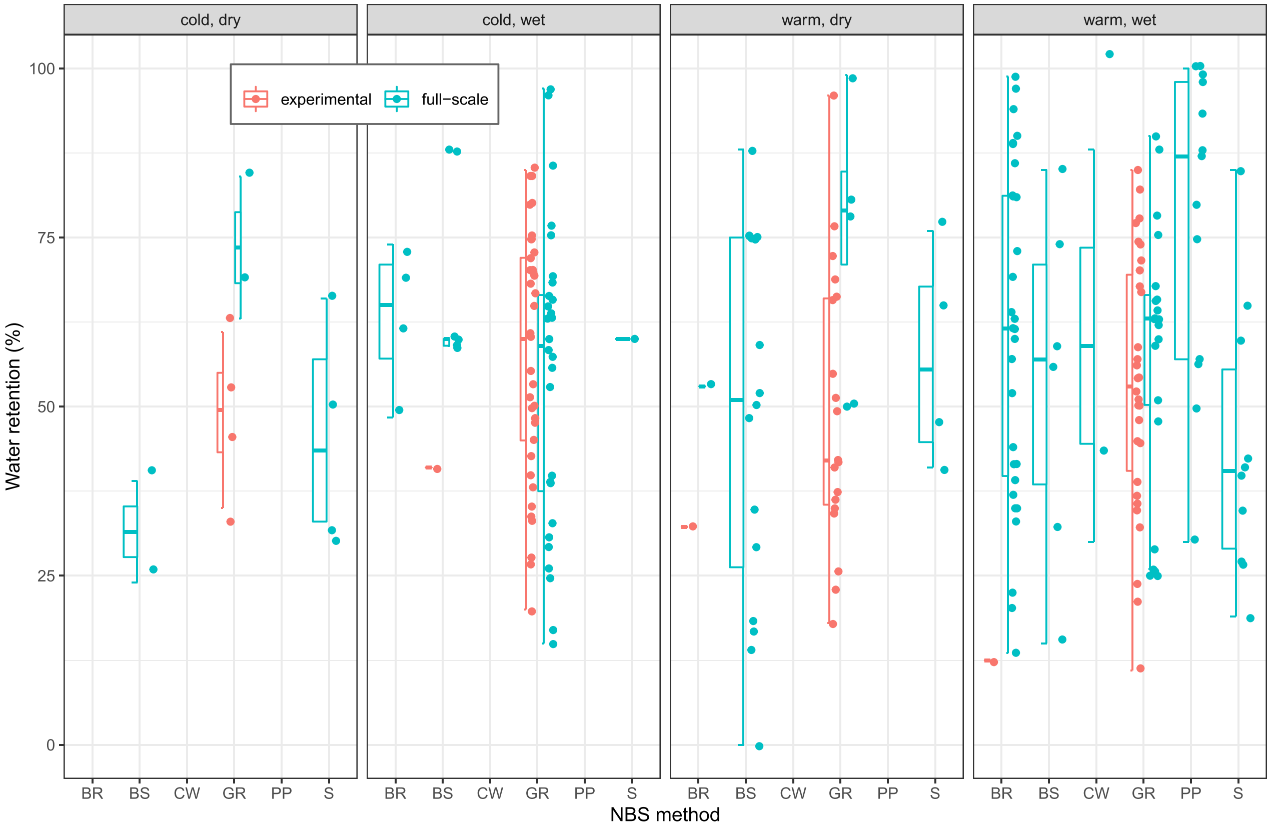

Fig. 4. Comparison of median water retention capacity (%) of selected SUDS for different climatic conditions. Abbreviations: BR – bioretention cell; BS – buffer strip; CW – constructed wetland; GR – green roof; PP – permeable pavement; S – swale.

climate change, the amount and frequency of extreme rainfalls has increased all over the world. Therefore, more information and science-based recommendations about the best available stormwater management solutions for all climate zones and their capacity to perform in these rapidly changing conditions, are needed.

4.2.1. *Green roofs*

There are large variations in investigated green roof design, size (test-plot scale or a full-scale rooftop), testing period (individual rain events or full-scale studies), rainfall origin (rainfall simulations or real-life conditions) and substrate depth/composition (see also Table S1). Despite many differences between the studies, we tried to summarize and analyze the data of the collected studies.

Since green roofs had the highest amount of available data concerning water retention (Fig. 1), we used that information as an example with the aim to analyze how different design parameters such as surface area and substrate depth can affect water retention efficiency in different climatic conditions (Fig. 6).

In Fig. 6, we can see high variability in gathered data and, therefore, it is hard to predict clear relationships and trends. Even though, the results indicated that a larger green roof area is more beneficial for ‘warm, dry’ zones (Fig. 6). In case of green roof depth, it seems that a thicker substrate layer improved water retention in ‘warm, dry’ and in ‘cold, wet’ conditions. For ‘warm, wet’ conditions, the depth of the substrate did not have any significant effect; it even indicated some decline in water retention capacity regarding thicker substrate conditions. However, this trend can be also due to high data variability (Fig. 6). Most green roofs have a 10-15 cm substrate depth and their water retention efficiency is highly variable. There could be other design parameters that affect performance of green roofs: i.e. type of substrate, vegetation and roof slope. However, as shown by Akther et al. [2] roof slope and media depth matter less than vegetation type when comparing hydraulic performances of green roofs in different climate zones. It seems that the green roofs’ efficiency to retain precipitation in wet conditions is lower, mostly due to the water saturation capacity or already saturated conditions. In dry conditions, the rainfall events are much shorter and green roof substrate will have a higher water retention capacity. In wet climatic conditions, the precipitation is often continuous with few massive storm events, but, overall, the water retention efficiency is lower. This does not mean that green roofs are not efficient in wet climate, but they are less so than in mostly dry conditions where the evapotranspiration rate is higher and gaps between rain events are long enough for the green roof to dry completely in-between the events.

Hydrological performances of green roofs have been studied by numerous researchers in the last 20 years [2,92,119]. Europe, United States and China are the main parts of the world where most of the investigations have been carried out [119]. At the same time, there are few or no investigations from South America, Central America, Central Asia and Africa, but in these regions, urbanization is rising rapidly [91,119]. Zheng et al. [119] also indicated that studies are unequally distributed between climates: 77% of the observations, which they analyzed, were recorded in temperate climate, and only 12%, 8%, and 3% of the observations were from continental, dry and tropical climates, respectively.

The average water retention (n = 144) in our study was 56%, which confirms findings by Akther et al. [2], where the mean runoff volume reductions ranged from 56 to 71%. Zheng et al. [119] analyzed 75 studies on green roof water regimes using regression models, and summarized that the mathematical mean of the green roof runoff retention rates is 62.2%. Retention rates for temperate (n = 112), subtropical (n = 22), tropical (n = 8), and boreal (n = 2) climates were in our study 54, 66, 58 and 60%, respectively. The means of the stormwater retention

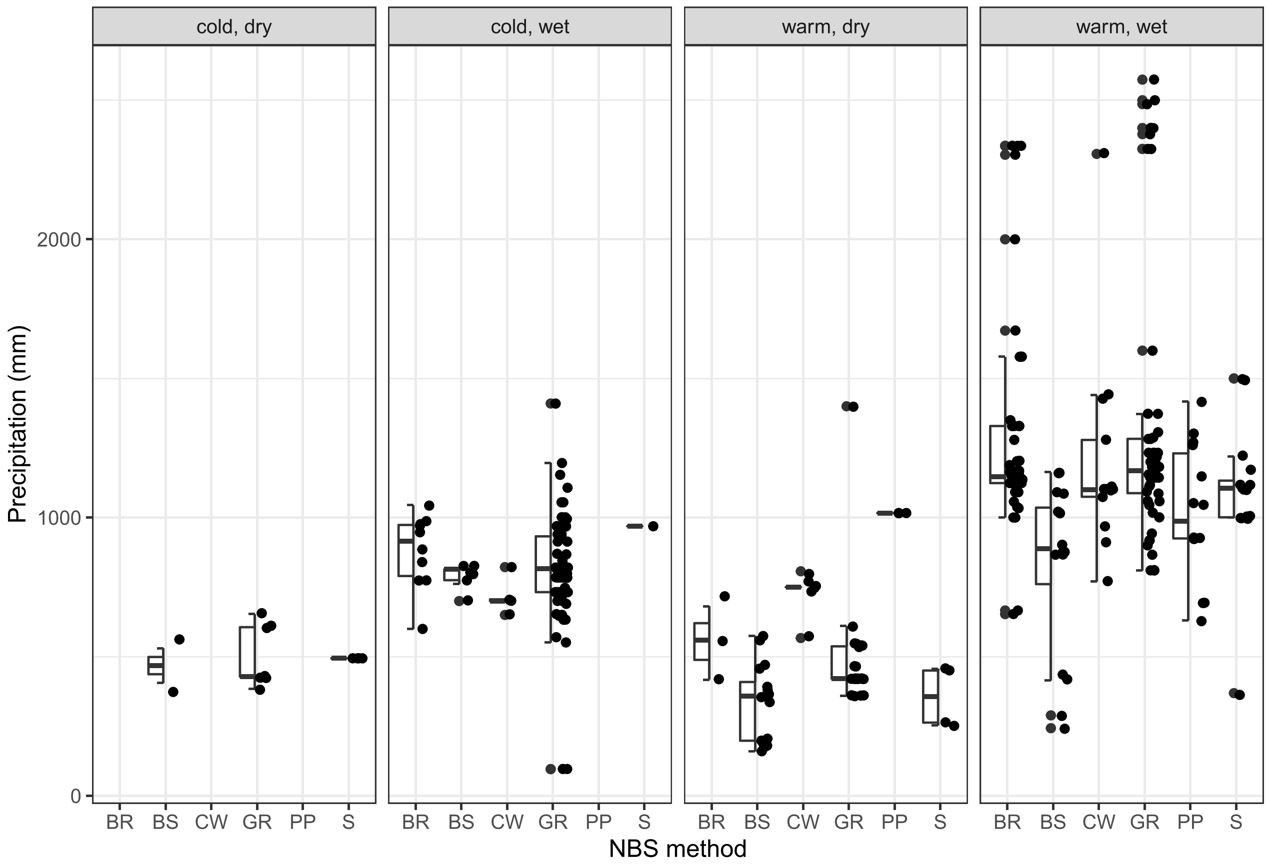

Fig. 5. Comparison of precipitation (mm) of selected SUDS for different climatic conditions. Abbreviations: BR – bioretention cell; BS – buffer strip; CW – constructed wetland; GR – green roof; PP – permeable pavement; S – swale.

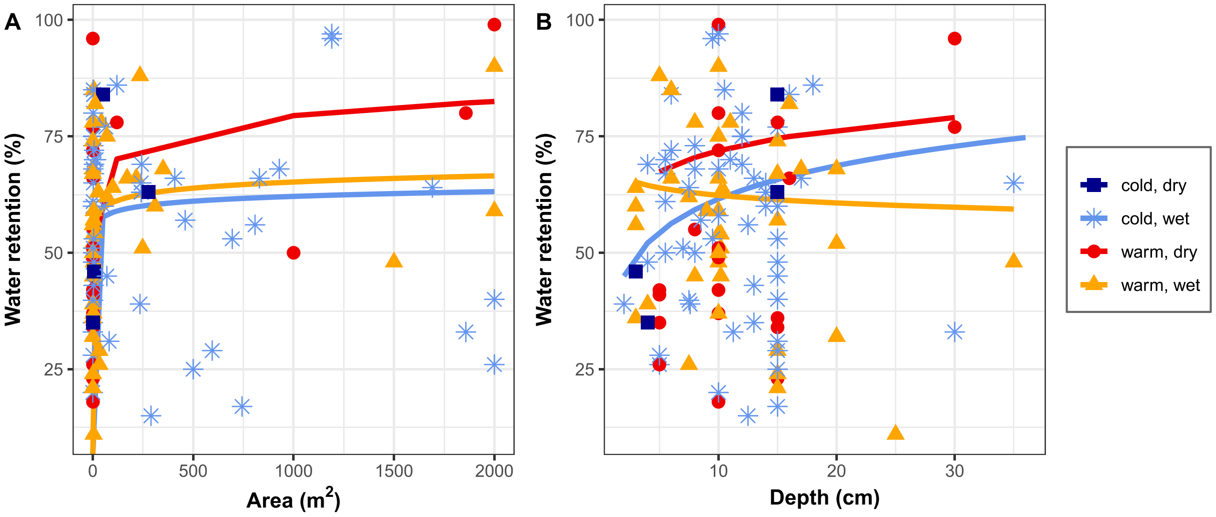

Fig. 6. Relationships between average water retention capacity (%), size (m^2) and media depth (cm) of the green roofs predicted by modeling (lines) and actual data points. Different colors represent climatic conditions at the locations of the SUDS. Because of almost no data points regarding ‘cold, wet’ conditions, we could not model these data with confidence.

rate in review by Akther et al. [2] were higher for arid (71%) and tropical (66%) climates and lower for continental (56%) and temperate (60%) climates. Following the Köppen climate classification, modeled green roof hydrological performance had the highest values in dry arid regions, and the lowest values in tropical and temperate areas [46]. Viola et al. [109] explored the hydrological behavior of green roofs in different climate regimes and summarized that the performance of the green roof increased when rainfall and potential evapotranspiration show similar seasonality during the hydrological year like in humid subtropical climates. Inversely, when these are in counter-phase, similarly to Mediterranean climate, the efficiency of the green roof is minimum. Thus, the hydrological performance of a green roof is strongly site-specific.

Firstly, the efficiency of green roofs is influenced by climate and season. There are general findings indicating that stormwater retention is higher in summer than in winter [70,88,95,97,102,105]. In summer, the evapotranspiration rate is higher and, thus, this increases the retention capacity of green roofs [70]. In subtropical climate (New Zealand), Voyde at al. [110] found that the extensive green roof retained about 82% of rainfall received per rainfall event. Research in southern Sweden shows that green roofs reduce the amount of stormwater less efficiently during September to February (34%) than during March to August (67%) [13]. Green roofs are still useful for water retention in cold climate conditions like shown in Finland, where annual retention varied from 40 to 70% [61]. Still, in cold and wet Norway, annual retention varied only from 11 to 30% [52].

It is clear that the rainfall retention rate of green roofs is relatively high for small events and low for large ones [19,42,93]. Carter and Rasmussen [19] divided storm events into three categories and found that for small storms (<25.4 mm), 88% was retained, for medium storms (25.4–76.2 mm), more than 54% was retained, and for large storms (>76.2 mm), 48% was retained. Mean retention rates for different rainfall categories in Hong Kong were 73–84% for light events, 36–47% for medium events, and 16–19% for heavy events [113]. Green roofs will effectively mitigate peak flows, which will be 62–90% lower than for the common roof like shown by Fassmann-Beck et al. [36] from New Zealand. Small and short rainfall can be delayed for 1–4.5 h [74]. The retention of rainfall by green roofs is more efficient if the preceding days are rainless and the substrate layer is dry. However, green roofs can also efficiently retain a moderate rainfall event when the substrate layer is wet from previously fallen rain [98]. A green roof with 150 mm thick substrate in Canada was able to delay heavy rainfall (60 mm/h) only for 4 minutes. However, minor rainfall (2.9 mm/h) was delayed for 95 minutes [67]. There is a very important antecedent dry weather period, which must be at least one week after the green roof will recover its retention capacity [55]. At the same time, in temperate climate zone where evapotranspiration rates are low for most of the year, the antecedent dry weather period is not a significant factor influencing the retention capacity of the green roof [76].

As expected, the retention capacity is also dependent on the specific infrastructure type [70]. The large range of the rainfall retention rates could be assigned also to the fact that there are numerous possibilities to construct substrate layers, depending on the local availability of materials. For example, an extensive green roof can retain a small rainfall, when no following rainfall events occur in a short time and the substrate is not saturated with water [63]. Heavy rainfall is not retained in an extensive green roof [106]. Intensive green roofs with much thicker substrate layers have shown higher water retention [11] capacity, but their heavy weight and high maintenance costs are reasons why there are only few studies about their water regime [119]. The soil depth has a considerable role in the water holding efficiency: there were 42.8–60.8% and only 13.8–34.4% reductions in runoff with 200 and 150 mm soil depths, respectively [63]. Thus, the substrate properties seem to be the most important for how much rainfall will be retained by green roofs. The slope of green roofs plays a role in water retention when comparing the intensities of rainfalls: the lower the slope and the rain intensity, the higher the retention capacity [108]. The role of vegetation on water retention is seen as moderate, especially if there are used *Sedum* species on the roof [106]. Nagase and Dunnett [75] showed that grasses were most effective in reducing water runoff, followed by *Forbe* and *Sedum* plants. Even more, Kuoppamäki [61] pointed out that in cold regions, green roofs established on site with plantings are a better choice to stormwater management than pre-grown mats. In Mediterranean climate, mixture of shrubs and grasses with a mat of moss was the most suitable vegetation cover to handle stormwater [16].

4.2.2. *Bioretention systems*

From a total of 60 data entries concerning bioretention systems in our database, we have information about the volume reduction efficiency for 37 studies/sites giving an average volume reduction of 58% (varying from 12 to 99%). According to a BMP database report [21] on volume-related data (total 20 systems in USA), bioretention systems can be effective in the reduction of runoff volumes and peak flow rates during frequently occurring storm events. The performance at individual sites depends on a variety of site-specific factors as well as BMP design, installation and maintenance. Likewise, similar results have been reported by other investigations. For example, Booth et al [15] have found a clear negative correlation between the percent of effective impervious area and the fraction of forest land in the urban watershed. They also demonstrated that for an effective impervious area of 10%, most stream channels studied have lost their stability. A negative correlation was found between the riparian buffers areas (forests and wetlands) and the stormwater peak flow values [15,47]. Therefore, restoration of disturbed riparian zones and their careful management in urban areas plays a crucial role in stormwater retention [83].

However, the reliability of categorical analysis results is still limited by the number of available studies (Table 1). Many studies have concentrated on a few areas of the country (e.g., mid-Atlantic/eastern seaboard). Additionally, while there are a wide range of bioretention designs and site conditions represented, some studies are understood to have been conducted on systems with somewhat atypical design conditions (i.e., very large footprints and very high infiltration rates). Because design and site conditions are believed to have substantial influence on volume reduction performance, design parameters should be considered when extrapolating results of categorical and study-level analyses to other bioretention installations [41].

4.2.3. *Constructed wetlands*

Constructed wetlands (especially treatment wetlands) are widely studied in terms of wastewater treatment [45], reduction of agricultural diffuse pollution [53,57,58] and advanced treatment of effluents from secondary or tertiary treatment processes. However, studies about the efficiency of constructed wetlands in urban environments for stormwater volume management are almost absent. In our database, the data (average volume reduction in CWs of 59%) are only available from a few sites in 'warm, wet' climatic conditions. This is probably due to the main function of CWs – treatment of polluted water, and the fact that volume reduction is not a main function of stormwater CWs [72]. Therefore, less research and monitoring has been done on the stormwater volume reduction capacity of CWs. Stefanakis [96] suggests ways to integrate wetland technology in the urban environment, also with the purpose to provide stormwater management function. The major limitation to implement CWs in urban areas as the source control measures is the lack of available and inexpensive land to construct such systems as they need relatively large area and since these are open systems, there is also a slight risk for human exposure to pathogens as the CWs receive polluted water from streets. However, there are good examples of large stormwater CWs in urban areas that have in addition to a sustainable urban water management role also recreational functions [96]. In warm climates, these systems can also become habitat for disease vectors to breed [44] as some vector species are especially attracted to water with high organic matter and stagnant water [12]. In 'warm, dry' conditions, most CWs will be dry for long durations of the year, which removes their ecological benefits, and they act as stormwater reservoirs, but without high aesthetic value.

4.2.4. *Buffer areas and filter strips*

Buffer areas and filter strips also provide protection against drought and water scarcity by retaining and slowly releasing water discharges and enhancing groundwater recharge [81]. Our overview shows an average of 51±24% of stormwater volume reduction with filter strips (Fig. 4). Similarly, previous studies have reported 20–85% of inflow runoff volume reduction [26,48,56,66].

4.2.5. Vegetated swales

Using vegetated swales requires their smart combination and sometimes parallel use with other SUDS and conventional retention measures (i.e. grey infrastructures) to capture a large fraction of runoff of intense precipitation events [116]. Shafique et al. [90] showed in their evaluation of runoff reduction capacity of grass swales 40 to 75% reductions during various small rain events. Seasonal differences in performance of cold climate swales has been shown by Zaqout and Andradóttir [118], having a reduction in peak flow attenuation in winter averaging 13% compared to a summer average of 38% for hydraulic loadings ranging between 19 and 131 cm/h. In this review, the performance of swales is highly variable from 19 to 85% (average of 48%) and depends on climatic conditions, season, swale type and design as well as characteristics of rainfall events (Fig. 4). Similarly to other reviewed SUDS, most data originate from ‘warm, wet’ regions.

4.2.6. Permeable pavements

As shown in Fig. 4, data on water retention capacity of pervious pavements are available mostly from warm and wet climatic conditions, where average reduction is quite high (78±23%). Braswell et al. [17] and Woods Ballard et al. [115] have shown that permeable pavements provide attenuation storage and, therefore, effectively help to reduce stormwater flow rates and peak flows.

4.3. Limitations in the use of NBSs in urban environments

A recent review by Ershad Sarabi et al. [31] highlighted the main objectives for developing NBS: climate change mitigation and adaptation; water management; coastal resilience; green space management; air quality; urban regeneration; participatory planning and governance; social justice and social cohesion; public health and well-being; and economic opportunities and green jobs. The water retention capacity of different types of SUDS plays an important role in fulfilling several of these NBS developing objectives.

The main barriers to develop and implement NBS in urban environments [31] are as follows: inadequate financial resources; path dependency; institutional fragmentation; inadequate regulations; uncertainty regarding implementation process and effectiveness of the solution; and limited land and time availability.

The barrier “*uncertainty regarding implementation process and effectiveness of the solution*” is directly connected with another great concern; the lack of available data to evaluate, if some of the measures are efficient enough in their main role for them to be confidently implemented by local municipalities. Water retention and removal data collection from full-scale SUDS is challenging and often not done at all. This is due to the design and functioning of SUDS whereas most of the solutions do not have a concrete location where the inflow could be easily measured (e.g., swales and barriers). Or the data comes from rainfall measurements (i.e. green roofs) that do not include any runoff and sheet flow on surfaces. For measuring the water balance in the stormwater management systems, we need to know in addition to the inflow water volume also the outflow that is almost impossible to measure when the solution relies on infiltration to the ground (e.g., most bioretentions, swales, filter strips and permeable pavements/surfaces).

Therefore, the easiest solutions for water retention monitoring are green roofs where it is quite easy to measure rainfall amount per surface area and also to monitor the so-called effluent amounts (i.e. from the downspouts). For green roofs the amount of collected data gives a great opportunity to evaluate the efficiency and therefore could serve as a good basis for future recommendation.

From the barriers we can also see that one of the crucial issues is also the availability of land. For efficient water retention with NBS like SUDS there is a high amount of space and volume needed for water retention and removal by infiltration. For example, in dense urban environments it is difficult to build large systems and therefore these measures often end up in peri-urban areas where their efficiency is lower. The best methods in densely populated areas are solutions that can be built on top of roof or to the walls; e.g., green roofs, green walls and rainwater harvesting. These measures do not require any land from the streets and therefore are much easier to implement. In addition to potential water retention, they are also important to reduce the urban heat island effect. Moreover, when building new urban communities in undeveloped or natural areas, it is crucial to implement NBS to these areas already during the planning process.

5. Conclusions and recommendations

Although NBS such as SUDS have been recently studied a lot in terms of general performance, potential enhancements, barriers and enablers, there is still a lack of definitive information about the efficiency of various solutions in stormwater retention and removal. Various guidelines (e.g., for urban planning) are suggesting different SUDSs to mitigate climate change consequences by, for example, reducing flooding and water pollution. However, we can see from our overview, that there is still a lot of missing information and quite a large range in water retention efficiency. Therefore, it is a challenge to back up this statement with certainty and this makes decision making much more challenging. Among reviewed SUDS, green roofs are quite well-studied in terms of their rainwater retention capacity. However, the large variability in water retention and its relationship with green roof’s size and depth in different climatic conditions does not give clear input for implementation guidelines. In addition, analyses based on current database indicate that actual average water retention capacity of permeable layers, constructed wetlands, swales etc. in different climatic conditions is almost non-existent. Some of the measures (e.g., constructed wetlands and buffer/filter strips) are well studied not only in urban environments, but also elsewhere and, therefore, we have a lot of information about their water treatment efficiency. However, data about water retention capacity are missing in most cases.

For urban planning, that also includes usage of various sustainable measures to mitigate flooding risks and to adapt to climate change, it is crucial to have definitive information about the actual performance of SUDS in different climatic conditions. Therefore, more full-scale case studies (especially in cold climatic conditions) have to be performed to gather missing data. Our overview is also pointing out gaps in much needed information. With more precise information about SUDS efficiency some of the barriers of the implementation would be reduced or lifted, and it would be possible to recommend optimal SUDS to stakeholders and decision-makers for reduction of risks and problems raising from stormwater runoff in urban environment. Finally, the further development of SUDS to support urban stormwater retention should be informed by and developed concurrently with the adaptation strategies to cope with climate change, especially with increasing frequency of extreme precipitation events that lead to higher volumes of stormwater runoff.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Review database is added to Supplementary material file

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2022.100038.

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