# Green Infrastructures in Stormwater Control and Treatment Strategies

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**Abstract:** Green infrastructures can provide multiple benefits and play an important role in cities' resilience to extreme stormwater events caused by climate change. Additionally, these techniques can contribute to the protection of transport infrastructures, averting major environmental and economical adversities. Stormwater can be treated through several processes, some processes being more effective than others for specific contaminants. A review of some of the most commonly used GI for stormwater management in urban environments was carried out, with emphasis on their efficiency in reducing peak flow rates, runoff volumes and the following pollutants: total suspended solids, heavy metals, total phosphorus and total nitrogen. The GI studied were green roofs, bioretention systems, filter strips, vegetated swales and trenches. In addition to the advantages in the urban water cycle, benefits of amenity and ecosystem services of these GI have also been identified. The discussion of the results and the comparative analysis of GI performance were carried out taking advantage of a table that summarizes the range of percentages of GI efficiency obtained in the various studies for the different functions.

**Keywords:** green infrastructures; stormwater control; stormwater treatment; combined sewer overflows; bioretention systems; swales; green roofs; trenches

## 1. Introduction

Urbanization affects the hydrological cycle, usually with widespread negative impacts. Progressive surface imperviousness leads to increased runoff and flow rates in sewers, aggravating the frequency and magnitude of flooding that occurs in many cities. Channelling natural watercourses and increasing discharges from combined sewer overflows (CSO) lead to the impoverishment of the urban landscape and the decline in water quality and hydrological amenities [1].

With the aging of conventional drainage systems, the problems of flooding, CSO discharges and sewer infiltration and exfiltration have been aggravating, requiring complex and expensive maintenance and repair interventions [2-4]. Over the past few decades, many countries have been implementing sustainable drainage measures as a way of adapting urban systems to these problems while controlling stormwater effects at source and keeping them as close to natural conditions as possible [5, 6]. Ever so more, countries have been addressing the impacts of climate change and implementing projects regarding the promotion of sustainability, the protection of water resources and the transformation of cities' water infrastructure into more resilient systems [7-10].

Implementing green infrastructures (GI) and aiming for a more sustainable world is crucial to improve the quality of millions of people's lives [11]. The main goals of the so-called Sustainable Urban Drainage Systems (SUDS) are to reduce the quantity of runoff from the source site, to slow down the velocity of runoff to allow sediments' filtration, to enhance infiltration, groundwater recharge and rainwater harvesting, and to provide a passive treatment to collected surface water before it being discharged onto land or into watercourses [10,12-14]. These infrastructures offer multiple benefits, including urban cooling, resilience to flooding and environmental health [15], and play an important role in cities' resilience to extreme events caused by climate change. In this context, urban planning is increasingly focused in designing places for people and valuing social and environmental issues, providing a strong way for communities to support and perceive the value of water use in public areas, where benefits relate to public safety, community enhancement and recreational opportunities [16].

It should be noted that GI can refer to a very wide range of nature-based solutions used to address engineering issues. Nevertheless, the GI covered in this work focus on the following small to medium sized stormwater management infrastructures that also improve amenity: green roofs; bioretention systems; filter strips; vegetated swales; trenches.

## 2. Main functions of stormwater management green infrastructures

### *2.1. Detention/Retention*

GI for detention purposes are able to store water during extreme or moderate rain events, slowly discharging it into the sewer system or downstream watercourses. Their main function is to attenuate peak flow rates. Examples of techniques that take advantage of these processes are ponds, detention basins and wetlands. In the latter, besides peak flow attenuation, there is also removal of contaminants, as explained in the treatment section.

Alternatively, retention systems can store water and slowly infiltrate it to the ground or convey it to other structures without connection to the sewer system [10,17]. Their main functions are to attenuate peak flow rates and also to reduce runoff volumes. Those with a soil medium also benefit from water percolating through soil, where filtration and biological actions remove contaminants. Trenches, bioretention systems and pervious surfaces are examples of techniques that exploit these methods.

### *2.2. Treatment*

GI for treatment purposes improve water quality by any physical, chemical and/or biological means. Soil particles have electrical charges which attract dissolved metals and phosphorus. Plants take up nitrogen and phosphorus to meet their nutrient needs and organic matter, especially carbon and nitrogen, break down (or decompose) by microorganisms. For carbon, this is usually referred to as reducing the biological oxygen demand (BOD) of the water. Microbes also consume harmful pathogens. Exposure to sunlight and dryness also helps kill off pathogens, which typically prefer wet conditions. Sedimentation and filtration are removal mechanisms for sediment, litter and debris, nutrients attached to sediment particles, such as some forms of phosphorus, and bacteria and other pathogens that are also attached to sediment [18].

In fact, one of GI main goals is effectively to improve water quality. In green roofs, bioretention systems, filter strips and vegetated swales, contaminant removal methods involve retention of particles by vegetation, that tends to slow down flows and retain coarse sediments, and filtering and adsorption by the soil layer. For instance, constructed wetland systems reduce or remove contaminants, including organic matter, inorganic matter, trace organics and heavy metals from the water, by diverse treatment mechanisms, including sedimentation, filtration, chemical precipitation and adsorption, microbial interactions and uptake by vegetation. The slow velocity of water in wetlands allows the sediments to settle to the bottom where plants hold the accumulated sediments in place [19]. In other examples of infrastructures that make efficient use of water treatment techniques, bioretention systems remove both dissolved pollutants and particulate matter from stormwater runoff and reduce the volume and rate of stormwater discharged, and pervious surfaces also trap suspended solids and pollutants, thereby reducing stormwater contamination.

### *2.3. Infiltration*

GI with an infiltration function can infiltrate runoff gradually into the ground, contributing to groundwater recharge. When stormwater passes through the soil, microbes can break down organic forms of carbon and nitrogen, and nitrogen and phosphorus can be adsorbed onto the soil particles.

The soil also acts as an effective filter that removes pathogens, sediment, and other particulates from the stormwater. Several techniques take advantage of this process, such as infiltration basins, pervious surfaces, ponds and wetlands. Studies showed that massive stormwater infiltration can affect the whole catchment water balance, increasing recharge and decreasing evapotranspiration. These changes can lead to a rise in the groundwater table, but under certain geological conditions they can also result in an increased likelihood of groundwater seepage above terrain [20]. The decision to improve infiltration in urban areas depends on soil permeability, but should also be carefully evaluated based on hydrogeological studies, due to the increasing risk of groundwater contamination [1].

### *2.4. Amenity and ecosystem services*

The benefits of amenity and ecosystem services are often more difficult to quantify because of their subjective nature, such as the enhancement of property values and the quality of services and goods. Examples of benefits offered by stormwater GI are erosion protection, climate regulation, carbon sequestration, water quality regulation and habitat protection are included in the amenity delivered by these techniques [21]. They also promote social interaction between various population groups and stimulate physical and mental well-being, both through social activities in public areas and through recreational activities in multipurpose spaces [10].

## **3. Review on the efficiency of different GI**

### *3.1. Green roofs*

Green roofs function as smaller scale stormwater treatment systems, located at or near the source of runoff. They are designed to promote evapotranspiration, retention, attenuation and treatment of rainwater, as well as mitigate urban heat island effects, help reduce local air pollution and lower energy costs regarding insulation [2,22].

Investigations in Belgium [23] predicted weather data for 2050s and showed that grass-herb covers reduce runoff more than sedum-moss ones (average runoff reduction of 61% to 75%), but were more sensitive to drought stress, and they concluded that vegetation choice and green roofs' design must have in mind the ongoing climatic changes in order to benefit the system's efficiency.

Studies in the UK [24] showed that green roofs' cumulative retention was 50%. Retention performance had a mean and median value of 70% and 91% per event (all storms) and 61% and 62% (all storms with rainfall >2 mm). Retention reduced to 43% (mean) and 30% (median) for storms with a return period greater than one year. The mean peak attenuation for these significant storms was 60%. Authors implied that green roofs can make a significant contribution to the mitigation of storm runoff associated with high frequency rainfall events. Researches in Greece [25] analysed different substrate depth and plant covered extensive green roofs and realised that runoff reduction ranged between 2% (16 cm substrate depth without vegetation cover) and 100% for the total runoff depth and between 17% and 100% when the peak runoff rate was considered.

Investigations in China [26] regarding dual-substrate-layer extensive green roofs, which used the mixture of activated charcoal with perlite and vermiculite as the adsorption substrate, concluded that they possessed better rainfall retention performance (66% and 55%) than the single-substrate-layer green roof (53%). Studies [27] showed that, in general, green roofs reduced the mean total suspended solids (TSS) of the first flush by an average of 63%. Results indicated that the media had a greater effect on TSS in the runoff, rather than the vegetation; nevertheless, vegetation absorbs and fixes heavy metals, both dissolved and particulate, (Cd, Cu, Fe, Mn, Ni, Pb, Zn) from tires, automobile exhausts, road asphalt, fuel combustion or parking dust in their tissues, which contributes effectively to pollutant removal [28].

Research [29] indicated that the role of substrate depth in green roofs is crucial to determine their retention performance, which increases, generally, from extensive to intensive settings and when rainfall and temperature are in phase. This study showed that Mediterranean climates present the worst efficiency in terms of retention performance, compared to other world climates.

### *3.2. Bioretention systems*

Bioretention systems are vegetation areas planted in a soil bed and are mainly used for pollutant removal, through a combination of mechanisms such as adsorption, sedimentation and filtration [30-32]. Runoff can be diverted into these areas, where water undergoes ponding and treatment, and excess runoff can be directed to another drainage system.

Investigations [6] showed that bioretention cells are effective in reducing runoff volume and first flush effect (FFE) and that the performance of peak flow reduction decreases with higher intensity storms. FFE refers to suspended solids, fine particles, heavy metals, nutrients, and organic chemicals having a greater pollutant mass or concentration discharge rate in the early part of the runoff volume as compared with later in the storm. Results from the authors also revealed that smaller drainage areas are desirable if peak flow control for moderate storms and intensive control strategies are of greater interest. In these cases, given a limited area of bioretention cells, some part of the catchment should be left uncontrolled by the bioretention cells to maximize the system-wide benefits.

Studies in China [33] showed that bioretention systems led to reductions in water volume and peak flow rates of 59–68% and 72–86%, respectively. Additionally, there is indication [34] that some plant species (mostly grasses) can reduce average concentrations of phosphates by 81%, ammonia by 90% and nitrates by an average of 69%. Most phosphate and ammonia treatment occurred within the soil medium. Research [35] compared the suitability of adopting bioretention design guidelines from temperate and tropical countries, while also summarizing laboratory-scale and on-site bioretention studies. Authors exposed that, generally, TSS, total phosphorus (TP) and total nitrogen (TN) removal was high in bioretention systems, and that removal performance of TSS in laboratory studies (85% to >90%) was better than on-site studies (53% to >90%). For the case of TP, the removal performance is effective in both laboratory and site studies, with a removal rate of 65 to 97%. For TN, removal performance rates present too wide ranges, from 1% (Hsieh and Davis, 2005) to 99% (Milandri et al. 2012). Investigations [36] indicated that high nutrient and metals removal rates can be achieved over a range of hydraulic conductivities using designed mixes of recycled organic and mineral materials.

Studies [37] stated that biofilters with a saturated zone have greater nutrient removal efficacy: 92 to 98% for TP and 77 to 97% for TN, as opposed to 77 to 93% for TP and 56 to 72% for TN without saturated zone. This suggests that inclusion of a saturated zone facilitates nutrient uptake, while also increasing plant growth and protecting against drying. Research [38] stated that dual-mode biofilters (stormwater and greywater) have a good removal of TSS (>83%), biochemical oxygen demand (BOD) (>86%) and some dissolved heavy metals (e.g. Cu 79 to 92%, Pb >96%, Zn, >93%). Plant species selection was critical for the removal of nitrogen (2 to 79%) and phosphorus (12 to 75%) under dual-mode operation, since non vegetated tests showed removal values of 0% for TP and-34% for TN. Analyses in Australia [39] concluded that biofilters in catchments with current or past industrial activities had elevated heavy metal concentrations in the filter media. In contrast, heavy metal concentrations in residential catchments are unlikely to (ever) reach levels that exceed soil quality guidelines for human health.

### *3.3. Filter strips and vegetated swales*

Filter strips are slightly sloped areas planted with vegetation, used to eliminate or mitigate the discharge of pollutants into receiving water bodies, normally used nearby roads, highways or parking lots. They are used in reducing suspended solids, hydrocarbons, heavy metals, pesticides or nutrients, by absorption, biological uptake, filtration or infiltration [40].

Vegetated swales consist in shallow, vegetated channels that convey, treat and attenuate surface runoff, regularly substituting conventional pipework alongside roads or car parks. Vegetation facilitates sedimentation, evapotranspiration, filtration and infiltration, with check dams or berms being applied to promote flow and pollutant retention [41].

Investigators in the USA [42] studied several filter strips and a vegetated swale and obtained an average runoff reduction of 43% and average removal capacities of 30% for TN, 35% for TP and 75% for TSS; the highest removals for these three pollutants were achieved by amending the media with a specialized phosphorus sorptive aggregate. However, according to alternative analyses [43], runoff reduction by swales ranged from 54% to 100% with a mean of 87%. Moreover, according to researchers also in the USA [44], roadside swales achieved event mean concentration (EMC) removal efficiencies of 53% for TSS and 25% for TP. Pollutant-load reductions for runoff were 77% for TSS, 67% for TN, and 33% for TP. Runoff attenuation through infiltration in vegetated swales accounts for all or most of the load reductions and points to the importance of maximizing infiltration rates in roadside swales.

Studies in China [45] showed that, in vegetated swales, the removal rates for TSS, chemical oxygen demand (COD), TN and TP reached 90%, 57%, 32% and 20%, respectively, in summer, and 34%, 8%, 57% and 13%, respectively, in winter, suggesting that vegetated swales showed higher water purification performance in summer than in winter. Soil filtration also showed high removal rates of TSS, COD, TN and TP in summer (98%, 59%, 34%, and 25% respectively). In addition, treatment showed a slight decrease in metal-ion concentrations at the surface of the swale, while the removal rates in the bottom samples were 38%, 41%, 34% and 40% for Cu, Cd, Pb and Zn, respectively.

Researchers [46] investigated parameters influencing the reduction of pollutant concentrations from swales. High efficiency ratios were observed for TSS (median 56%) and total trace metals (median ≥ 62%), suggesting that these pollutants are efficiently trapped by sedimentation in swale bed and/or filtered within swale soil. On the other hand, efficiency ratios for nutrient species were lower (median ≤ 30%). For some pollutants, higher values are obtained when the geometrical design of the swale increases the hydraulic residence time.

If soil permeability and contaminant removal is maintained, swales present a conveyance capability that efficiently promotes pollutant removal without posing a risk to underlying groundwater. However, nitrates could have a potential impact on groundwater due to increased soil concentration over time, but a filter bed beneath swales can provide a safeguard and frequent inspections are recommended [47].

Studies in France [48] showed that predominantly particulate pollutants, including Pb, Zn and polycyclic aromatic hydrocarbons, were very efficiently removed (90%) in a filter strip and a swale treating road runoff. On the other hand, lower removals were observed during the first months of operation and for total concentrations of moderately particulate micropollutants.

### *3.4. Trenches*

Trenches can be perceived as more linear and shallower soakaways, with the advantage of distributing the infiltration area. They can have a vegetative cover or be simply filled with permeable aggregate material, where runoff is stored or conveyed. They are best suited to infiltrate runoff from smaller areas, such as roofs or driveways, or areas that don't present risks of soil erosion and groundwater contamination [41].

Investigations in the USA [49] evaluated redox conditions of urban stormwater runoff in an infiltration trench and concluded that anoxic (<0.5 mg/L) conditions often occurred within hours of stormwater events and persisted from a few hours up to 2 days. Those conditions and rapid $O_2$ reduction rates in the infiltration trench have important implications for many stormwater pollutants, and particularly for denitrification of $NO_3^-$ in stormwater runoff, indicating that microbial respiration can be a limiting factor for dissolved oxygen. The estimated $O_2$ reduction rate was 0.003 mg $L^{-1}$ $min^{-1}$, which was 2 to 5 orders of magnitude higher than in groundwater from other studies. Higher rates of $O_2$ reduction are a function of the more oxic and organic-rich stormwater runoff that drives faster microbial $O_2$ reduction.

Furthermore, researchers in Australia [50] investigated stormwater runoff in infiltration trenches and concluded that it's reduction ranged from 5 to 44%, with an average of 18%; moreover, experts in Denmark [51] studied percolate samples from filter soils and established that concentrations in the percolate were in most cases reduced, but phosphorus increased and, despite reduced concentrations, Cu, Pb and benzo(a)pyrene still exceeded guiding criteria for protection of groundwater and freshwater. Scientists in Korea [52] stated that an infiltration trench incorporating physical processes of sedimentation and filtration proved to be efficient in removing dissolved heavy metals from runoff, which attained above 90% for Pb and Zn removal. Investigations also in Korea [53] indicated that an infiltration trench that received runoff from urban environments had average removal efficiencies of 65% for TSS, 23% for TN, 23% for TP, 54% for BOD and 41% for COD.

## 4. Comparative analysis and discussion

Based on the review in the previous chapter, Table 1 summarizes the results for the different stormwater management functions of the studied GI. The table presents the range of total percentages for each case.

**Table 1.** Percentage ranges of hydraulic benefits and pollutant removal for the studied GI.

| | | Green roofs | Bioretention systems | Filter strips / Vegetated swales | Trenches |
|---|---|---|---|---|---|
| Hydraulic performance | Peak flow attenuation | 17 - 100%[1]<br>60% (mean) | 72 - 87% | 10 - 56%<br>[54-56] | 20-46% [57] |
| | Volume reduction | 2 - 100%[1]<br>43-70%[2] (mean) | 59 - 68%<br>5%[3] | 23 - 100% | 5 - 44%<br>18% (mean) |
| Pollutant removal | TSS | 54 - 71%<br>63% (mean) | 53 - >90%[4]<br>98%[3] | 17 - 98%[6] | 27 - 89%<br>18% (mean) |
| | Metals | 80 - 97% | 0[5] - 97% | 4[6] - 93% | 60 - 90%<br>[58] |
| | TP | 27 - 79% | 12 - 98% | -126 - 70% | -29 - 74%<br>23% (mean) |
| | TN | 52 - 78% | 1 - 99% | -1 - 59% | -54 - 59%<br>23% (mean) |

[1] 2% for deep substrate without vegetative cover; 100% for small rainfall events and drier initial substrate moisture conditions. [2] 43% for 1 year return period; 70% for 16 years return period. [3] using MUSIC. [4] 53% for on-site tests; >90% for on-site and lab tests. [5] 0% Pb for sandy loam (FAWB specification). [6] 17% for winter and 98% for summer conditions.

Among the GI studied in this review, all are effective in removing suspended solids, with filter strips and vegetated swales being able to achieve the highest removal rates, as they provide the largest extent of vegetation to trap sediments. One limiting factor of filter strips and vegetated swales is the need for a higher level of construction area. Furthermore, the heterogeneity of monitoring methods to sample events and analyse pollutant concentrations used in each GI study presented in this work appears most definitely as another limiting factor.

Trenches present some heavy metal and suspended solids removal capacity, can effectively prevent erosion and can be easily managed and maintained. They stand out for their lower performance in reducing runoff volume.

Bioretention systems and green roofs are effective in removing suspended solids by using diverse vegetation that enhances sedimentation, and laboratory studies demonstrated better removal performances than those of on-site ones. Heavy metal removal is promoted through the soil media, so, in situations where it is not engineered for this purpose, rates are usually lower. Higher nutrient and metals elimination rates can be achieved using designed mixes of recycled organic and mineral materials. Plants and soil media can play a crucial role in the process of removing both nitrogen and phosphorus from stormwater.

Green roofs' soil media has a greater effect than vegetation on treating suspended solids in the runoff. In areas with rigorous water quality regulations for stormwater runoff from developed sites, media selection may be an imperative consideration. Moreover, including a saturated zone when designing GI translates a greater nutrient removal efficiency, since vegetation promotes nutrients uptake.

Removal capacities are dependent on factors such as vegetation, soil filter media, influent concentration and hydraulic aspects, being able to present too wide ranges for each GI.

Research done in Italy [29] showed that Mediterranean climates present the worst efficiency in terms of retention performance, compared to other world climates.

**5. Conclusions**

Climate change, circular economy and the need for local solutions and water reuse are key drivers for the growing implementation of GI. A review of some of the most commonly used GI for stormwater management in urban environments was carried out, with emphasis on their efficiency in reducing peak flow rates, runoff volumes and pollutants (TSS, heavy metals, TP and TN). The GI studied were green roofs, bioretention systems, filter strips, vegetated swales and trenches.

In addition to the advantages in the urban water cycle, benefits of amenity and ecosystem services of these GI have also been identified. The comparison of results was summarized in a table showing the range of the efficiency percentages of different studies, for the different functions and the various GI.

The range of efficiencies of each GI varies significantly, depending on local conditions and design criteria such as influent concentration, hydrological regime, hydraulic factors, vegetation and soil filter media.

GI's capability of mimicking natural environments and the combination of its use with other control approaches is increasingly crucial in the development of stormwater management strategies.

**Acknowledgments:** This work has been supported by Fundação para a Ciência e Tecnologia (FCT), in the scope of the project H2Doc 2014-2020 PD/00206/2012, grant PD/BD/135592/2018.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

The following abbreviations are used in this manuscript:
BOD: Biochemical Oxygen Demand
COD: Chemical Oxygen Demand
CSO: Combined Sewer Overflows
EMC: Event Mean Concentration
FFE: First Flush Effect
GI: Green Infrastructures
SUDS: Sustainable Urban Drainage Systems
TN: Total Nitrogen
TP: Total Phosphorus
TSS: Total Suspended Solids

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