# Chapter 9 Green infrastructure: An ally to improve urban runoff management in semi-arid areas

# Capítulo 9 Infraestructura verde: Una aliada para mejorar la gestión de escorrentías urbanas en zonas semiáridas

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**Abstract**

The growth of cities negatively alters the urban hydrological cycle, and causes problems such as the reduction of their permeable surfaces, increases in temperature that affect the thermal comfort of buildings, large volumes of urban runoff that produce floods, and its contamination. This work highlights the hydrological, hydraulic, and ecosystem advantages of green infrastructure as a strategy of climate change adaptation in cities with a semi-arid climate. Case studies published in international journals, design criteria in technical manuals, national and international standards, and regulations were reviewed. The types of green infrastructure most studied and implemented in various regions with a semi-arid climate were selected, and the most frequently applied criteria and recommendations were chosen. It was possible to determine the most appropriate design and construction parameters for their adaptation in spaces already provided with gray infrastructure, where they can be applied as complementary works that help to solve problems of water shortages to the population, as well as damage to infrastructure due to floods, aquifer overexploitation and pollution.

**Water scarcity, Floods, Sustainable infrastructure**

**Resumen**

El crecimiento de las ciudades altera negativamente el ciclo hidrológico urbano, y ocasiona problemáticas tales como la reducción de sus superficies permeables, aumentos en la temperatura que afectan el confort térmico de las edificaciones, grandes volúmenes de escorrentía urbana que producen inundaciones, así como su contaminación. En este trabajo se destacan las principales ventajas hidrológicas, hidráulicas y ecosistémicas de la infraestructura verde, como una estrategia de adaptación al cambio climático en ciudades con clima semiárido. Se revisaron casos de estudio publicados en revistas internacionales, criterios de diseño en manuales técnicos, normas y reglamentos nacionales e internacionales. Se seleccionaron los tipos de infraestructura verde más estudiados e implementados en diversas regiones con clima semiárido y se eligieron los criterios y recomendaciones más frecuentemente aplicados. Fue posible determinar los parámetros de diseño y construcción más apropiados para su adaptación en espacios que ya cuentan con infraestructura gris, donde se pueden aplicar como obras complementarias que ayuden a resolver problemáticas de desabasto de agua a la población, así como daños a la infraestructura por inundaciones, sobreexplotación de acuíferos y contaminación.

**Escasez hídrica, Inundaciones, Infraestructura sostenible**

## 1 Introduction

Nearly one billion people living in arid or semi-arid areas of the planet are at risk due to water scarcity problems (UN, n.d.). An arid zone is defined as a region where water supply is insufficient because precipitation and atmospheric humidity are lower than the global annual average of 840 mm (González-Medrano, 2012). Other authors define semi-arid zones as those with precipitation between 250-500 mm (Lane and Nichols, 1999). In Mexico, the average annual precipitation is 780 mm and some authors consider that about 63% of the national territory has some level of aridity; in addition, these areas are inhabited by about 41% of the total population (Díaz-Padilla *et al*., 2011).

The rainy season mainly comprises the months of June to September; however, about 49% of these rains occur in the southeastern region of the country, while the central-northern region experiences significant droughts (CONAGUA, 2018). The constant population growth has also decreased water availability; in 1950 it was 18,000 $m^3$/inhabitant/a, while by 2015 this was reduced to only 20.5% (3,692 $m^3$/inhabitant/a) (CONAGUA, 2018). Similarly, a large part of the country experiences a high degree of water pressure (40-100%); this has caused that, at present, about 9 million people do not have access to drinking water, while 10.4 million do not have access to sewerage services (INEGI, 2015).

This scarcity situation makes it necessary to look for more water supply sources to meet the population's demand; however, alternative options to conventional infrastructure must also be considered, in order to mitigate the problems of evaporation, overexploitation, scarcity, contamination and low availability that exist today. Green infrastructure offers a series of options designed to mitigate the impacts caused by the natural risks associated with climate change.

Among its main advantages are environmental (conservation of resources and biodiversity), social (construction of water drains or green spaces, which generate an environment that promotes outdoor coexistence) and economic (job creation, increased property appreciation) (Austin, 2017). Overall, this type of infrastructure represents benefits by providing more efficient water management, as well as additional benefits to those of gray or conventional infrastructure. The adaptation of this type of infrastructure seeks to mimic the conditions that the environment had prior to its urbanization, where the soil surface and vegetation had the capacity to absorb rainwater, evapotranspire it, infiltrate it, and recharge aquifers, among other natural functions (UN-HABITAT, 2018). In contrast, we are familiar with gray infrastructure (that construction that serves as a base for urban activities, their services, technical means and facilities), which generally fulfill a single function: supplying drinking water to the population, channeling wastewater through sewage works, improving wastewater quality through treatment plants, disposing of solid waste in landfills, or mobilizing the population through communication and transportation routes, among others (NWRM, 2014). Currently, it has been demonstrated that this type of infrastructure is insufficient to meet the needs of a constantly growing population with a sustainable vision.

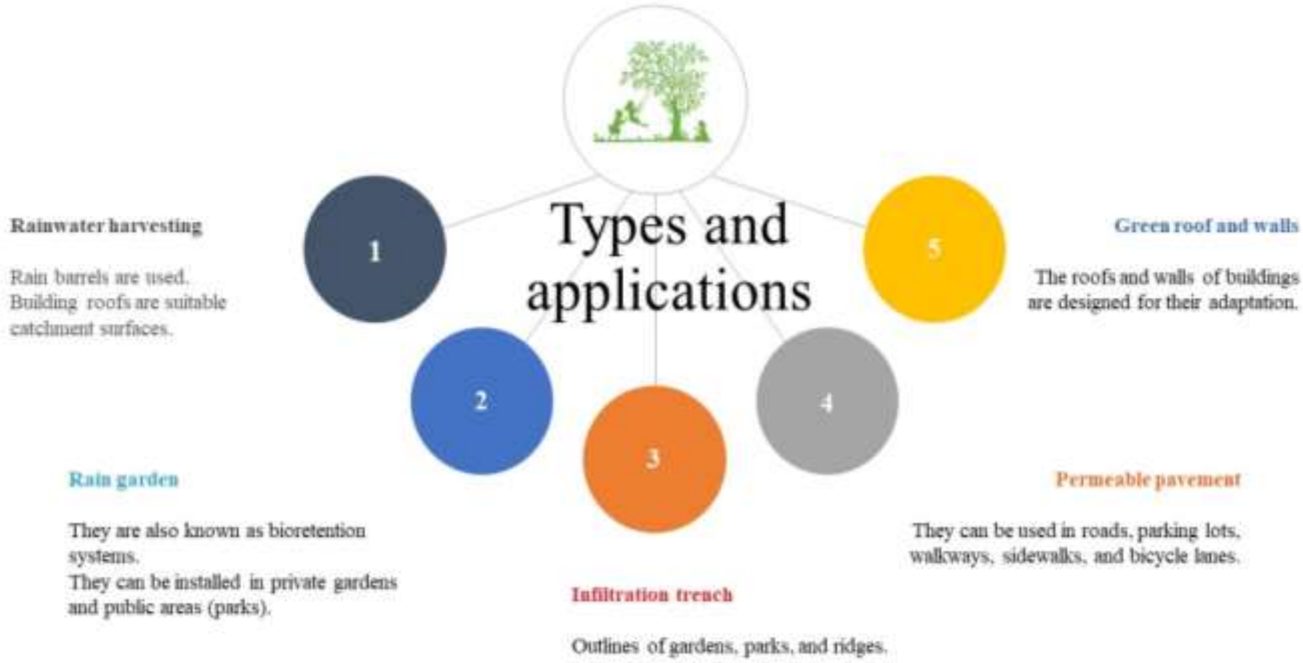
One of the alternatives to mitigate the consequences of urban growth and the negative effects it represents is to introduce green infrastructure in cities. Among the most common examples are permeable pavement (Liu *et al*., 2014; Jia *et al*., 2015), bioretention systems or rain gardens (Chapman and Horner, 2010), infiltration trenches (Ahiablame *et al*., 2012) rainwater harvesting on rooftops (Martin-Mikle *et al*., 2015), as well as green roofs and green walls (Jia *et al*., 2015; Martin-Mikle et al., 2015). The implementation of green infrastructure is an effective tool for climate change adaptation (Melo dos Santos *et al*., 2019). Its use in urbanized environments with semi-arid climate can help restore up to 82% of the hydrological balance (Feng *et al*., 2016). In arid sites such as Arizona in the United States, green infrastructure was adapted with xeric vegetation and sustainable irrigation practices; the positive effect of these measures achieved a saving of $0.77 \pm 0.05 \pm 0.05 \times 108$ $m^3$ of water (Yang and Wang, 2017) and an increase in water availability for the population (Guertin *et al*., 2015). Choosing this type of strategies can annually reduce urban runoff (35-45%; Feng *et al*., 2016) and restore evapotranspiration (18-25%; Li and Davis, 2009; Feng *et al*., 2016); moreover, infiltration is favored and ponding is decreased (84%; Braswell *et al*., 2018); they have the capacity to remove pollutants through natural processes (Kamali *et al*., 2017); they provide ecological benefits (Li and Davis, 2009); they are an option for domestic self-consumption and waste discharge management (Melo dos Santos and Farias, 2017); they improve the thermal and acoustic insulation of buildings (Reyes *et al*., 2016), among others.

The objective of this work is to review the positive effects of green infrastructure as an adaptation strategy in cities with semi-arid climates where the hydrological cycle has been negatively altered due to urbanization. Its main hydrological and ecosystemic functions, most commonly recommended design criteria, physical factors necessary for its adaptation in previously urbanized environments, as well as its hydraulic efficiency to mitigate flooding and water scarcity problems are defined. The scope of this work is limited to the effects of urban surface runoff and its management through examples of green infrastructure in semi-arid climate zones.

## 2 Main approaches to green infrastructure

Green infrastructure is defined as an emerging urban planning and design concept (Dige, 2015) that contributes to the resilience of urban ecosystems by providing services to maintain or restore ecological and hydrological functions (Zölch *et al*., 2017). Its main applications include reducing runoff from impervious areas (Martin-Mikle *et al*., 2015), facilitating infiltration and increasing evapotranspiration (Zahmatkesh *et al*., 2015), replicating water balance to preserve local ecosystem integrity (Feng *et al*., 2016), and improving infiltrated water quality (Obropta *et al*., 2018), to name a few. Among their main attractions are their low cost compared to gray infrastructure works (Jia *et al*., 2015) and their ability to adapt to a previously urbanized environment. Its variety of applications is wide, as it can be adapted from the micro-scale (a building) to the macro-scale (watershed or city). This depends, among other things, on the function they perform, the space available, as well as the budget and the management of users and authorities for their implementation. The most common examples are shown in Figure 9.1.

**Figure 9.1** Most common green infrastructure applications




*Source of reference: Image prepared by the authors*

The green infrastructure also has several hydrological functions that help to improve the restoration capacity of the water cycle. The composition of materials and construction elements used is simple and practical to install. Table 9.1 defines their basic components, as well as the most well-known hydrological functions.

**Table 9.1** Composition and hydrological functions of the green infrastructure.

| Ranking | Composition | Hydrological function | Author |
|---|---|---|---|
| Permeable pavement | Aggregates (gravels), cement and water | Infiltrate and reduce runoff | Liu *et al*. (2014); Jia *et al*. (2015) |
| | Photocatalytic film on its surface | Improve the quality of infiltrated water | Martin-Mikle *et al*. (2015); Zahmatkesh *et al*. (2015); Ortega-Villar *et al*. (2019) |
| Rain garden | Coarse aggregate layer at the bottom, medium aggregate layer in the middle layer, soil and vegetation layer on its surface | Retention and infiltration of runoff | Chapman and Horner (2010) |
| | | Reducing the amount of pollutants | Zahmatkesh *et al*. (2015); Zúñiga-Estrada *et al*. (2020) |
| | | Temporarily storing and treating a volume of runoff water and improving its quality | Winston *et al*. (2016); Zölch *et al.* (2017); Eaton (2018); Tavakol-Davani *et al*. (2019) |
| Rainwater harvesting | Tanks for storing rainwater that is normally used for non-drinking purposes | Public supply | Martin-Mikle *et al*. (2015) |
| Green roofs and walls | They have waterproofing at the base, anti-root layer, intermediate layer to reduce saturation, soil substrate and vegetation on its surface | Reduce nutrients and sediments | Martin-Mikle *et al*. (2015) |
| | | Reducing the amount of runoff and pollutants | Jia *et al*. (2015); Tavakol-Davani *et al*. (2019) |
| | | Increase evapotranspiration | Zölch *et al*. (2017) |
| Infiltration trench | A layer of fine aggregate on the bottom and a layer of coarse aggregate on its surface. It is used parallel to walkways, sidewalks and medians. May or may not have vegetation | Reduce runoff, increase infiltration and filtration, and reduce pollution | Ahiablame *et al*. (2012); Lizárraga-Mendiola *et al*. (2017) |

*Source of reference: Table prepared by the authors*

### 2.1 Adaptation of green infrastructure in urban spaces

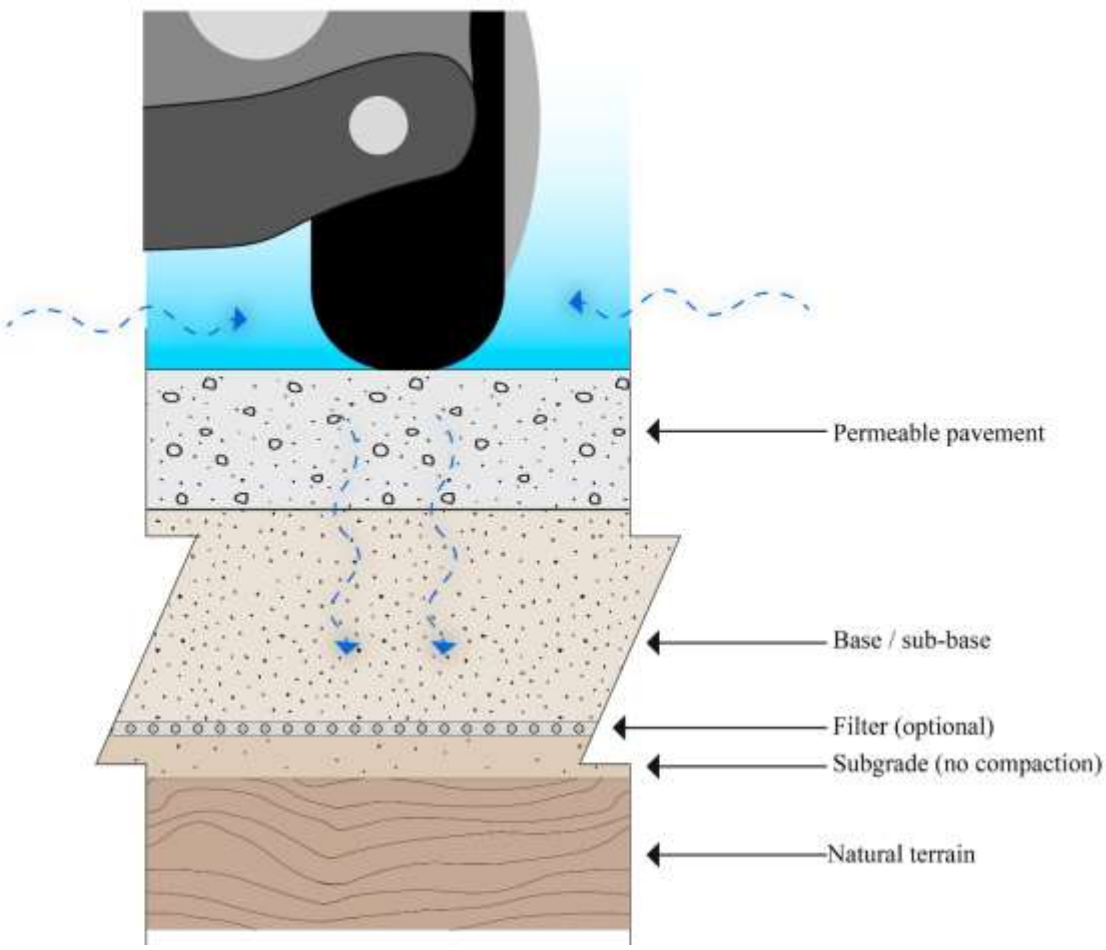
It is necessary to adapt existing infrastructure in cities to reduce the vulnerability of the population to water scarcity and flooding, particularly in areas where rainfall is scarce (Liu and Russo, 2021). Strategies for better urban runoff management have been employed for years (Chao *et al*., 2015). Green infrastructure is widely considered in urban and regional planning processes in different parts of the world (Li and Davis, 2009; Melo dos Santos and Farias, 2017; Martí *et al*., 2020; Tirpak *et al*., 2021). This is composed of a variety of alternatives, from street trees, green walls and roofs on buildings, parks and playgrounds, and permeable pavements, walkways and parking lots, among many other examples (US EPA, 1999). The benefits are broad, as they not only contribute to restoring the urban hydrological cycle, but also promote the wellbeing of the population, the reintroduction of local animal and plant species, and increase the value of real estate, to name a few (Li and Davis, 2009). The following is a description of the most commonly used types of green infrastructure. The focus of this paper is to highlight mainly the benefits on the urban hydrological cycle, such as flood and water shortage mitigation.

#### 2.1.1 Permeable pavement

Main features and functions

There are several types of permeable pavement, including cobblestones, adopasto, gravel pavement, porous asphalt and permeable concrete (Wanielista *et al*., 2007). Pervious concrete is widely used in roads, walkways and bicycle paths and is basically composed of three layers: a bearing surface sufficiently permeable to allow water to enter through its voids, a base layer of fine granular material that favors the optimal conditioning of the bearing surface, and a sub-base layer with coarse granular material that facilitates water infiltration into the subsoil (Wanielista *et al*., 2007). Its interconnected porous structure favors the reduction of surface runoff through physical processes such as infiltration.
(Figure 9.2).

**Figure 9.2** Common configuration of a permeable pavement

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Its average porosity varies between 15 and 25% (NRMCA, 2010). Although it does not have a strength like conventional concrete, the water/cement ratio (0.28-0.40) provides sufficient bearing capacity for light traffic roads (US EPA, 1999; Yahia and Kabagire, 2014). Its strength depends in part on the porosity of the material, ranging from 44 to 15 MPa for pavements with lower and higher porosity, respectively (Chandrappa and Biligiri, 2016). A low compressive strength (compared to that of a conventional concrete) requires a pavement with higher thickness to help distribute the vehicular load. In a regular pavement the recommended thickness is 10 cm, while in this type of green infrastructure it is 12.5 cm or higher (Wanielista *et al*., 2007). The most commonly used granulometry contains coarse aggregates in a volume between 50-65%, with particle diameters varying between 19-9.5 mm (NRMCA, 2010), although other authors suggest between 2-8 mm (Deo and Neithalath, 2010).

Physical factors required for design and installation

Commonly, these pavements are adapted on soils with good permeability (low clay content, <30%), gentle slope (<5%) and in areas with light traffic (US EPA, 1999). However, in the case of sites with clay soil (low hydraulic conductivity), they have also proven to be efficient in the removal of pollutants and urban runoff (Braswell *et al*., 2018) although their application is uncommon (Dreelin *et al*., 2006). Moreover, when there are low rainfall events (< 8 mm) they can be even more efficient than during heavy rainfall, reducing up to 84% of surface runoff (Braswell *et a*l., 2018). Factors such as pavement age or periodicity of maintenance influence its hydraulic capacity; however, the recommended contributing impervious area ratio for best hydraulic performance is < 5 (Selbig *et al*., 2019). The use of technologies to improve its pollutant removal capacity can also slightly affect its infiltration coefficient; Liang *et al*. (2019) found that, although not significant, the use of titanium dioxide nanoparticles slightly reduced the permeability of permeable pavement, although without deteriorating its hydraulic efficiency.

Hydrologic/hydraulic efficiency

Permeable pavements are characterized because all the layers that compose them are capable of infiltrating runoff; in addition, their internal structure serves as a reservoir to store water and minimize the negative impacts of runoff (Saadeh *et al*., 2019). Their hydraulic behavior is determined by the mix and pavement design, as well as maintenance during operation, making it complex to simultaneously optimize their mechanical and hydraulic properties (Xie *et al*., 2019). It has been reported, for example, that there is a 50% decrease in its strength for every 10% increase in porosity, so a balance must be found to obtain a material that is mechanically and hydraulically efficient (Chandrappa and Biligiri, 2016). Its infiltration capacity (0.1-2 cm/s) is associated with the aggregate size and its compaction level, so it is not recommended to include fine aggregates (Chandrappa and Biligiri, 2016). Their physical characteristics help filter pollutants carried by urban runoff (Wanielista *et al*., 2007). However, sediment accumulation in the pores can reduce their permeability by up to 95% over time and this decreases their hydraulic performance, durability and functionality (Sandoval *et al*., 2020). It has been found that after 5 years, pavement permeability tends to decrease up to 40% due to the clogging of its pores by sediment accumulation. Given the above, it is advisable to provide annual maintenance to prolong its original permeability for a longer period of time (Sandoval *et al*., 2020).

Pollutant removal capacity

They have the capacity to retain runoff water pollutants such as total suspended solids (TSS), nitrates ($NO_3^-$), nitrites ($NO_2^-$), ammonium ($NH_4^+$), phosphates ($PO_4^{-3}$), and other pollutants (Kamali *et al*., 2017). (Kamali *et al*., 2017). It is believed that the decrease in dissolved phosphorus (*P*) is due to its interaction with calcium (*Ca*) and magnesium (*Mg*) available in concrete, as they precipitate it as phosphate. (Hassan *et al*., 2017). It was also found that pavements remove suspended metals better (such as *Pb, Al* and *Fe*) than the soluble ones (such as *Cu, Zn* y *Mn*) (Selbig *et al*., 2019). Its main purifying mechanisms are filtration and sedimentation, since most of the particles are retained in the first centimeters of the pavement (Selbig *et al*., 2019). However, after some time its treatment capacity tends to decrease, possibly due to a loss in its adsorption capacity due to problems of clogging of its pores (Zhang *et al.*, 2018).

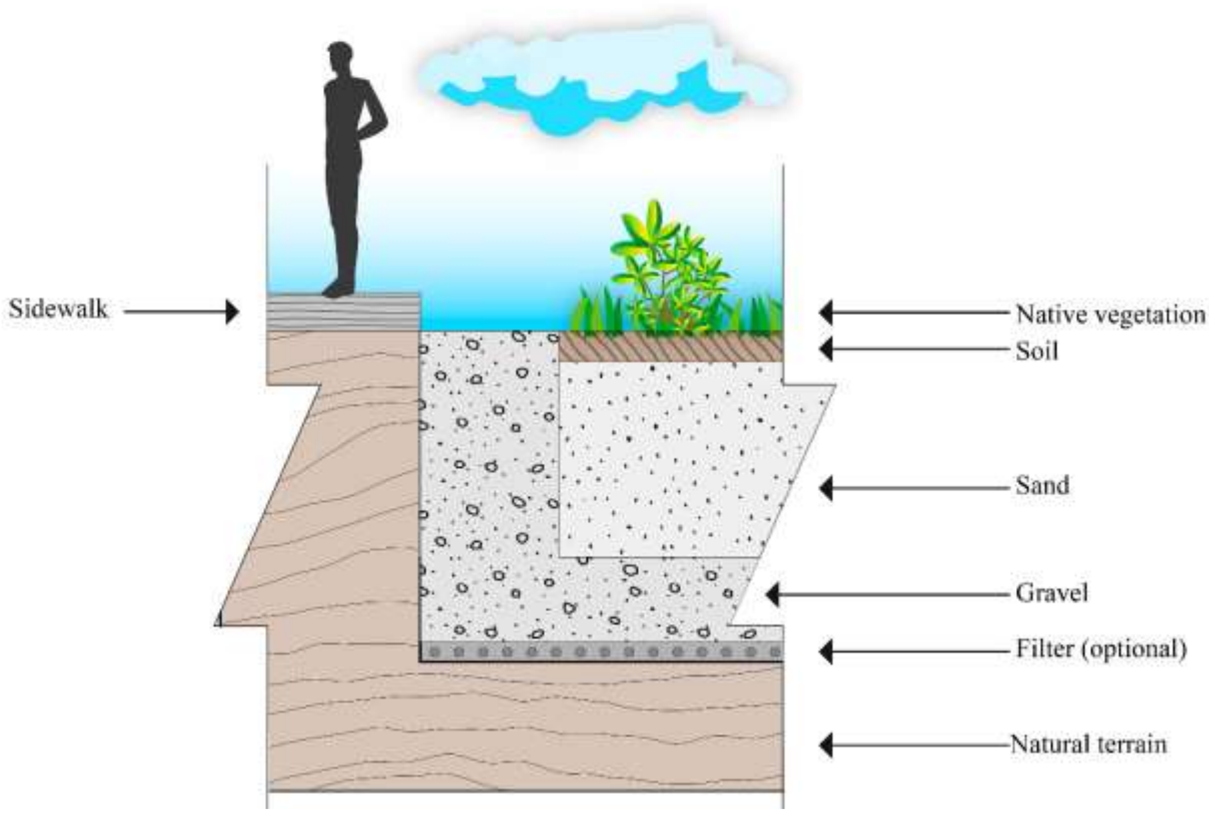
Technologies have also been used for urban runoff treatment such as the incorporation of photocatalytic coatings, e.g., based on nanoparticles of $TiO_2$, for the removal of various pollutants from runoff water (Liang *et al*., 2019). Photocatalytic oxidation occurs on the surface of permeable pavement in contact with ultraviolet light (Hassan *et al*., 2017). Then, Xu *et al*. (2020) determined that a permeable pavement with a granulometry between 5-10 mm impregnated with nanoparticles of $TiO_2$ had a greater capacity for oxidation of $NO$ than one with larger particles. In another study, nanoparticles of $Fe_2O_3$ as a coating were found to be capable of removing $Mn$ and various microbiological indicators due to oxidation processes (Ortega-Villar *et al*., 2019).

### 2.1.2 Rain gardens

Main features and functions

They are also known as bioretention systems, biofilters or swales (Le Costumer *et al*., 2009). They are widely used in urban environments to improve their quality and hydrological impacts on infrastructure (Vijayaraghavan *et al*., 2021). They are able to reduce runoff, mitigate its pollutants and provide aesthetic and ecological benefits (Li and Davis, 2009). They favor the development of local flora and fauna, improve water quality and infiltrate stormwater runoff, thus mitigating waterlogging problems (Tirpak *et al.*, 2021). Although they can have different sizes and shapes, they are mainly composed of vegetation on a substrate layer, fine (sand) and coarse (gravel) granular material; occasionally, they can include drainage at their base to increase their hydraulic conductivity (Vijayaraghavan *et al*., 2021) (Figure 9.3). The granulometry of the filter media must drain quickly, but at the same time, it must allow sufficient retention time for the treatment of runoff and vegetation growth (Le Costumer *et al*., 2009).

**Figure 9.3** Common configuration of a rain garden




*Source of reference: Own image*

Physical factors required for design and installation

They are a very versatile type of green infrastructure; however, it is important to consider the catchment area and the type of pollutants they will infiltrate, since selecting the most efficient design will depend on this (Tirpak et al., 2021).

It is possible to combine their shape, size, filtering materials and the type of vegetation, adapt facilities to partially store the infiltrated water or increase its hydraulic conductivity. On the other hand, in climates with low rainfall it is advisable to increase the density of native vegetation in this type of infrastructure, since they have the capacity to absorb pollutants through plants and microbial communities that proliferate in their soil (Houdeschel *et al*., 2012). Likewise, it is advisable to previously characterize the filtering materials in order to improve their decontaminant treatment capacity and predict negative interactions with runoff water (Zúñiga-Estrada *et al*., 2020). Some examples used are gravels of granitic composition with very low dissolving capacity (Caldelas *et al*., 2021) as well as pebbles, quartz sand, slag, loess and activated carbon due to their high porosity and adsorption capacity (Zhang *et al*., 2021a).

Hydrologic/hydraulic efficiency

Their hydrological performance depends on many factors, such as design configuration, location, average annual precipitation, potential evapotranspiration, ratio of catchment area to rain garden area, subsoil infiltration rate, as well as the composition of the growing substrate (Skorobogatov *et al*., 2020). The pore size of the filter media is also thought to influence water availability to plants, so the presence of mesopores (0.2 to 60 μm) is desirable (Skorobogatov *et al*., 2020). Its permeability may decrease as incoming sediment accumulates and clogs the pores of the material; however, vegetation roots play an important role in counteracting this effect (New Jersey Department of Environmental Protection, 2004). It is recommended that its hydraulic conductivity be at least 12.5 mm/h (ARC, 2003), although other sources recommend between 50-200 mm/h (Melbourne Water, 2005) and 4-6 mm/min (Zhang *et al*., 2021b).

Depending on the type of vegetation selected, their roots have the ability to promote the passage of water and air through the pores, mainly in the surface layers. Houdeschel *et al.* (2012) found that grasses can neutralize clogging due to sediment accumulation in this type of infrastructure. Le Costumer *et al*. (2012) demonstrated that plants with thick roots maintain their infiltration capacity and also delay the clogging of their pores with sediments. However, regardless of these benefits, the selection of vegetation should take into account other factors such as its adaptation to the local climate, its phytoremediation potential, sorption capacity, high biomass production and extensive root systems, among others (Vijayaraghavan *et al.*, 2021). Another important hydrological function in rain gardens is evapotranspiration, which can account for up to 19% of intercepted urban runoff, even when the ratio of catchment area to garden area is 1:0.045 (Li and Davis, 2009). In another study, it was found that when this ratio is 2.5%, its retention capacity increases up to 88% (Le Costumer *et al*., 2012).

Pollutant removal capacity

Rain gardens are effective in treating suspended sediments, heavy metals, nutrients and organic compounds (Vijayaraghavan *et al*., 2021). Water quality improves through a complex combination of natural processes that take place in the filter material, such as adsorption, precipitation, microbial biodegradation, photodegradation, volatilization and absorption through plants (Caldelas *et al*., 2021). As for the materials selected for backfilling, those commonly used (soil with organic matter, sand, clay loam and clayey sand) have a limited capacity to treat dissolved contaminants, which tend to infiltrate into the subsoil (Tirpak *et al*., 2021). Studies have proven their ability to reduce the presence of nutrients (N and P), metals and metalloids, as well as microplastics (Smyth *et al*., 2021). The presence of microplastics in urban runoff is considered to come from various anthropogenic sources such as tire and road wear, plastics, paints, construction materials, industrial waste, among others. Their concentration tends to be higher (66-191 particles/L) during the first rains after prolonged periods of drought (Piñon-Colin *et al*., 2020). When they enter a rain garden, retention of up to 84% is possible (Smyth *et al*., 2021).

### 2.1.3 Rainwater harvesting

Main features and functions

The collection, storage and use of rainwater in urban areas can have a positive impact on the public supply system, since it would not only facilitate the reduction in the demand and use of drinking water, but also mitigate the volume of urban runoff that occasionally causes flooding and negative damage to infrastructure (Melo dos Santos and Farias, 2017).

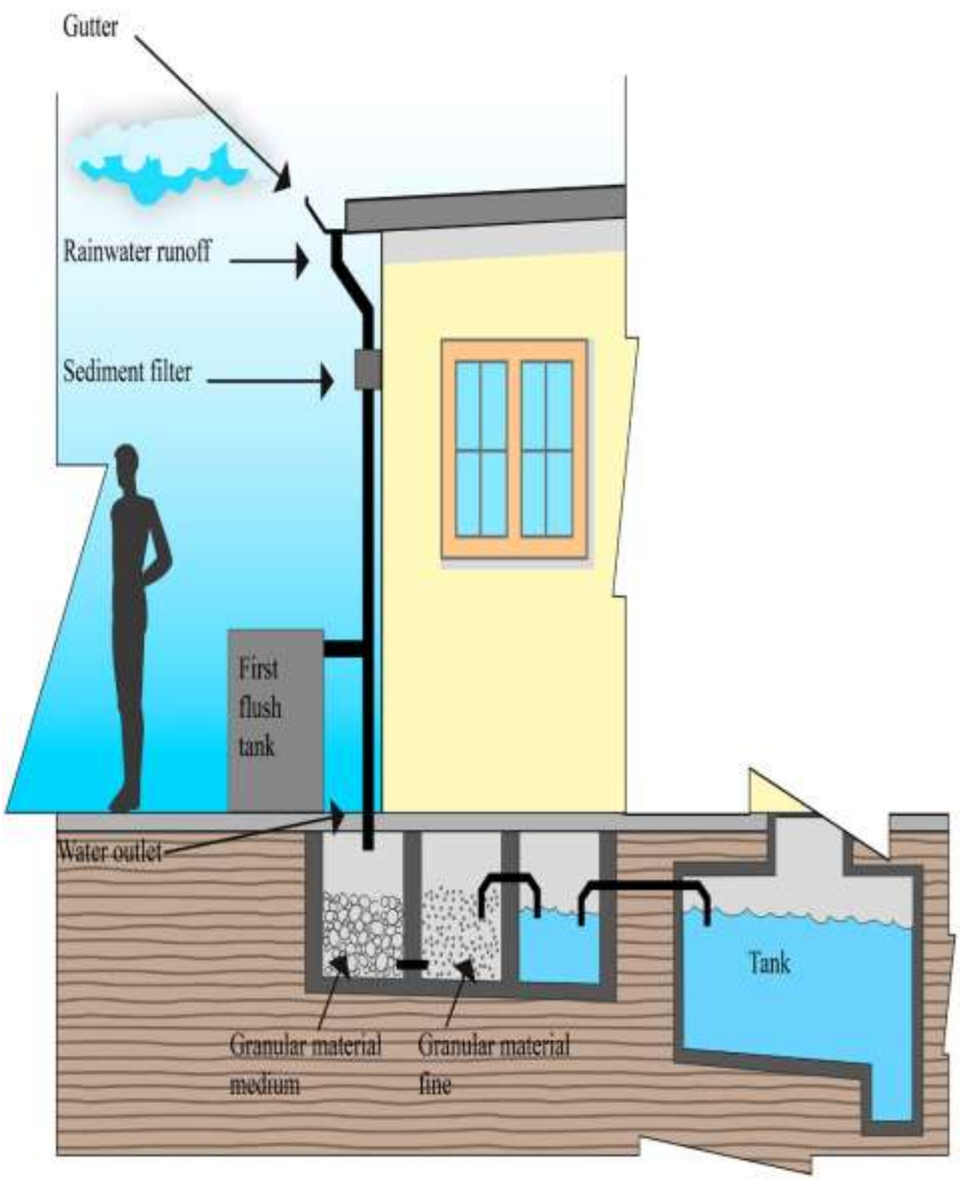
However, it is important to take into account that captured rainwater requires a first rain separator and treatment prior to its reuse, since the catchment surfaces or rooftops may have dirt, leaves, bird feces, insects and garbage that can contaminate the water, as well as particles in the atmosphere (WHO, 2011). The collection capacity of the rooftop will depend, among other factors, on the available area, its slope, type of material, as well as the amount of precipitation (Jing *et al*., 2017). In sites with semi-arid climates, the temporal variability of rainfall and the aforementioned factors affect the harvestable volume; however, it will depend on the purposes for which it is intended to fully or partially meet the necessary demand (Abdulla and Al-Shareef, 2009; Ali *et al*., 2020).

Physical factors required for design and installation

It is necessary to have an available catchment surface (rooftops), minimum slope of 2%, materials such as concrete or sheet metal (Secretaría de Obras y Servicios del Gobierno de Distrito Federal, 2008); gutters and pipes (PVC, aluminum, galvanized steel) for collection, the first rainfall separator tank, as well as a storage tank with filter (CONAGUA, 2016).

Regardless of the roof material and slope, some designers consider 20% annual losses due to splashing, evaporation and collection failures (Abdulla and Al-Shareef, 2009). Its efficiency will depend on the temporal distribution of rainfall, water demand, the available catchment area (rooftop) and the size of the separator tank, mainly (Ali *et al*., 2020) (Figure 9.4).

**Figure 9.4** Common configuration of a rain harvesting system




*Source of reference: Own image*

Hydrologic/hydraulic efficiency

In semi-arid climate zones (< 800 mm) rooftop rainwater harvesting systems are more efficient if they have storage capacities greater than 20 $m^3$ (Jing *et al*., 2017) and 60 $m^3$ (Ali *et al*., 2020), although they have a lower cost-benefit ratio than 1 (Jing *et al*., 2017; Ali *et al*., 2020). With large storage volumes and extended periods of rainfall during the year (more than 6 months), it is possible to meet domestic demand more efficiently (Abu-Zreig *et al*., 2019) and reverse the cost-benefit ratio. To obtain the desirable tank size, it is important that cost, reliability, technical feasibility and user interest are in balance to ensure sustainability (Alim *et al*., 2020). In a study conducted in a logistics company located in Mexico City, it was found that the installation of these systems is technically and economically feasible, since the cost-benefit ratio was 1.9 with a recovery rate of 5 years (López-Zavala *et al*., 2018).

Pollutant removal capacity

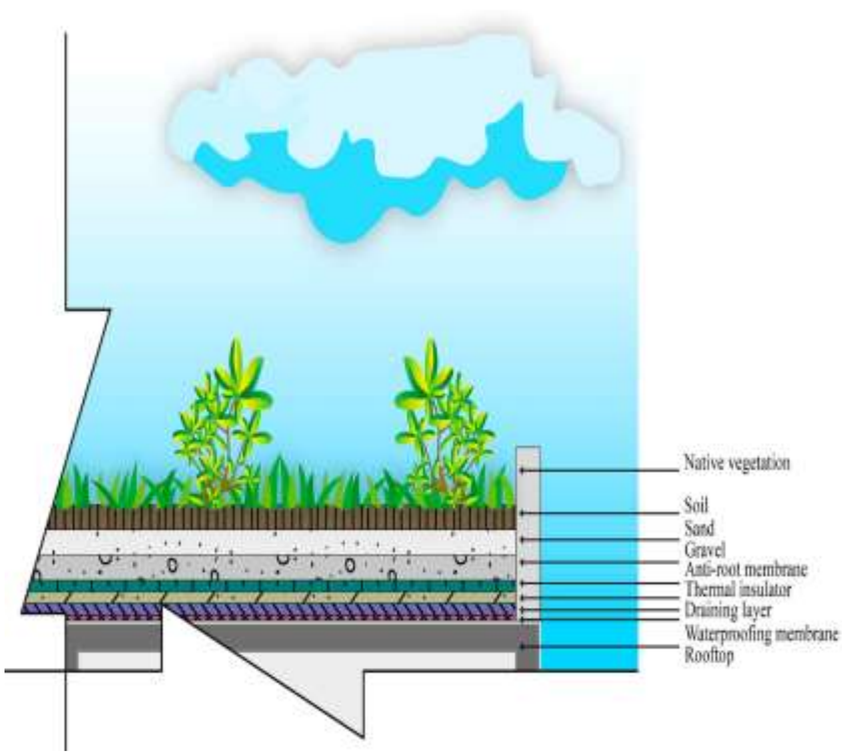
The quality of the rainwater that is stored is usually higher than that of the first rainfall separator tank (described in the previous section), so it is essential to have this treatment prior to its final storage (Mao *et al*., 2021). Also, water quality improves after the first rains, as this is when the roof surface is washed (Zhang *et al.,* 2014). On concrete surfaces (one of the most commonly used materials in Mexico), as well as on roofs with metal sheets, the presence of total suspended solids is common, as well as $K^{+}$, $Ca^{2+}$, $Si^{4+}$, *Al* y *Fe* (Méndez *et al*., 2011; Zhang *et al*., 2014). The presence of microorganisms has also been reported (*Legionella*, *Escherichia coli* $O157:H7$) (Bae *et al*., 2019). Without an adequate treatment system, its consumption is recommended only for non-potable purposes (Mao *et al*., 2021), so at least filtration and disinfection are suggested (Méndez *et al*., 2011).

### 2.1.4 Green roofs

Main features and functions

Green roofs can significantly reduce urban runoff volumes through two hydrological processes, rain retention (subsequently lost through evapotranspiration) and runoff detention (through transient storage of rainfall as it infiltrates due to the hydraulic conductivity of the substrate) (De-Ville et al., 2018) (Figure 9.5). Among its known advantages are its ability to reduce the concentration of atmospheric $CO_2$ and provide an urban aesthetic approach. (Gong *et al*., 2021).

**Figure 9.5** Common configuration of a green roof

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In addition, they extend the useful life of the roof and improve the thermal and acoustic insulation of the building (Reyes *et al*., 2016; Melo dos Santos *et al*., 2019). Green roofs with 10 cm deep substrates have a buffering effect on changes in temperature in the root zone (up to 13 °C lower than ambient temperature) (Reyes *et al*., 2016), while a substrate with 15 cm depth increases its runoff attenuation capacity (Zhang *et al*., 2021b). In places with semi-arid climates, they may reduce 2.2 °C (Melo dos Santos *et al.*, 2019) and up to 5.3 °C (Reyes *et al*., 2016) the interior temperature of the building, compared to a regular roof. In this type of climate, atmospheric conditions in spring and summer expose green roofs to evaporation, high solar radiation and air temperature. Therefore, the selection of plants is crucial to facilitate the retention of moisture in the substrate, since the flow of water that infiltrates depends on the type of roots (Zhang *et al*., 2019). This promotes better moisture retention throughout the year, which is important in arid and semi-arid climates where sustainable irrigation conditions are required.

Physical factors required for design and installation

These surfaces consist of a series of layers such as a waterproofing membrane over the deck or roof, a drainage system, anti-root layer and filtering material (if necessary) to be placed under and over the drainage, respectively, as well as a layer of substrate and plants (Reyes *et al*., 2016). In addition to the hydraulic conductivity and weight of the substrate, its absorption capacity (Melo dos Santos *et al*., 2019) and a low bulk density should also be taken into account to avoid structural damage to the roof (Zhang *et al*., 2021b). The thickness of the substrate can vary from a few cm to one meter. Depending on the type of rooftop, substrate depth, and irrigation needs of the selected vegetation, there are two types of green roofs: extensive and intensive. Extensive-type green roofs have a substrate layer 2 to 20 cm deep, require minimal or no irrigation, and are generally planted with moss, succulents, grasses, and some herbaceous plants (Reyes *et al*., 2016). Those of the intensive type are more than 20 cm deep, are often designed as gardens for human use and require irrigation and maintenance. The former are adaptable to any type of building (single-family house, building), while the latter require more specific structural conditions and are dependent on irrigation (Reyes *et al*., 2016).

Hydrologic/hydraulic efficiency

Green roofs have higher retention capacity in arid and semi-arid climate sites (67%, Sims *et al*., 2016; 81%, Zhang *et al*., 2021a); furthermore, the use of plants such as the different species of *Sedum*, require little water to subsist and can increase their retention capacity by 89 to 95%. (Zhang *et al*., 2019). It has been reported that the use of mixed vegetation can improve both plant survival (especially in low rainfall conditions) and the retention capacity of a green roof (Gong *et al*., 2021). Substrates with low hydraulic conductivity (0.46 mm/min) show higher moisture detention than those with higher hydraulic conductivity and higher porosity (Zhang *et al*., 2021a). It has also been pointed out that the moisture condition antecedent to the onset of a rainfall event defines its retention efficiency, while rainfall above 45 mm can reduce its efficiency to 16-29% (Sims *et al*., 2016). On the other hand, although temperature has a direct effect on substrate moisture retention, those with thicknesses greater than 10 cm have a buffering effect (Reyes *et al*., 2016). Regarding their potential to mitigate urban runoff, they are capable of reducing it by up to 50% with respect to other impervious areas (Buffam *et al*., 2016).

Pollutant removal capacity

Green roofs are an alternative for absorbing and storing carbon in plants and soils and, therefore, reducing the high concentration levels of carbon dioxide in the soil $CO_2$ atmospheric in cities (Zhang *et al*., 2021a). Similar to natural ecosystems, this type of infrastructure can undergo seasonal changes in the quality of filtered water, due to factors such as plant development, microbial activity, or other temperature- or light-dependent factors, antecedent humidity, and so on (Buffam *et al*., 2016). They can also degrade the water quality by leaching nutrients (*P, C, N*) and metals (*Cu* and *Fe*) during the rainy season, so it is important to reduce the amount of runoff that will be diverted into the local drainage system (Buffam *et al*., 2016). As for runoff treatment, the adsorption process could be the main factor in reducing nutrient concentration, especially when there is low rainfall (Gong *et al*., 2021). For example, it was found that low concentrations of ammonium ion may be due to its binding to negatively charged organic matter, clays through adsorption or ion exchange, as well as N fixation in the plant; in the case of P, the decrease in its concentration may be associated with physical retention in the substrate (Gong *et al*., 2021).

Other processes such as microbial mineralization of organic matter, desorption or weathering, rather than plant uptake or hydrological variation between storms, are mechanisms controlling the quality of filtered water (Buffam *et al*., 2016).

### 2.1.5 Green walls

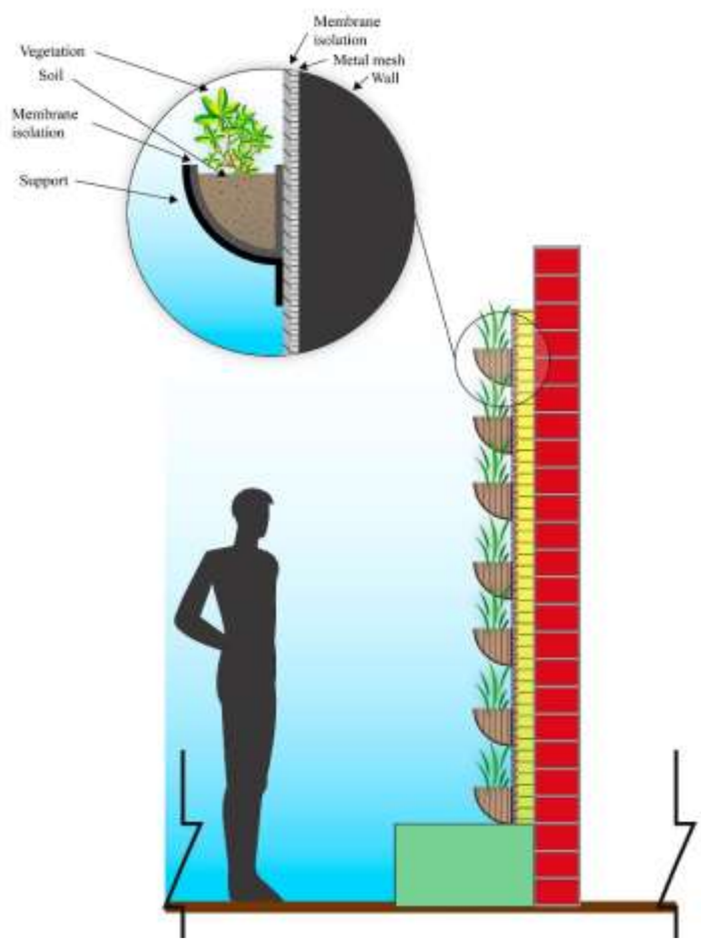
Main features and functions

They are also known as vertical gardens. They can be installed on any vertical surface (building walls), so they take up little space horizontally and add aesthetic value to the real estate (Prodanovic *et al*., 2020). Green walls provide thermal insulation to the buildings in which they are installed, cool the surrounding microclimate, provide acoustic damping and improve air quality (Prodanovic *et al*., 2019). This type of infrastructure requires high amounts of irrigation water in areas with a semi-arid climate (up to 20 L/m$^2$), which often makes them unsustainable for water-stressed regions (Prodanovic *et al*., 2019). Fortunately, there is the practice of reusing gray water generated in buildings (sink, washing machine or shower) for irrigation, which makes them part of the solution to address water scarcity issues (Prodanovic *et al*., 2020).

Physical factors required for design and installation

In the case of green walls that are irrigated with gray water, it is important that their design includes a filter media that functions as a treatment system to purify pollutants during infiltration (Prodanovic et *al*., 2020). Regarding the filter media used, the mixture (1:2) of perlite and coconut fiber is common (Jørgensen *et al*., 2018), as this mixture is highly permeable and has shown to have a high capacity to remove pollutants from graywater used in irrigation. The filter material must have sufficient macroporosity (>60 μm) to achieve a hydraulic conductivity sufficient for water to flow downward by gravity and then spread with the help of capillary action through mesopores (0.2-60 μm) and micropores (<0.2 μm) (Jim, 2015) (Figura 9.6).

**Figure 9.6** Common configuration of a green wall




*Source of Reference: Own Image*

Hydrologic/hydraulic efficiency

It is common to see green walls installed with pots (where irrigation and plant growth occur in isolation) and as continuous blocks (there may be a combination of plants and irrigation is applied from the highest elevation and runs through the entire system to its bottom) (Prodanovic *et al*., 2020).

Block-installed green walls have been found to be more resilient to drought conditions, as they tend to retain moisture due to less surface area exposed to the elements. In addition, the selection of sufficiently porous filter material will favor plant absorption and evaporation, as it allows for better water distribution in the substrate (Prodanovic *et al*., 2019).

The time of the year, which defines the amount of rainfall received, temperature and relative humidity, play an important role in the hydrological balance of the green wall. In the rainy season, evaporation can account for 35-50% of water loss (Prodanovic *et al*., 2019). In the upper part of the wall, evapotranspiration and water retention may be mainly due to the fact that in this zone the plants have greater exposure to the sun and use a greater amount of water to increase their metabolic activity; this also means that it is in this zone where they have greater growth with respect to the lower part of the wall (Dal Ferro *et al*., 2021).

Pollutant removal capacity

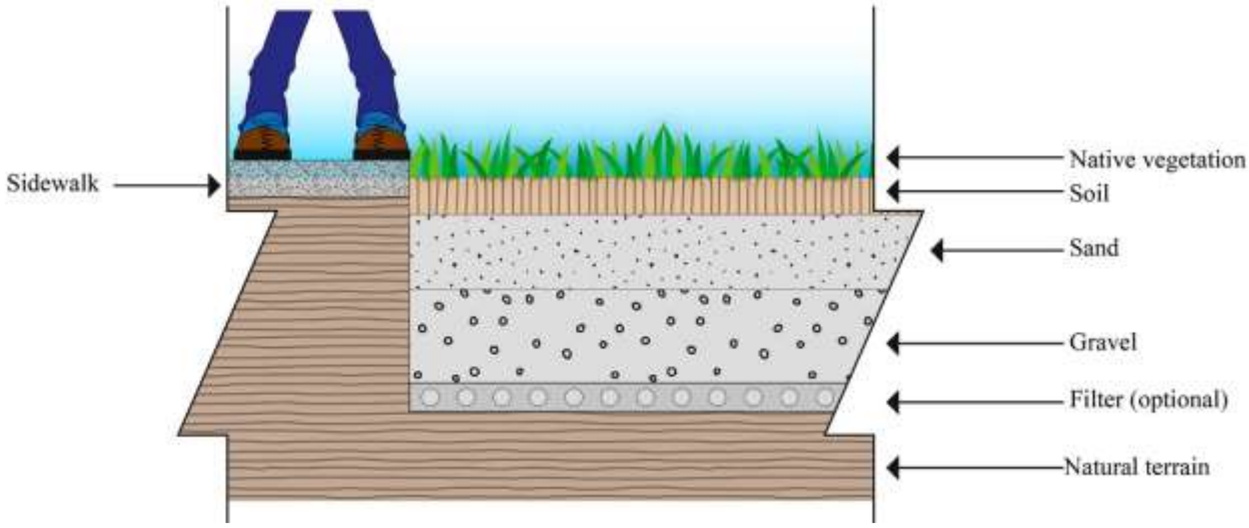
Both the filtering material and the vegetation selected in this type of infrastructure play an important role in water treatment. Plants such as *Mentha aquatica L., Oenanthe javanica DC.* and *Lysimachia nummularia L.,* have been efficient in the removal of organic pollutants and nutrients from graywater (Dal Ferro *et al*., 2021). In another study, species of ornamental plants (*lirios de Canna, Lonicera japonica*, vid ornamental) eliminated some contaminants ($N$ > 80%, $P$ entre 13% y 99) (Fowdar *et al*., 2017). On the other hand, the selection of filtering materials favors both infiltration and treatment of pollutants. Coconut fiber, perlite, vermiculite, gravels and sands of high hydraulic conductivity have been used as decontamination treatment systems (Prodanovic *et al*., 2017). Those materials with lower hydraulic conductivity, such as perlite and coconut fiber, showed higher treatment capacity, possibly due to longer retention time and physical-chemical processes (Prodanovic *et al*., 2020). This indicates that green walls are not only an option for reinserting vegetation in limited urban spaces, but are also an option for reusing and treating wastewater, thus reducing the amount of water that is discharged into the sewage system.

### 2.1.6 Infiltration trench

Main features and functions

This type of infrastructure is very simple to build; in cities they can be installed in areas adjacent to roads, sidewalks and green areas, either in public spaces or private gardens, since they do not require large areas for their adaptation. It consists of a shallow excavation with a minimum slope (2%) and a level bottom surface; its surface has an overflow area (Bureau of Watershed Management, 2006). It is filled with sand on top of the natural ground and coarse aggregates and perforated pipe may be placed to facilitate further infiltration into the subsoil vertically and laterally (NWRM, 2015). On the superficial part it contains a layer of soil and may include vegetation (Figure 9.7). It can be adapted as a complementary drainage work to the storm sewer system or as a surplus infiltration area (e.g., the volume of rainwater that was not stored for reuse). As a constraint, it is important to take into account the depth to groundwater before trench design, as a shallow water table can negatively affect its recharge capacity (Locatelli *et al*., 2015).

**Figure 9.7** Common configuration of an infiltration trench




*Source of reference: Own Image*

Physical factors required for design and installation

In contact with the natural soil, perforated pipe is installed to increase its infiltration capacity. It is recommended that its width not exceed 240 cm; aggregates (gravels with sizes of 2.5-5 cm and void volume of 40%, ASTM-C29) are placed at a maximum depth of 180 cm. A 15 cm layer of soil and native vegetation with low water requirements can be deposited on this surface (Bureau of Watershed Management, 2006). They are usually long, narrow structures that rely primarily on their infiltration capacity to reduce runoff (Ebrahimian *et al*., 2021). In one study, a ditch was designed with a 20:1 ratio with respect to its impervious area, with a capacity to absorb 23 mm rainfall. It was found that its hydraulic efficiency was adequate even for higher rainfall (36 mm), since the surrounding soil was able to absorb more infiltration volume, so its oversizing is common (Ebrahimian *et al*., 2021).

Hydrologic/hydraulic efficiency

Its greatest hydraulic efficiency is observed under light rainfall conditions, since it favors infiltration and recharge. Its design should allow the ditch to be emptied within 72 hours after the rainfall event (Bureau of Watershed Management, 2006). Another factor to consider is hydraulic conductivity, as this will determine the capacity of the trench to manage infiltration of urban runoff (Locatelli *et al*., 2015). The type of material used plays an important role in the hydraulic conductivity value, as a sandy loam soil will behave more efficiently than a silty clay loam type, for example, mainly due to its porosity (Locatelli *et al*., 2015). It is important to have adequate maintenance on a regular basis, otherwise, the clogging of their pores due to sediment carried by infiltrated urban runoff can reduce their hydraulic efficiency (Bergman *et al*., 2011). Like other types of infrastructure, infiltration trenches can also increase their hydraulic efficiency (in periods of low water or low rainfall) or decrease it due to their antecedent moisture content (periods of continuous rainfall) (Ebrahimian *et al*., 2021). Locatelli *et al*. (2015) found that annual seasonal changes can affect their runoff reduction capacity by 10-15%, while permeabilities of $8.2\text{x}10^{-7}$ m/s produce a catchment volume of 68-87%. If there is higher porosity (silty sands), its permeability may increase. ($4\text{x}10^{-5}$ m/s) and the volume of uptake, too (up to 92%).

Pollutant removal capacity

This type of infrastructure is used to remove suspended solids, coliforms, organic pollutants and some soluble forms of metals and nutrients from urban runoff (EPA, 1999). Seasonal changes can alter the geochemical and hydraulic behavior of infiltration ditches, particularly those built on the sides of roads, since they receive, among other things, pollutants from industrial activities and vehicular traffic (Ebrahimian *et al*., 2021). In one study it was determined that during the rainy season there was an increase in the concentration of some dissolved metals (Fe and Mn), while some nutrients decreased; this was possibly due to the washing of the surrounding impervious surfaces (Mullins *et al*., 2020).

Also, when large amounts of runoff are received and the water table is shallow, saturation of the filter material may increase and form anaerobic zones, leading to some heterotrophic bacteria rapidly consuming the little oxygen available (Machusick *et al*., 2011). This behavior facilitates the mobilization of some metals and metalloids through the reduction of metal oxides (Mullins *et al*., 2020).

## 2.2 Mitigation of water scarcity

It is evident that water scarcity affects a large part of the population living in arid and semi-arid areas, either due to prolonged droughts or poor management (Yang and Wang, 2017). This paper reviews green infrastructure alternatives to mitigate this problem, identifying that rainwater harvesting on rooftops can positively and directly impact users, by collecting *in situ* and have it available almost immediately. Among its main advantages are that most buildings can collect it; it is only necessary to have a minimum slope, adequate surfaces to avoid contamination or unnecessary losses, as well as periodic maintenance. As for its storage and treatment prior to consumption, it will depend on the space available, as well as the user's budget for its installation, since, as mentioned by Ali *et al*. (2020), the larger the collection and storage area, the greater the availability of water for self-consumption. Table 9.2 shows examples studied in different parts of the world with semi-arid climates.

**Table 9.2** Rainfall distribution and rainwater availability in different semiarid regions

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| Location | Annual precipitation (mm) | Annual precipitation ($mm/m^2$) | Annual availability ($m^3$) | Author |
|---|---|---|---|---|
| Brazil | 800 | 9.83 | 15.61 | Melo dos Santos and Farías (2017) |
| Jordan | 300 | 1 | 0.56 | Abdulla and Al-Shareef (2009) |
| | 446.5 | 0.44 | N/D | Abu-Zreig *et al*. (2019) |
| Pakistan | 295 | 1.05 | 3.39 | Ali *et al*. (2020) |
| China | 600 | 1.66 | N/D | Jing *et al*. (2017) |

*Source of reference: Table prepared by the authors*

As can be seen in Table 9.2, in semi-arid regions there are important variations in the amount of annual precipitation. While in those regions with higher precipitation (800 mm/year) it is possible to have large volumes of water available for self-consumption, in those regions with lower precipitation (800 mm/year) it is possible to have large volumes of water available for self-consumption (15.61 $m^3$), in sites with very low rainfall (295 mm/a) the available volume is reduced 4.6 times. Seasonal periods, the duration of rainfall events, as well as their intensity, possibly influence the amount of water that can be collected through rooftops in these areas (Melo dos Santos and Farias, 2017). However, in those sites where there are water scarcity problems, they are an alternative option to reduce dependence on the public supply system and achieve better management of drinking water.

## 2.3 Reduction of urban runoff

All of the examples of green infrastructure discussed in this chapter help reduce urban runoff through different processes, and their hydraulic efficiency tends to be greatest when light rainfall occurs (Bureau of Watershed Management, 2006). Some types do this through detention by infiltration (permeable pavement, rain gardens, infiltration trenches) and storage (rainwater harvesting), others through retention and evapotranspiration (green roofs, green walls). Their advantages include facilitating the recharge of aquifers in waterproofed spaces, reducing the temperature in buildings and their surroundings, and reducing waterlogging and damage to infrastructure. If complemented with storage facilities, they can help to recover part of the infiltrated volume and use it for non-potable purposes such as irrigation of public parks and gardens (Prodanovic *et al*., 2020). Factors such as the impermeable area, the appropriate selection of materials with good hydraulic conductivity and capacity to reduce pollutants, the space available for their construction, among others, determine their efficiency in mitigating flooding problems and increasing the recharge of groundwater sources. Among the positive ecosystemic effects are the reinsertion of native plants and the removal of contaminants through different physical, chemical and microbiological processes. Periodic maintenance is essential to avoid clogging of pores and the accumulation of sediments, organic matter and other debris. Moreover, the selection of vegetation should take into account both its adaptation to local hydrological conditions, as well as its phytoremediation potential (Buffam *et al*., 2016; Vijayaraghavan *et al*., 2021).

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**Conclusions**

The examples of green infrastructure most frequently used to mitigate water scarcity and flooding problems in cities with semi-arid climates were reviewed. The main design criteria required for their installation were highlighted, such as available space, slope, type of surface and materials to be used during their construction. In addition, their capacity to retain and detain urban runoff, infiltrate it into the subsoil, evapotranspirate it, purify the pollutants it acquires during its trajectory (in the atmosphere and on the urban surface), as well as its reuse for supply purposes were highlighted. Although their hydraulic and environmental potential may be limited, if properly designed and constructed, they are a sustainable option to complement the capacity of existing gray infrastructure and mitigate problems of water shortages, overexploitation and flooding. It is recommended that planners and designers take into account the appropriate choice of the site, the composition of the materials and the selection of the vegetation to be used, since this will determine their efficiency. Although in Mexico there are national standards and local regulations that take into account aspects of green infrastructure, it is still necessary to promote the main sustainable benefits it offers to the population, especially those living in places with semi-arid climates.

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