Report on Stormwater Management

E²STORMED PROJECT
Improvement of energy efficiency in the water cycle by the use of innovative storm water management in smart Mediterranean cities
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UNIVERSITAT POLITÈCNICA DE VALÈNCIA

L'Europe en Méditerranée
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ANNEX 1. INFRASTRUCTURES COSTS REVIEW

1. STORMWATER MANAGEMENT IN THE URBAN WATER CYCLE

1.1. INTRODUCTION

The overall objective of stormwater management is the control of rainwater to ensure minimum impacts with regards to flooding, erosion and the dispersal of pollutants within the urban environment and downstream (Philip, 2011b). This management process encompasses the interaction between the amount of rainfall, the urban environment and orography, the existing infrastructure and the water bodies into which the water finally ends up.

Stormwater is directly linked with other parts of the urban water cycle (Figure 1.1): good and poor management of one element can influence the successful management of another. The linkages between the different elements of the urban water cycle can cause negative impacts. However, these linkages can also be used to provide positive effects. Integrated management ensures that interventions are designed to maximize multiple benefits in different parts of the cycle while minimizing negative impacts in others (Philip, 2011a). Effective stormwater management will produce benefits in the other parts of the urban water cycle and environment (Ellis and Revitt, 2010).

The linkages within the water cycle are numerous, which makes integrated planning a complex business, so water administrations and entities must prepare for integrated urban water management. Examples of the links between stormwater management and other areas of the urban water cycle are (Philip, 2011b):

- **Water supply:** Stormwater can be reused directly for non-potable uses and can also be, after treatment, a potential source for supplementing urban water supply.
- **Water treatment:** Stormwater entering water supply sources, such as aquifers and reservoirs, influences the water quality of the source.
- **Wastewater collection and treatment:** Stormwater is mixed with wastewater in combined sewer networks, which increases the volume and cost of wastewater treatment. Heavy rainfall can produce overflows in the network, releasing untreated sewage into the environment. Furthermore, stormwater can negatively influence the operation of wastewater treatment plants, since it introduces new pollutants and produces important variations on inflow quantity.
- **Water quality:** Potential pollutants carried in urban stormwater runoff can cause environmental deterioration.
- **Groundwater recharge:** The replacement of natural vegetation with impermeable surfaces reduces stormwater infiltration into aquifers.

Furthermore, stormwater interacts with other urban management sectors like transport, parks and recreation, waste management and urban development.

All these interactions are also important from an energy point of view. For instance, effective stormwater management can reduce the amount of both potable water needed and wastewater treated, which may result in lower energy consumption.

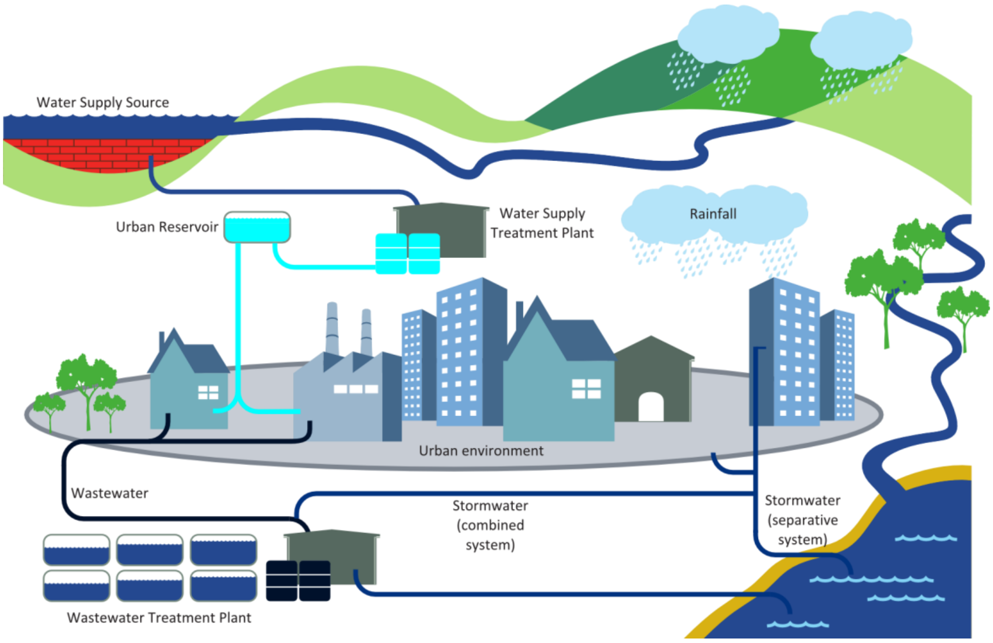


Figure 1.1. Typical urban water cycle. Adapted from (CM, 2009)

In this report, the different components of an urban drainage system are described, and the main features and advantages are developed. Next, some guidelines are explained to estimate the effect of using them on stormwater quantity and quality. Finally, guidance is provided to estimate the benefits and costs of stormwater management, considering the linkages between the different parts of the urban water cycle.

1.2. STORMWATER HYDROLOGY IN URBAN AREAS

City and stormwater are not, at first sight, always compatible, since the natural drainage systems (rivers, streams, wetlands, etc.) are modified and polluted by urban development (Philip, 2011b). When land is developed, the hydrology, or the natural cycle of water is altered. In general, urban development removes the vegetation that intercepts, slows and returns rainfall to the air through evaporation and transpiration. Terrain is flattened and natural depressions which slow and provide temporary storage for rainfall are filled. Therefore, rainfall that once seeped into the ground now runs off the surface. The addition of buildings, roadways, parking lots and other surfaces that are impervious to rainfall further reduces infiltration and increases runoff. Furthermore, development increases both the concentration and types of pollutants carried by runoff (ARC, 2001).

As can be observed in Figure 1.2, urban development produces higher and more rapid peak discharge, with higher runoff volume and a more rapid return to low flows. The alteration of natural flow patterns may lead to flooding and channel erosion downstream of the development. Moreover, the decrease in percolation into the soil can lead to low baseflows in watercourses and reduced aquifer recharge (Woods-Ballard *et al.*, 2007).

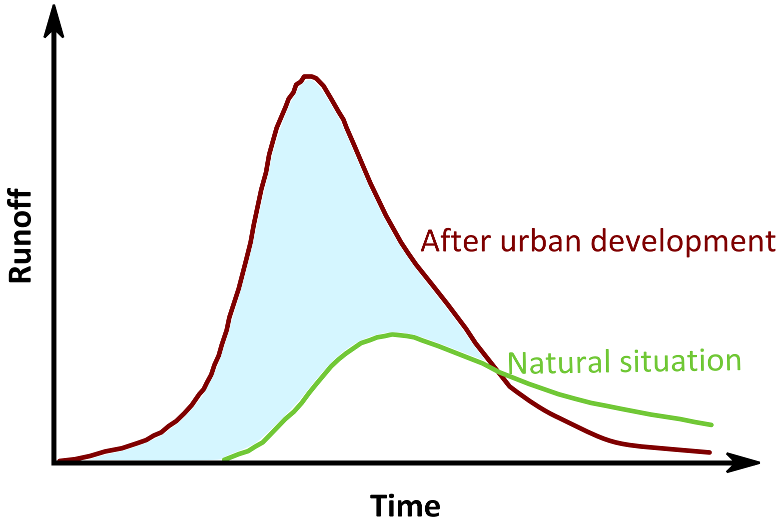


Figure 1.2. Runoff production in natural situation and after urban development.

In response to these changes in the local hydrology, cities have generally been designed to remove rainfall from the urban environment as rapidly as possible using drainage channels and underground pipes. Two types of **conventional drainage systems** are usually used (Philip, 2011b):

- **Combined sewer systems:** Stormwater is mixed with domestic and industrial wastewater before being treated in centralized wastewater treatment plants and released to a receiving water body.

- **Separate sewer systems:** Collect only stormwater and discharge it to a receiving water body with little or no treatment.

Conventional drainage systems are designed based on historical hydrologic data and their main purpose is to avoid urban flooding often with little considerations for downstream impacts.

In contrast to the conventional approach, **sustainable stormwater management** reduces the amount of impervious surfaces, disconnect flow paths and treat stormwater at its source, helping to minimize the impacts to local hydrology (USDHUD, 2003), as shown in Figure 1.3.

Sustainable stormwater management recognizes stormwater as a resource rather than a nuisance, providing tangible benefits like flood risk management, environmental protection, urban greening and the provisions of an alternative source of water supply (Philip, 2011b).

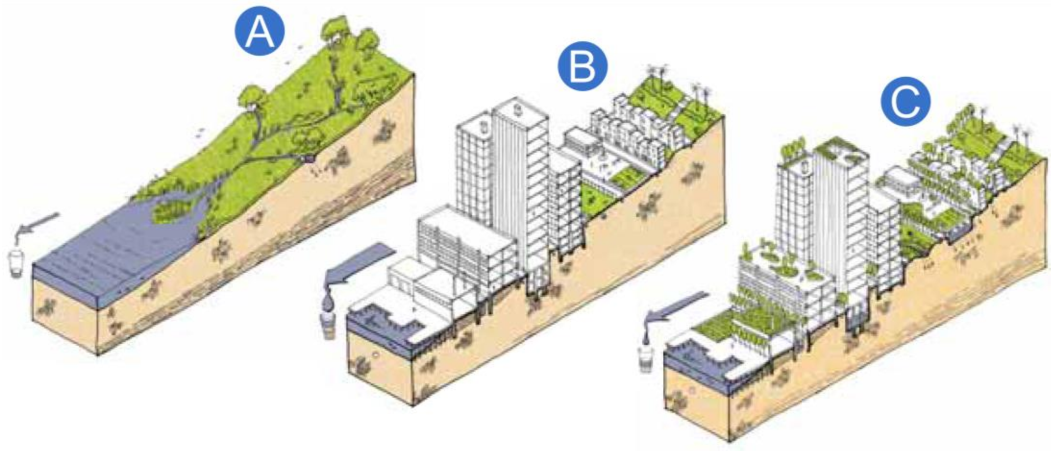


Figure 1.3. Hydrologic comparison of natural situation (A), conventional urban development (B) and sustainable urban development (C). Adapted from (SFPUC, 2009).

1.3. THE NEED FOR SUSTAINABLE STORMWATER MANAGEMENT

Some of the most important problems within urban drainage systems are (Philip, 2011b):

- **Combined sewer overflows:** Heavy rainfall causes combined sewer to exceed capacity, resulting in overflows of untreated wastewater release to the environment.
- **Diffuse pollution:** Non-point source pollutants as heavy metals, oils, nutrients and pesticides are dispersed by runoff into receiving water bodies.
- **Decreased base flow:** Increases in impervious surfaces decreases groundwater recharge.
- **Costs:** Centralized stormwater treatment is costly and energy intensive.
- **Heat island effect:** The rapid removal of urban stormwater reduces evapotranspiration, which results in a hotter urban microclimate.
- **Waste of a valuable resource:** If stormwater is rapidly removed from urban areas, it cannot be re-used for non-potable uses.
- **Downstream flooding:** The rapid collection and disposal of stormwater into receiving water bodies such as rivers and streams increases the risk of downstream flooding.

In addition to these problems, climate change might be a problem in the following years, since it might produce important impacts on urban drainage systems (Woods-Ballard *et al.*, 2007):

- More frequent periods of intense rainfall would increase runoff, particularly following periods of drought when land is hard and slow to absorb water.
- More intense rainfall events would increase flooding and the frequency of sewer overflows discharging untreated wastewater into the environment.

- Less annual precipitation would reduce the availability of water for groundwater recharge with consequent effects on water supplies and aquatic ecosystems dependent on groundwater.

Therefore, current problems of drainage systems may be worsened due to climate variability and larger urban developments. In order to solve these problems, urban drainage needs to move towards more flexible and adaptive approaches (Willems and Arnbjerg-Nielsen, 2013). Changing to a more sustainable approach can solve these problems and exploit the many benefits that stormwater can bring to a city.

Sustainable Drainage Systems (SuDS) are designed both to manage the risks resulting from urban runoff and to contribute to environmental and landscape improvement. SuDS objectives are, therefore, to minimize the impacts from the urban development on stormwater quantity and quality and maximize amenity and biodiversity opportunities (Woods-Ballard *et al.*, 2007), as shown in Figure 1.4. This type of systems can help to solve the previously described problems contributing to flood control, pollution control and providing an alternative source of water, as explained in section 0

Sustainable stormwater management changes the perception of stormwater from 'a nuisance that should be removed' to a 'resource that should be utilized'. The key differences with the conventional approach are (Philip, 2011b):

- With a conventional approach, stormwater is conveyed away from urban areas as rapidly as possible, whereas with a sustainable approach stormwater is retained and attenuated at source, allowing it to infiltrate into aquifers, if quality is good enough.

- Stormwater is not treated in a centralized wastewater treatment plant, but is treated using decentralized natural systems, such as soils, vegetation and ponds.

- A sustainable approach enhances the urban landscape and provides recreational opportunities.

- Stormwater is harvested for water supply and retained to recharge aquifers.

- Urban ecosystems are restored and protected.

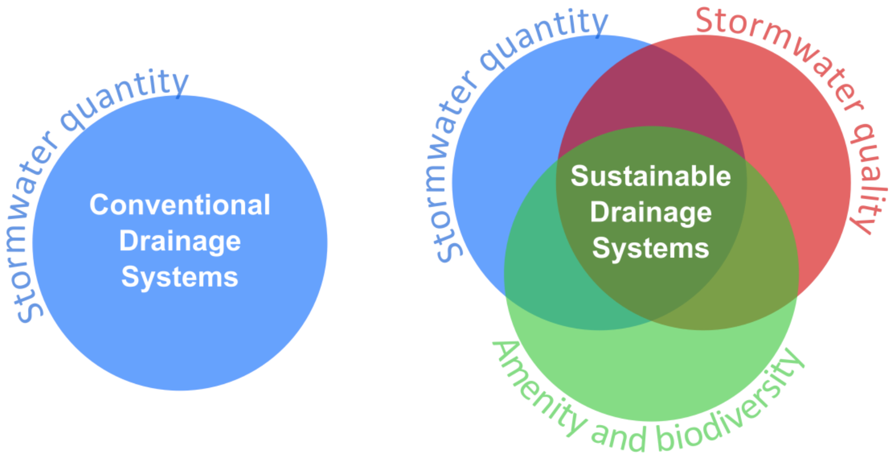


Figure 1.4. Comparison of objectives between Conventional Drainage Systems and Sustainable Drainage Systems.

More specifically, sustainable solutions for stormwater management can achieve one or many of the following benefits (Philip, 2011b):

- **Flood control:** The attenuation and infiltration of stormwater during heavy rainfall events reduces the peak runoff, which reduces the risk of overflows locally and downstream.
- **Pollution control:** Natural systems such as soils, vegetation and wetlands have different treatment capabilities that can be exploited in SuDS.
- **Protection against erosion:** SuDS reduce runoff velocity, avoiding erosion of riverbanks.
- **Alternative source of water:** Stormwater can be collected and reused either directly for non-potable purposes or, following treatment, for potable use.
- **Amenity value:** The construction of ponds and wetlands has the advantage of creating natural habitats, increasing biodiversity and providing recreational opportunities.
- **Climate change adaptation:** The use of natural systems to attenuate runoff provides greater flexibility to cope with flows from unexpectedly heavy rainfall.
- **Economic efficiency:** Many decentralized stormwater solutions are cheap to construct and maintain in comparison to conventional technologies.

International recommendations (EC, 2012; USEPA, 2008) have been developed to encourage the implementation of more sustainable, flexible and efficient drainage systems.

2. INFRASTRUCTURE FOR STORMWATER MANAGEMENT

Stormwater structure can be divided in two groups: conventional drainage systems and Sustainable Drainage Systems (SuDS). In this chapter, different types of drainage systems structure are presented. The following characteristics are defined for each:

- **Description:** General description of each type, indicating its main parts and how stormwater is managed.
- **Benefits and limitations:** Main benefits and limitations for each type.
- **Performance summary:** A performance chart to define the main characteristics of each drainage type:
    - **Runoff peak reduction:** Detention structures that help to reduce peak flow.
    - **Runoff volume reduction:** A runoff volume is delivered structure. Further, when stormwater is treated later, this volume reduction produces savings in water treatment costs.
    - **Construction cost:** A qualitative indicator of construction cost.
    - **Maintenance cost:** A qualitative indicator of maintenance cost.
    - **Urban environment and landscape:** Represents amenity and urban biodiversity benefit of each infrastructure.
    - **Pollution control:** Indicates the pollution removal efficiency of each infrastructure. It also indicates when they can help to avoid discharge from Combined Sewer Overflows.
    - **Buildings insulation:** Benefits of buildings thermal insulation improvement. These benefits are only produced by green roofs.
    - **Water reuse:** To indicate if stormwater can be reused for non-potable uses in households or for groundwater recharge.
- **Picture:** A picture of each type of infrastructure.
- **Design considerations:** General issues that must be taken into account to design each drainage infrastructure.
- **Operations and maintenance:** General guidelines for operation and maintenance of each infrastructure.
- **Approximate construction cost:** A best estimate and a range are provided for the unitary construction costs. These unitary values can be used to estimate infrastructure construction cost. These values are based on international guidelines according to project costs in other

countries, mainly United Kingdom and United States, as shown in Annex 1. They can only be used as a general guidance. To obtain more accurate data, a construction budget must be elaborated according to local conditions. Land take costs are not included in these unitary costs.

- **Approximate maintenance cost:** A best estimate and a range are provided for the unitary maintenance costs. These unitary values can be used to estimate infrastructure maintenance and operational costs. They are obtained from international guidelines and manuals, as shown in Annex 1, and they can only be used as a general guidance. To obtain more accurate data, a maintenance budget must be elaborated according to local conditions.

- **Approximate lifespan:** Estimated lifespan estimation.

- **More information and references:** References used to elaborate the data of each drainage type for further information.

2.1. CONVENTIONAL DRAINAGE SYSTEMS

Conventional drainage systems are designed to remove rainfall from the urban environment as rapidly as possible using drainage channels and underground pipes. In general, their main purpose is to avoid urban flooding. In this section, the different components types of conventional drainage systems are described:

- Urban impervious surfaces: Conventional roofs and pavement collect water and transport it to the drainage network. They are usually quite impervious. Data about impervious surfaces such as roofs and pavements are also included in this catalogue in order to compare them with green roofs and permeable pavements.

- Pre-treatment devices: Can be used to improve stormwater quality before it is transported through the drainage network. A general description of the most common types of devices is provided in this section.

- Pipe networks: Collect urban stormwater and convey it as rapidly as possible to the outflow point or treatment plant. There are two types of networks: combined with wastewater and separate

- Structural detention facilities: Underground stormwater storage tanks that can be used to reduce runoff peaks and floods downstream and to avoid releasing Combined Sewer Overflows and contaminated runoff first flush into the receiving water body.

- Treatment Plant: In combined systems, stormwater and wastewater are usually treated in a wastewater treatment plant before being released into the environment. In separate systems, stormwater is sometimes treated too. The types of treatments and their costs are analyzed in detail in Section 4.1. and 4.2.

2.1.1. Conventional roof

Description

A roof is the covering on the most upper part of a building, protecting it from rainfall. Conventional roofs are usually very impervious so they convey urban stormwater away quickly.

Roofs can be flat or sloping. Sloping roofs produced higher runoff rates. These structures have been included in this catalogue to compare conventional roofs with green roofs.

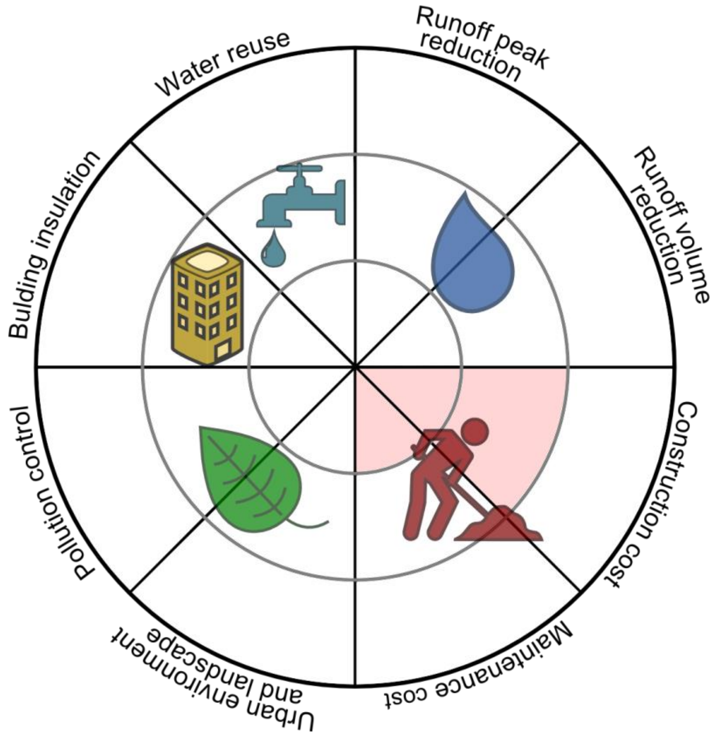
Benefits

- Their use is very widespread.
- The materials used are easily available.
- Rapid collection of stormwater, with less risk of standing water on roofs.

Limitations

- Runoff peak and volumes are higher due to impervious surfaces.
- They do not provide environmental value.

Performance summary



Figure

Figure 2.1. Conventional roof. Adapted from (KC, 2007).

Approximate construction cost	60 €/m^2	20-82 €/m^2
Approximate maintenance cost	0.4 €/m^2/year	0.16-1.2 €/m^2/year
Approximate lifespan (CNT, 2006)	23 years	15-30 years

2.1.2. Standard pavement

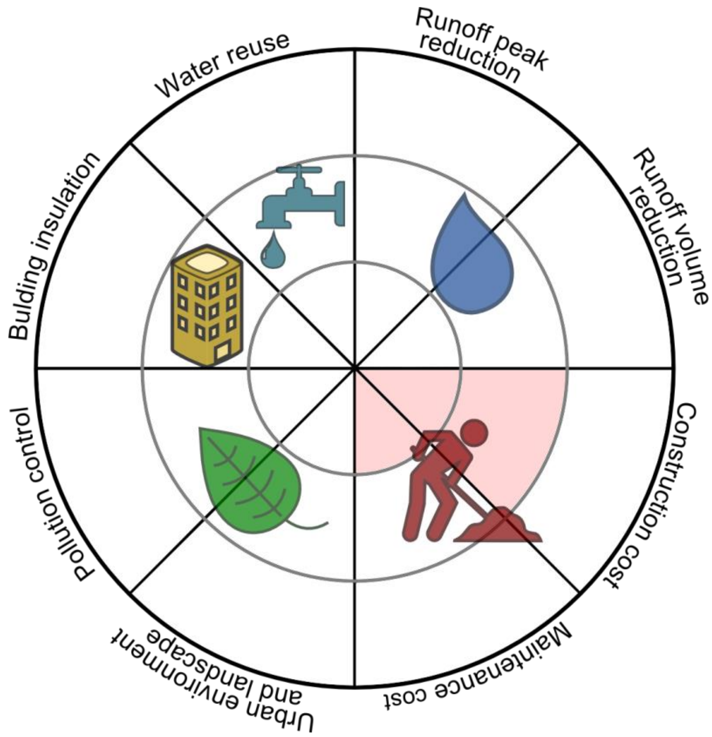
Description

Pavements are the surface materials laid down in urban areas to sustain the traffic of vehicles and pedestrians and include roads and walkways. In general, standard pavements are completely impervious and they do not allow water to infiltrate into the subsoil. Water is collected and introduced into the drainage network through kerbs and gutters.

Standard pavements are usually designed to convey urban stormwater away as quickly as possible using pavement gradients towards gullies and diches. These surfaces have been included to compare standard pavement with permeable pavements.

Benefits	Limitations
• Their use is very widespread. • The materials used are easily available. • Rapid collection of stormwater, avoiding flooding in streets and houses.	• Runoff peak and volumes are higher due to impervious surfaces. • Stormwater quality is not improved at source. • Stormwater is not reused. • They can produce downstream flooding due to the rapid collection and disposal of stormwater into receiving bodies.

Performance summary | **Figure**



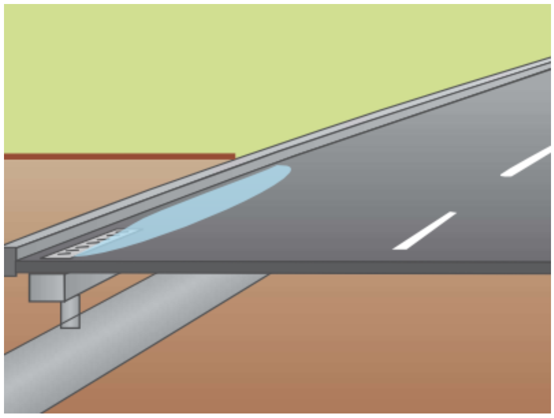


Figure 2.2. Standard pavement. Adapted from (KC, 2007).

Approximate construction cost	50 €/m^2	23-101 €/m^2
Approximate maintenance cost	0.45 €/m^2/year	0.4-0.5 €/m^2/year
Approximate lifespan (CNT, 2006)	35 years	20-50 years

2.1.3. Pre-treatment devices

Catch basin inserts

Catch basin inserts are manufactured filters, fabrics, or screens placed in a trench drain or catch basin to remove sediment and debris. They are inserted into standard kerb or grate inlets. Catch basin inserts are a flow-through separator technology, designed to provide treatment but not peak flow attenuation or volume reduction. There are three main types of catch basin inserts: socks, boxes, and trays. They can capture a high proportion of trash and litter.

Benefits

- They are relatively small and can easily be retrofitted into existing drainage infrastructures.
- They come in a wide range of sizes and can also be modified to capture other pollutants.
- They are constructed for easy access and some models can bypass high flows during peak storm.

Limitations

- Some models are susceptible to clogging under high loading.
- Peak flows could reintroduce trash into the system if not designed properly.
- Cleaning had to be done immediately before and during storm events.
- No aesthetic or habitat value.
- During heavy storms, they can reduce the inflow capacity of the drainage system.

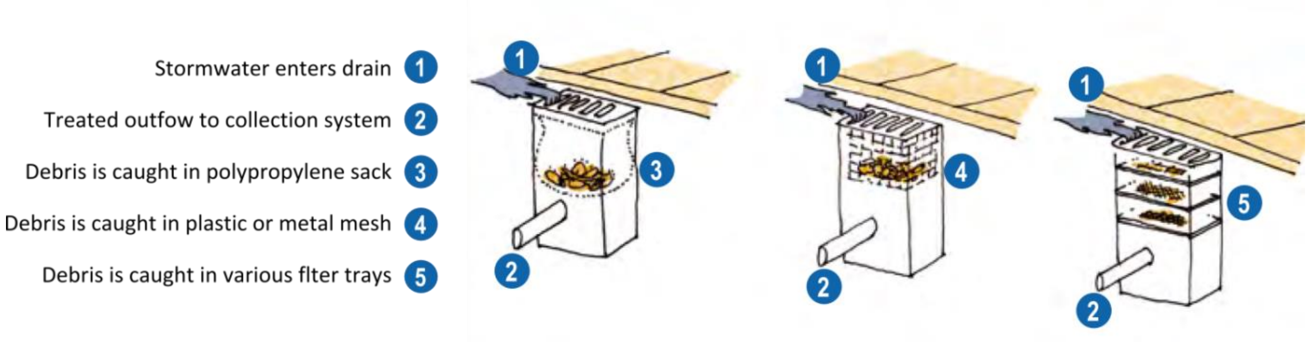


Figure 2.3. Catch basin inserts (SFPUC, 2009).

Hydrodynamic separators

Hydrodynamic separators are vault structures, with a gravity settling or separation unit to remove sediments and other stormwater pollutants. The water moves in a circular manner between inlet and outlet thus facilitating the sediment removal process within a small space. The forces created by the circular motion cause suspended particles to move to the centre of the device where they settle to the bottom. Manufacturers have developed several proprietary versions of hydrodynamic separators for stormwater treatment, all of which function differently and include different internal components.

Benefits

- Improves water quality by removing coarse sediment and floatables; some models remove oil and grease and attenuate peak flows.
- Low space requirements and good for sites where infiltration is not an option.
- Ideal as part of a treatment train.
- Low maintenance costs.

Limitations

- They are not effective in removing soluble pollutants and smaller, less-settleable solids.
- Some systems have standing water between storms that could raise mosquito breeding concerns.

- Relatively high capital and installation costs.
- No aesthetic and habitat value.

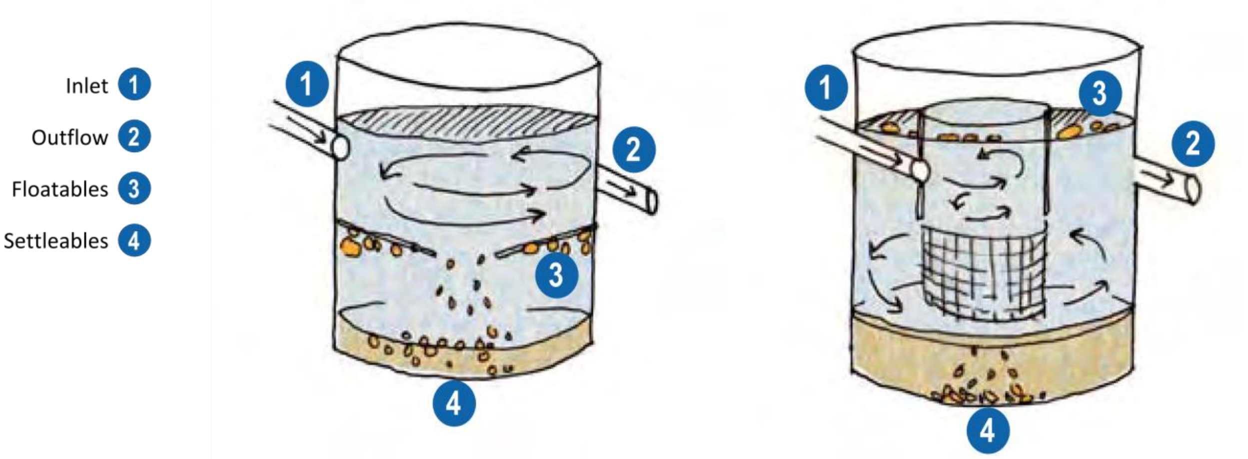


Figure 2.4. Hydrodynamic separators (SFPUC, 2009).

Screening devices

The simplest screening devices are catch basin screens, which are mesh wire or perforated plates that cover the openings of catch basins. They prevent gross solids from entering into the stormwater drainage system. There are also other more complex screen devices, like inline screening devices, which are vaults that contain some configurations of screens that filter gross-solids from stormwater. Gross-solids are held in a surrounding chamber so they do not accumulate on the street before removal by street sweeping activities.

Benefits

- Catch basin screens are relatively easy to install and are easy to retrofit into existing catch basins.
- These devices are ideal as part of a treatment train.
- They can help reduce or prevent drain pipe blockages.

Limitations

- Capital and installation costs of inline screening devices can be relatively high.
- They can contribute to flooding problems during high flows.
- Devices should be designed to eliminate standing water which can provide breeding habitat for vectors.
- Frequent maintenance requirements.

Figure 2.5. Screening devices main mechanism (SFPUC, 2009).

Media filters

Media filters detain and treat stormwater via filtration and adsorption of pollutants to the filter media. The most common filter media is sand (sand filters). They are generally two-chambered treatment devices consisting of a pre-treatment sedimentation area to remove larger solids and a filtration area to remove fine solids, metals, organics, and some bacteria. There are two general categories of sand filters: surface filters, which are at ground-level and typically earthen and perimeter filters, which are located in concrete vaults below an impervious surface.

Benefits

- Effective removal of suspended solids, oil and grease, debris, and other attached pollutants.
- Applicable in most soil types, appropriate in areas with poor infiltration.
- Easily customized to site size and dimension constraints.

Limitations

- Minimal stormwater volume reduction, some peak flow attenuation.
- Requires flat site and sufficient hydraulic gradient to support gravity flow.
- Limited ability to remove dissolved pollutants such as soluble metals such as copper and zinc.

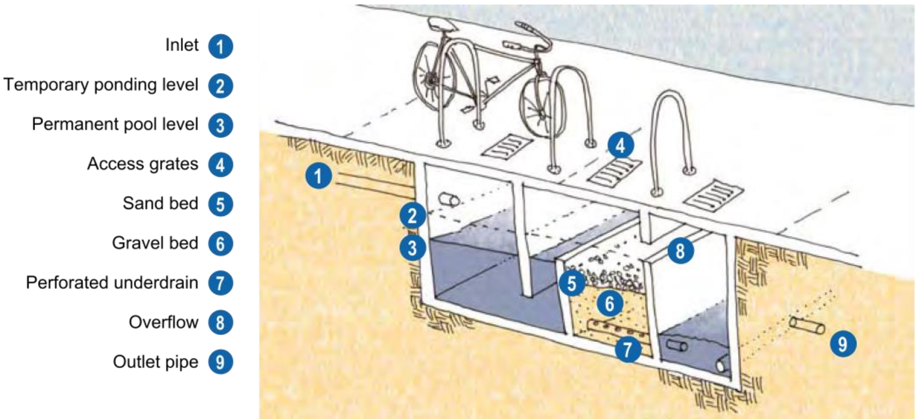


Figure 2.6. Perimeter sand filter (SFPUC, 2009).

Advanced filtration systems

More advanced filtration systems consist of specially designed underground concrete or prefabricated vaults. In these systems, there is an initial sedimentation process to remove larger particles. After this initial treatment, stormwater flows upwards through a filter media that removes oil and grease, metals and dissolved stormwater pollutants. Some devices also include a tertiary treatment with biofilms that digest organics and nutrients. Manufacturers have developed several proprietary versions of advanced filtration systems, all of which function differently and include different internal components.

Benefits

- A complete filtration system produces very high retention of pollutants and high water quality.
- Applicable in most soil types, appropriate in areas with poor infiltration.
- Low space requirements.

Limitations

- Minimal stormwater volume reduction and peak flow attenuation.
- Relatively high capital and maintenance costs.
- If not tertiary treatment is included, provides low to moderate level of nitrogen removal.

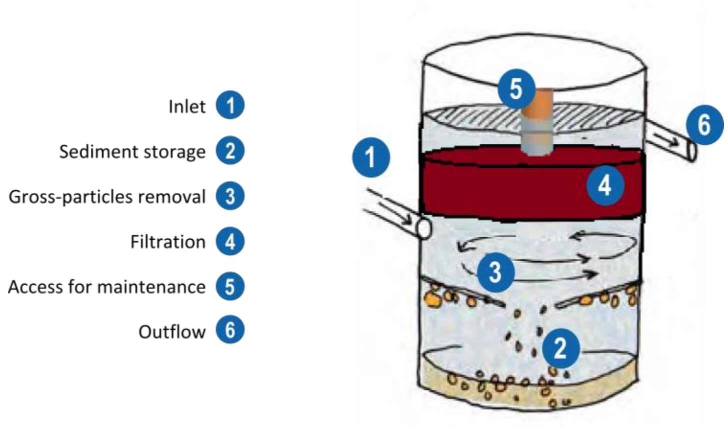


Figure 2.7. Example of advanced filtration system. Adapted from (SFPUC, 2009).

Water quality inlet

Water quality inlets consist of one or more chambers that promote settling of coarse materials and separation of oil from stormwater. Some devices also contain screens to help retain larger or floating debris. They are typically used in industrial areas. Most water quality inlet designs include three chambers: the first captures larger solids, the second traps oil, grease, and other floatables, and the final chamber collects and discharges the treated runoff.

Benefits

- Effectively traps trash, debris, oil and grease, and other floatables.
- Can provide spill control for contaminated or heavily polluted runoff.
- Effective as part of a treatment train to reduce the burden on downstream infrastructures.

Limitations

- Minimal peak flow or volume reduction.
- Limited removal of dissolved pollutants (e.g. nutrients, emulsified oil) and requires frequent cleaning.
- No aesthetic or habitat value.

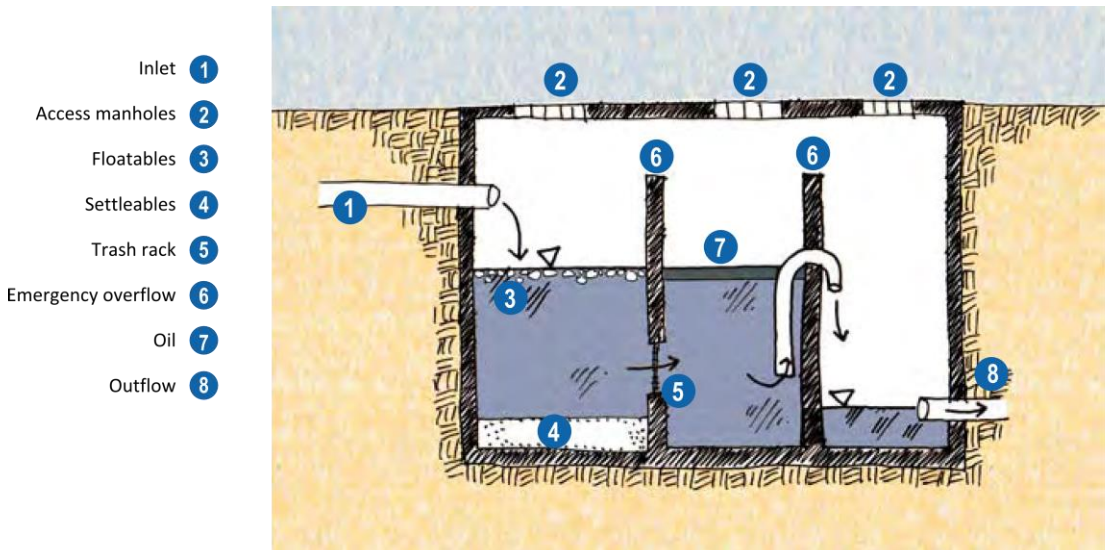


Figure 2.8. Water quality inlet (SFPUC, 2009).

More information and references

(Dierkes *et al.*, 2006), (NSWEPA, 1997), (SCVURPPP, 2007) (SFPUC, 2009), (Woods-Ballard *et al.*, 2007).

2.1.4. Piped networks

Description

Underground piped networks are usually designed to convey urban stormwater away as quickly as possible. These networks can be combined or separate:

- Combined sewer systems: Stormwater is mixed with domestic and industrial wastewater before being treated in centralized wastewater treatment plants and released to a receiving water body.
- Separate sewer systems: It collects only stormwater and discharges it to a receiving water body, usually with little or no treatment.

Piped networks are mostly designed based on available historical meteorological data and predicted urban development patterns. Kerbs and gutters introduce stormwater from the surface.

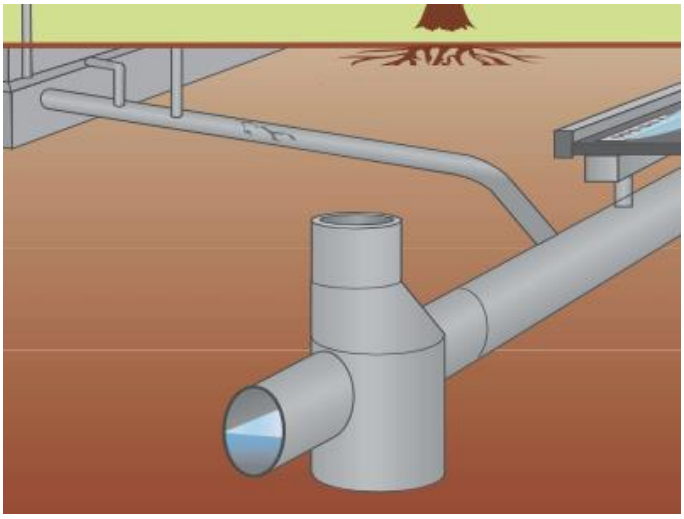


Figure 2.9. Pipe networks. Adapted from (KC, 2007).

Benefits

- Conventional piped networks are very simple, especially combined networks.
- Their use is very widespread.
- The materials used are easily available.
- Rapid collection of stormwater, avoiding flooding in streets and houses.
- Construction of combined systems is moderately cheap, since they use municipal/regional wastewater infrastructures for water treatment.
- Water can be treated in a Wastewater Treatment Plant.
- They can be combined with structural detention facilities to reduce runoff peaks.

Limitations

- In combined systems, their capacity can be exceeded producing wastewater release to the environment.
- Stormwater is not reused.
- Separate systems usually released stormwater directly into receiving water bodies without previous treatment, which can have an important environmental impact.
- They can produce downstream flooding due to the rapid collection and disposal of stormwater into receiving bodies.

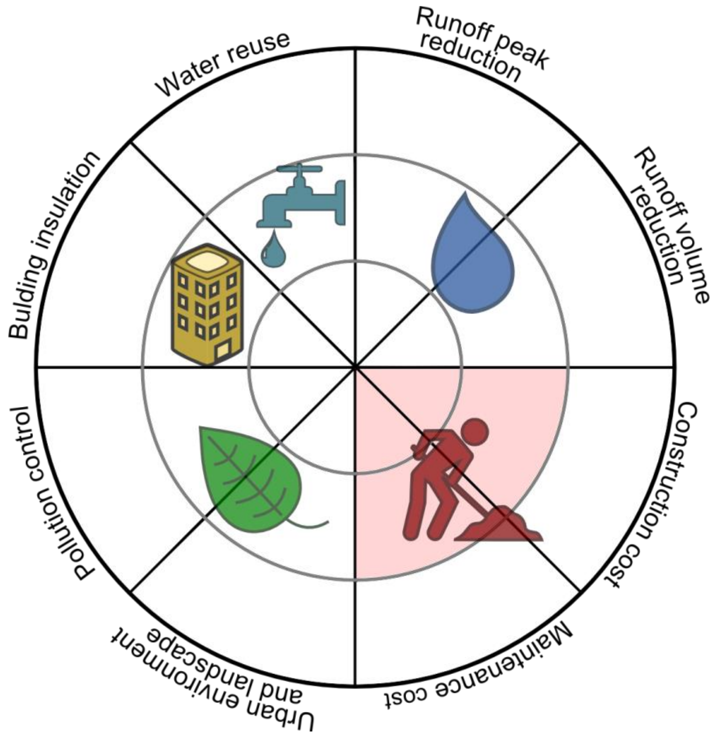
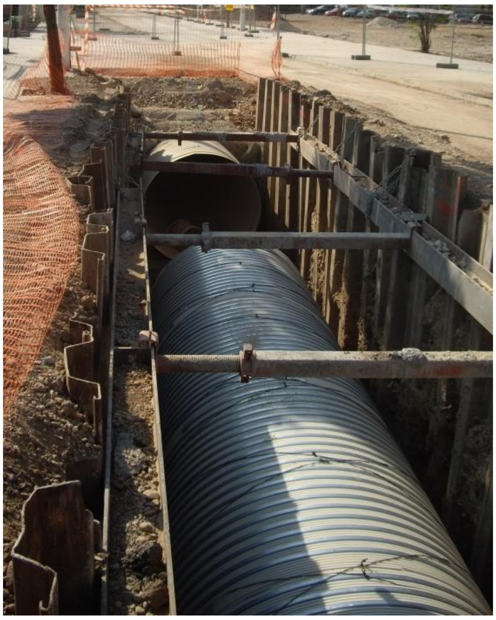
Performance summary	Picture
	

Figure 2.10. Pipe network construction in Sagunto, Spain.

Design considerations

The design of most conventional pipe networks was based on historical hydrologic data and its main purpose is to avoid urban flooding. In combined systems, its capacity should be enough to avoid frequent spillage from Combined Sewer Overflows. If a new combined sewer system were to be implemented, downstream impacts need to be considered in order to avoid downstream flooding.

Operations and maintenance

The two most important activities of sewerage maintenance are inspection and cleaning. Inspection is necessary to check that all parts are working properly and that there are no cracks and leakages of wastewater into the soil. Cleaning must remove sediments in order to maintain drainage system capacity. Sewerage must be designed to allow these two operations. This type of infrastructure may include pumping of stormwater, which normally increases operational costs and energy consumption significantly.

Approximate construction cost	200 €/m	50-400 €/m
Approximate maintenance cost	1 €/m/year	0.1-5 €/m/year
Approximate lifespan (CNT, 2006)	35 years	20-50 years
More information and references	(ARC, 2001), (Livingston *et al.*, 1997), (Potter, 1988), (Philip, 2011a), (Woods-Ballard *et al.*, 2007), (WSDE, 2012).	

2.1.5. Structural detention facilities

Description

Structural detention facilities are underground stormwater storage tanks typically made of reinforced concrete. They serve as an alternative to surface detention for stormwater quantity control, particularly for space-limited areas but their potential for treatment is very limited. These facilities can have two main purposes:

- Flood routing: Reducing runoff peak discharge to avoid flooding in downstream areas.
- Retention: In combined systems, they can be used to minimize the release of discharges from combined sewer overflows into receiving water bodies. In separate systems, they can be used to retain the first flush which will need further treatment. When designed properly in conjunction with other infrastructure components, structural detention can also help to control pollution.

Detention facilities are classified according to how they are connected to the sewer system. For detention tanks connected in series with the conveyance system, the term in-line storage is used. In contrast, storage facilities connected in parallel to the sewer system are termed off-line storage. With in-line detention, both dry and wet weather flow passes through the tank. The outlet for in-line detention facility has less capacity than the inlet, and consequently flow passes through the tank until the inflow rate exceeds the outlet capacity. The excess inflow is then stored within the tank until the inflow rate decreases, where the detained water empties through the outlet. Off-line storage is connected in parallel to the sewer pipe, and as such dry weather flow bypasses the storage tank, leaving the tank empty between storms. In this case, during storms, excess water is stored within the tank and is pumped to the collection system when the storm has passed.

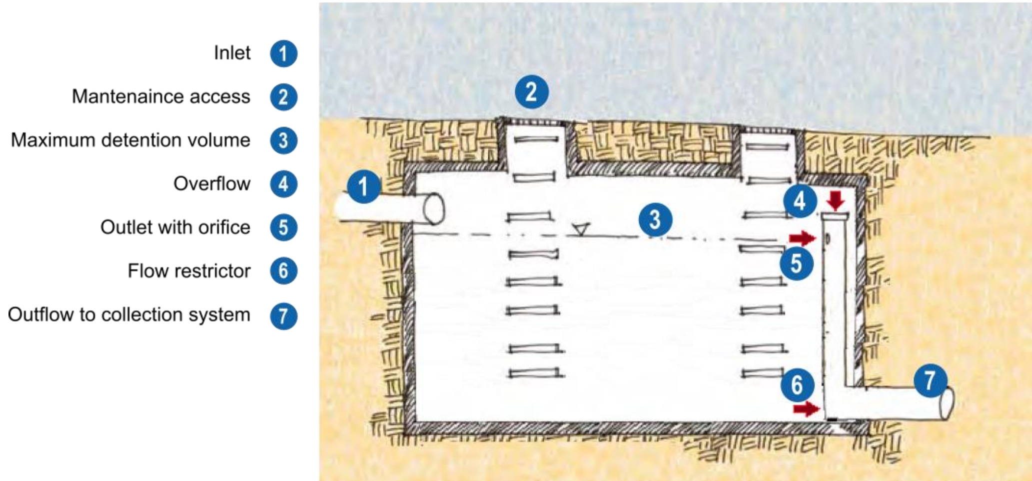


Figure 2.11. Parts of a detention facility. Adapted from (SFPUC, 2009).

Benefits

- Reduces flooding and peak flow rate.
- Can be placed underground in most areas.
- Advantageous in areas unsuitable for infiltration.
- Versatile, wide variety of appropriate scales and locations.
- Downstream infrastructure can be reduced in size because flow rates are lower.
- Avoids releasing into the receiving water bodies Combined Sewer Overflows and contaminated runoff first flush

Limitations

- Potentially high excavation and installation costs.
- Not beneficial to urban environment or landscape.
- Must be large enough to meet minimum confined space entry requirements for maintenance.
- Stormwater is not reused.

Performance summary	Picture

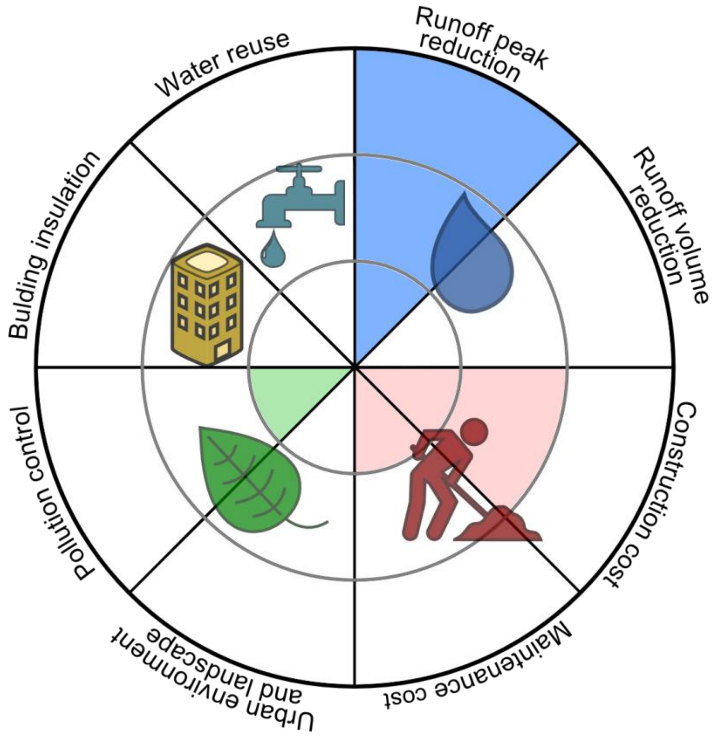


Figure 2.12. Structural detention facility in Valencia, Spain.

Design considerations

Detention facilities must be designed not only for their function as runoff flow control facilities, but also to withstand an environment of periodic inundation, potentially corrosive chemical or electrochemical soil conditions and heavy ground and surface loadings. Underground detention facilities must meet structural requirements for overburden support and traffic loading as appropriate.

Detention facilities typically do not usually have a design for containing sediment, as do multi-cell ponds. Therefore, when detention facilities are used for detention storage, either a sedimentation manhole or surface sediment containment pond shall be placed upstream of the detention structure or this structure shall be oversized to allow for the temporary accumulation of sediment. Another option is to install sediment removal (flushing) mechanisms inside the tank.

Operations and maintenance

Detention facilities should be large enough and accessible to allow maintenance operations. The two main maintenance activities are carrying out structural repairs to inlet and outlets when required and removing any trash/debris and sediment buildup in the underground tanks. Because accumulated sediment reduces treatment efficiency over time, this removal may be required after each important storm event.

Operational costs can be quite high if water needs to be pumped from the retention structure to the sewage network when the storm has passed (off-line storage), due to the water pumping costs, as explained in the Report on Energy in the urban water cycle (E^2STORMED project).

Approximate construction cost	400 €/m^3 stored volume	115-690 €/m^3
Approximate maintenance cost	1.5 €/m^3 stored volume/year	0.4-3 €/m^3/year
Approximate lifespan (estimation)	50 years	25-75 years
More information and references	(ARC, 2001), (CP, 2008), (GRUNDFOS, 2011), (SFPUC, 2009), (USDHUD, 2003).	

2.1.6. Treatment plants

Description

In conventional drainage networks, water is usually transported to treatment plants, where water quality is improved before being released into the environment. Treatment plants improve the water quality of stormwater before it is released into the environment. Depending on the type of drainage network (combined or separate), treatment plants can be divided in two groups:

- Wastewater treatment plants: In a combined drainage system, stormwater goes into the sewerage system and it usually delivers it to centralized facilities for intensive treatment before it is discharged to water bodies or land, or reused. The different wastewater treatment techniques and its costs are analyzed in detail in Section 4.1.
- Stormwater treatment plants: In some separate networks, stormwater is treated in centralized treatment plants. In general, these treatments are mainly primary treatments (filtering and sedimentation). Stormwater treatment is analyzed in Section 4.2.

Figure 2.13. Wastewater treatment plant in Xátiva (Spain).

Benefits	Limitations
• Their use is very widespread. • Water quality is improved. • They are very important to control pollution in receiving water bodies. • Treated water can be reused. • Simple centralized systems.	• Stormwater and wastewater do not have the same types of pollutants. These differences can reduce the treatment plant efficiency. • In combined systems, treatment plants capacity may not be enough during rainfall events and Combined Sewer Overflows may be produced. • Many decentralized stormwater solutions are cheaper to construct and maintain than conventional centralized technologies to treat run-off.

2.2. SUSTAINABLE DRAINAGE SYSTEMS

Sustainable Drainage Systems (SuDS) are designed both to manage the risks resulting from urban runoff and to contribute to environmental and landscape improvement. In practice, conventional drainage systems and SuDS can be mixed in management trains to get a sound stormwater management scheme. Stormwater management trains lie on drainage infrastructures in sequence that incrementally improve runoff water quality and reduce flow rates and volumes. Each drainage system infrastructure can be placed in one or several parts of the management train, as shown in Figure 2.14. The hierarchy of the infrastructures that should be considered in developing the management train is as follows (Woods-Ballard *et al.*, 2007):

- **Source control:** Control of runoff at or very near its source. Treating at source can result in smaller, less costly and more effective stormwater treatment facilities (SFPUC, 2009).

- **Site control:** Attenuation and treatment of runoff from a larger area. This management is made within the site boundary.

- **Regional control:** Management of runoff from a number of sites.

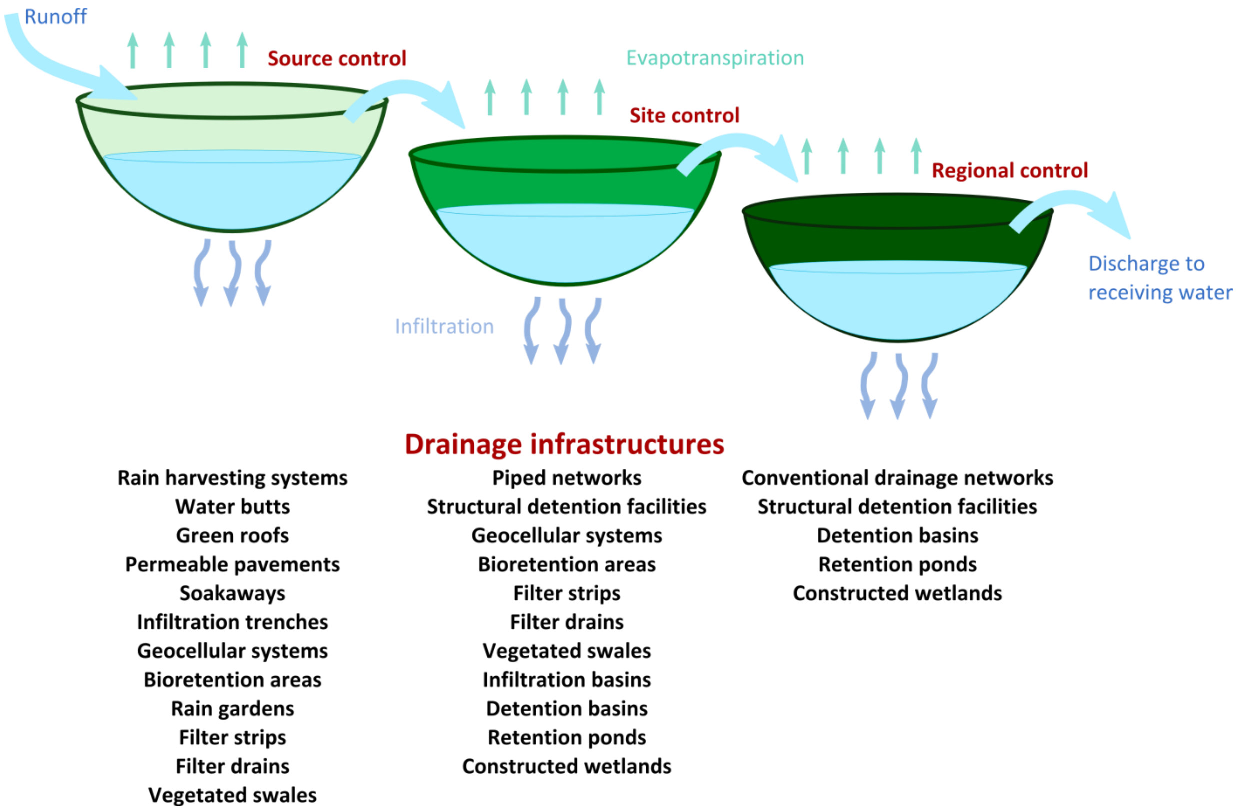


Figure 2.14. Stormwater management trains.

2.3.1. Rain harvesting systems

Description

Stormwater from roofs and impervious surfaces can be stored and reused in and around properties. With these systems, water collected is used for non-potable purposes, such as flushing toilets, washing machines and irrigation. There are three different types of rainwater harvesting systems:

- **Direct system:** The water is pumped from the storage tank via a submersible pump direct to the outlets in and around the building.
- **Gravity system:** The water is pumped from the storage tank via a submersible pump into a header tank. From there the water is gravity fed to the outlets.
- **Centralized system:** The pump is located in the building. If there is a requirement for water, it is drawn from the tank into the building and then supplied to the outlets.

This factsheet refers to complex rainwater harvesting systems. The simplest rainwater harvesting systems (water butts) are explained in the next section.

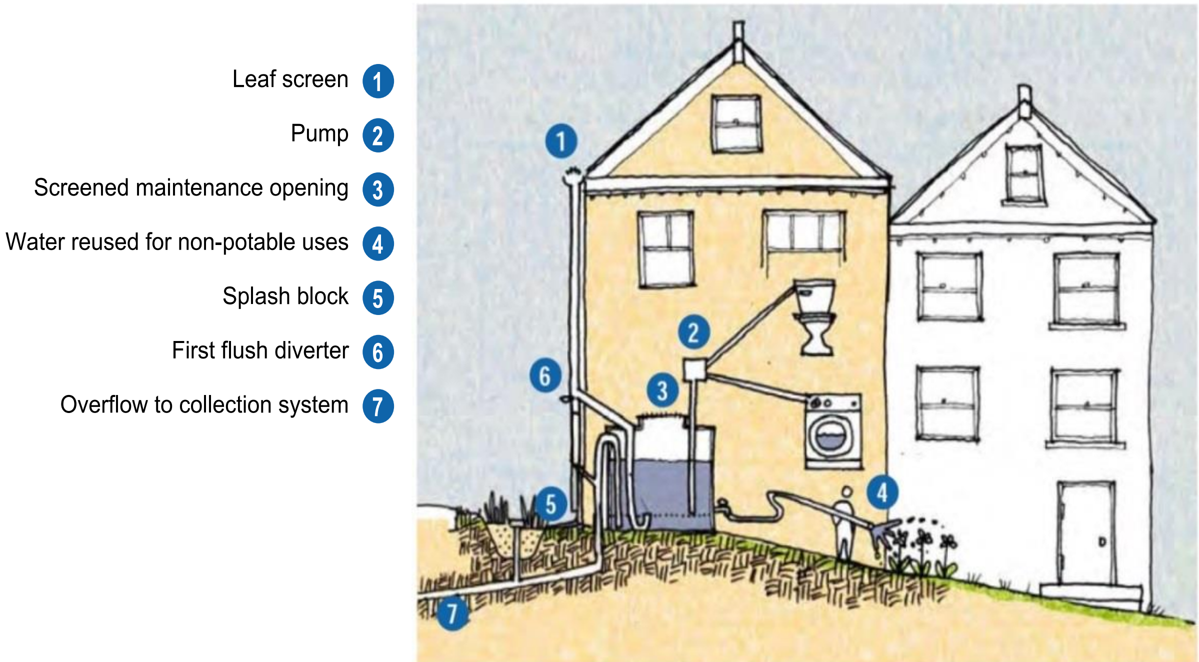


Figure 2.15. Parts of a rainwater harvesting system (SFPUC, 2009).

Benefits	Limitations
• Offsets the volume of potable water used for non-potable applications. • Keeps relatively clean water out of the collection system, thereby enhancing the performance of the sewer infrastructure. • Reduces the volume and peak flows of stormwater entering the sewer. • Reduces the energy consumed transporting and treating potable water. • Good for sites where infiltration is not an option.	• Limited storage capacity. • Requires added components (pumps or valves) to use stored water. • Systems can be complex and costly to install. • There might be health risks if drinking harvested rain water.

Performance summary	Picture

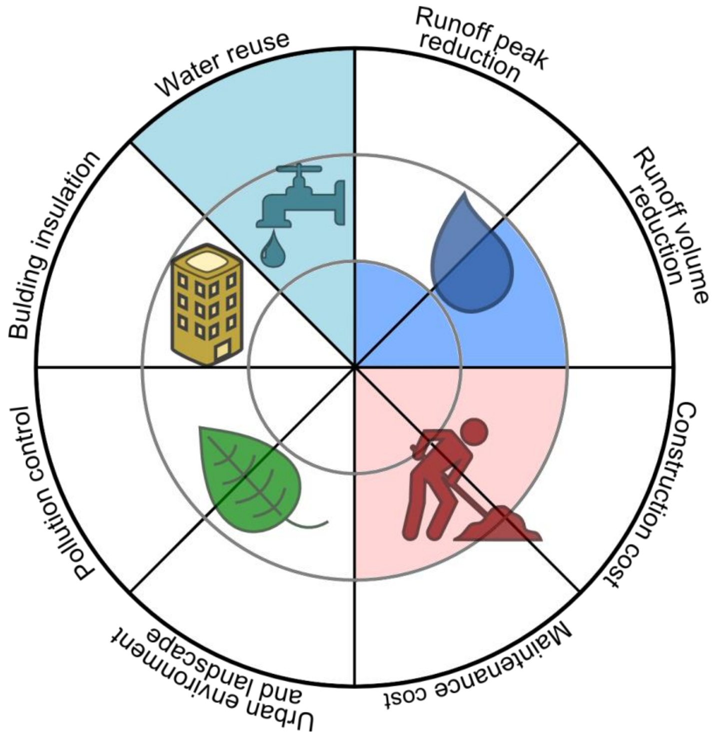


Figure 2.16. Rainwater harvesting system in Coventry (United Kingdom).

Design considerations

Rainwater harvesting systems can also be used to provide potable water but a sophisticated water treatment system may be necessary to ensure compliance with potable water quality standards.

Proper design and sizing of the rainwater harvesting system is critical to ensure full peak flow benefits. The storage tank volume must be sized according to the water demand, the catchment area, the seasonal rainfall pattern, the retention time and the cost.

Prior to harvesting rainwater from the roof, the roof must be cleaned, and the downspout must be disconnected from the sewer and connected to the rainwater harvesting system. Rain barrels and cisterns should be made of opaque material to prevent light from entering the container to avoid algal growth. All openings should be screened to prevent litter and mosquitoes or other disease vectors from entering. Generally, cisterns have an access on top that allows maintenance and monitoring.

Operations and maintenance

Semi-annual inspection is advisable to confirm that all parts are operable and not leaking. Rainwater harvesting systems, including drainage management area and gutters, must be kept clear of debris, and all screens must be properly maintained to prevent mosquitoes and other vectors from breeding. Rain barrels and cisterns should be cleaned annually with a non-toxic cleaner.

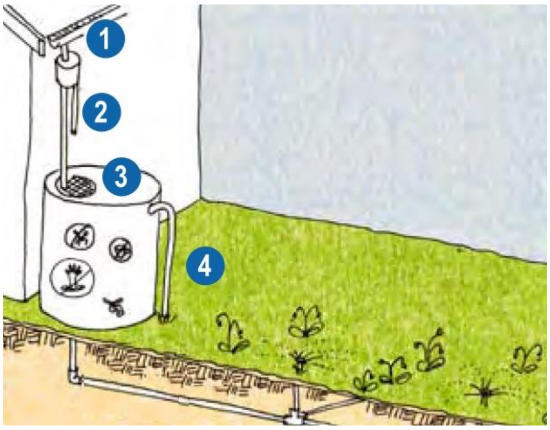
Approximate construction cost	250 €/m^3 capacity	200-400 €/m^3
Approximate maintenance cost	70 €/m^3 capacity	20-300 €/m^3/year
Approximate lifespan (CNT, 2006)	30 years	20-50 years
More information and references	(CP, 2008), (SCSMC, 2010), (SFPUC, 2009), (TWDB, 2005), (Woods-Ballard *et al.*, 2007).	

2.3.2. Water butts

Description

Water butts are the most simple and common type of infrastructure for rainwater harvesting. They are small, off-line storage devices which capture and store runoff. A water butt collects rainwater runoff from roofs via an inlet that is connected to the down-pipe. The butt is normally constructed from polyethylene, which is often sourced from recycled material. Water butts are manufactured in a wide variety of sizes and some models consist of inter-connectable units.

Water stored in butts is typically used for irrigation, vehicle washing, or other non-potable applications. Rain barrels are inexpensive, easy to install and maintain, and well suited to small-scale residential sites.



1. Screen on gutter prevents large debris from entering cistern
2. First flush diverter
3. Screened access prevents mosquite breeding
4. Overflow to collection system

Figure 2.17. Parts of a water butt. Adapted from (SFPUC, 2009).

Benefits	Limitations

Benefits

- Easy to construct, install and operate.
- Can offset the volume of potable water used for non-potable applications.
- Keeps relatively clean water out of collection systems, thereby enhancing the performance of the infrastructure.
- Reduces the volume and peak flows of stormwater entering the sewer.
- Reduces the energy expended transporting and treating potable water.
- Low maintenance and construction requirements.
- Good for sites where infiltration is not an option.

Limitations

- Limited storage capacity.
- Very limited water quality improvements.
- During the rainy season, it can be difficult to use the stored water because irrigation is generally not necessary.
- High risk of blockage of small throttles.
- It only reduces stormwater runoff from roofs.
- During wet periods, water butts are often full, resulting in low attenuation of runoff.

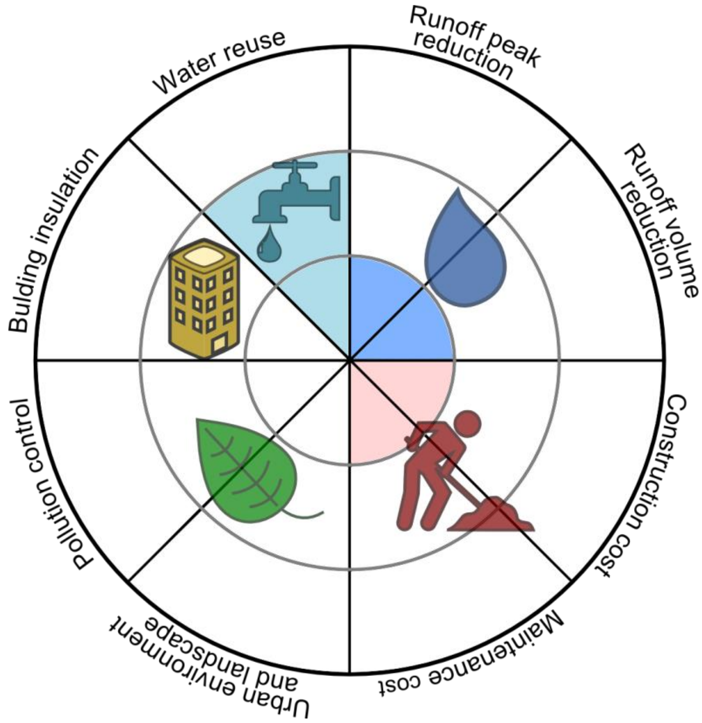
Performance summary	Picture
	

Figure 2.18. Water butts in Xàtiva (Spain).

Design considerations

Water butts are best-suited to low and medium density residential housing, where rainwater is regularly used for garden watering.

Water butts should be made of opaque material to prevent light from entering the container. This will avoid algae growth. All openings should be screened to prevent litter and mosquitoes or other vectors from entering. Water butts must have a firm base that is strong enough to withstand the weight of the full container and should be appropriately fixed to prevent it falling over. Water butts should be easily cleaned. They can be placed underground, in which case pumping will be required.

Operations and maintenance

Water butts are low maintenance devices. They should be cleaned annually with a non-toxic cleaner. Annual inspection is advisable to confirm that all the parts are operable and not leaking.

Water butts must be kept clear of debris, and all screens must be properly maintained to prevent mosquitoes and other vectors from breeding.

Approximate construction cost	250 €/m^3 capacity	145-1082 €/m^3
Approximate maintenance cost	1 €/m^3 capacity	0-5 €/m^3/year
Approximate lifespan (CNT, 2006)	30 years	15-50 years
More information and references	(CP, 2008), (NYSDEC, 2010), (SCSMC, 2010), (SFPUC, 2009), (TWDB, 2005), (Woods-Ballard *et al.*, 2007).	

2.3.3. Green roofs

Description

A green roof is a vegetated roof system that filters, absorbs, and retains or detains the rain that falls upon it. Green roofs comprise a layer of soil media planted with vegetation over a waterproofing membrane. They may also include additional layers such as a root barrier and drainage and irrigation systems. Green roofs serve several purposes for a building, such as absorbing rainwater, providing thermal insulation, creating a habitat for wildlife, and helping to lower urban air temperatures and mitigate the heat island effect. There are two types of green roofs:

- **Intensive roofs:** They are thicker and can support a wider variety of plants, but are heavier and require more maintenance.
- **Extensive roofs:** They are covered in a light layer of vegetation and are lighter than an intensive green roof. This is the type usually used for stormwater management.

Water is stored in the substrate of a green roof and then taken up by the plants from where it is returned to the atmosphere through transpiration and evaporation. When the soil media becomes saturated during rainfall events, the excess water percolates through to the drainage layer and is discharged through the roof downspouts. Green roofs can provide high rates of rainfall retention and decrease the peak flow rate because of the temporary soil storage during discharge events. Furthermore, the layer of vegetation provides effective insulation of a building, preventing the escape of heat during cold weather and keeping the interior cool during hot weather.

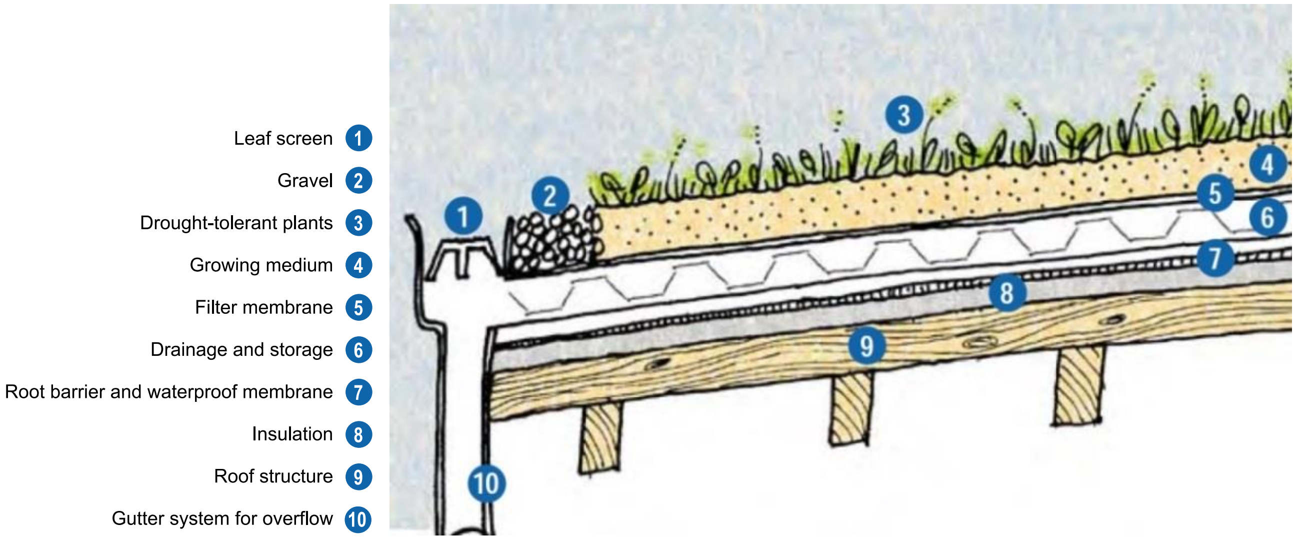


Figure 2.19. Parts of a green roof (SFPUC, 2009).

Benefits	Limitations
• Provides insulation and can lower heating and cooling costs for the building. • Extends the life of the roof. • Provides noise reduction. • Reduces the urban heat island effect. • Creates habitat and increases biodiversity in the city. • Provides aesthetic and recreational amenities. • Reduces runoff volume and attenuates peak flows.	• Generally limited to roof slopes shallower than 20 degrees. • May require additional structural support to bear the added weight. • Irrigation may be necessary to establish plants and maintain them during extended dry periods. • Vegetation requires maintenance without which it can look overgrown or weedy.

Performance summary	Picture

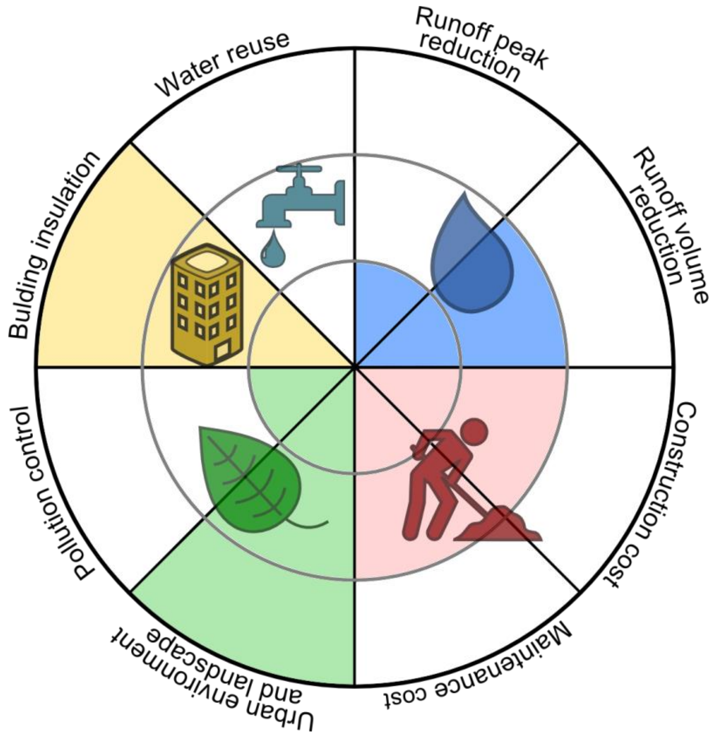


Figure 2.20. Greenroof in Xàtiva (Spain).

Design considerations

An intensive vegetated roof may consist of shrubs and small trees planted in deep soil arranged with walking paths and seating areas. In contrast, an extensive vegetated roof includes a shallow layer of soil with low-growing vegetation (such as serums) and is more appropriate for roofs with structural limitations. Ideal vegetation for vegetated roofs has the following characteristics: drought tolerance, self-sustainability, ability to survive over a range of temperatures and moisture conditions, minimal maintenance requirements, fire resistance, and perennial life cycle.

All vegetated roofs are assembled in layers. The top layer includes the soils and the plants. The soil is a lightweight mix that includes some organic material. Under the soil there is a drainage layer that includes filter fabric to keep the soil in place and a core material that stores water and allows it to drain off the roof surface. Next is the root barrier, which prevents roots from puncturing the waterproof membrane that lies below it, then a layer of insulation, and finally the roof structure.

Operations and maintenance

In the first few years watering, light weeding, and occasional plant feeding will ensure that the roof vegetation becomes established. Routine inspection of the waterproof membrane and the drainage systems is important to the roof longevity.

The most important maintenance operations are removing debris and litter to prevent clogging of inlet drains, removing nuisance and invasive vegetation and replacement of dead plants as required.

Approximate construction cost	145 €/m^2	48-205 €/m^2
Approximate maintenance cost	15 €/m^2/year	0.2-45 €/m^2/year
Approximate lifespan (CNT, 2006)	40 years	25-50 years
More information and references	(ARC, 2001), (Philip, 2011b), (SCSMC, 2010), (SFPUC, 2009), (VanWoert *et al.*, 2005), (Woods-Ballard *et al.*, 2007).	

2.3.4. Permeable pavements

Description

Permeable pavements provide a pavement suitable for pedestrians and/or vehicles, while allowing rapid infiltration of water into the soil or a reservoir. This reservoir provides temporary storage as runoff infiltrates into underlying permeable soils and/or out through an underdrain system. There are two main categories of pervious pavements:

- **Pervious asphalt and pervious concrete:** Similar to conventional asphalt and concrete in structure and form, except that the fines (sand and finer material) have been removed. The top layers are thicker than traditional pavements to provide the required stability.
- **Permeable pavers:** Structural units, such as concrete blocks, bricks, or reinforced plastic mats, with regularly dispersed void areas used to create a load-bearing pavement surface. The void areas are filled with pervious materials (gravel, sand, or grass turf) to create a system that allows for the infiltration of stormwater runoff.

Permeable pavements have very good removal of both soluble and particulate pollutants, where they become trapped, absorbed or broken down in the underlying soil layers.

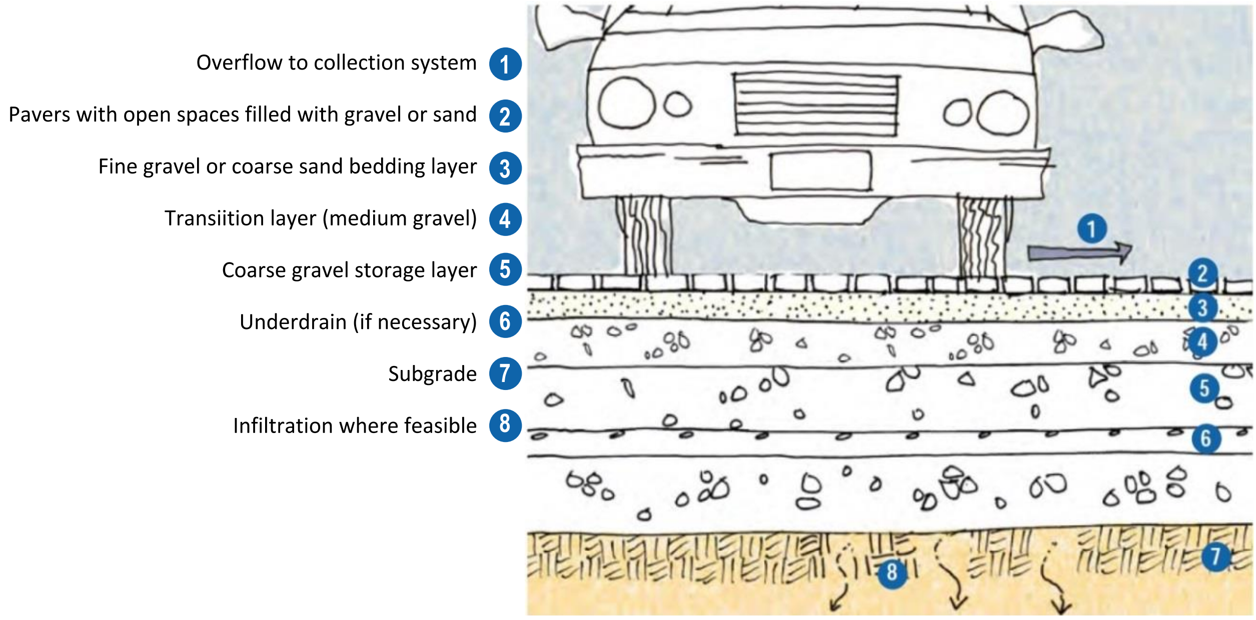
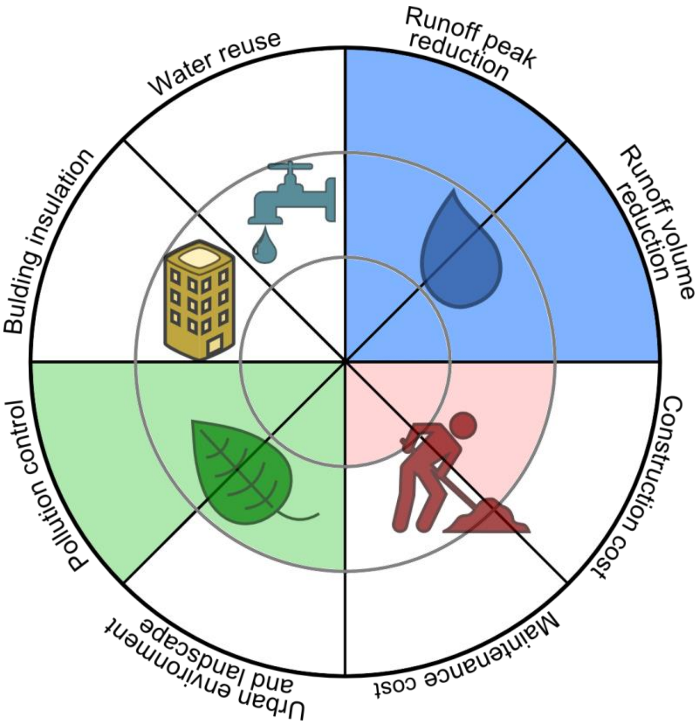


Figure 2.21. Permeable pavement (SFPUC, 2009).

Benefits	Limitations
• Reduces runoff volume and attenuates peak flow. • Improves water quality by reducing fine grain sediment, organic matter, and trace metals. • If the underlying soil and rock is appropriate, they facilitate groundwater recharge. • May increase driving safety by reducing ponding. • Construction costs can be comparable or less than for traditional paving.	• Limited to paved areas with slow and low traffic volumes. • Maintenance costs can be greater than for traditional paving. • Infiltration feasibility needs to be checked (Section 3.1.).

Performance summary	Picture
	 *Figure 2.22. Pervious asphalt in Benaguasil (Spain).*

Design considerations

Permeable pavements are typically used in low-traffic areas (car parks, small roads, etc.). They should not be located over cisterns, utility chambers, underground parking, or impervious surfaces. They are typically used in applications where the pavement only receives additional runoff from impervious areas. If runoff is coming from adjacent pervious areas it is important that those areas be fully stabilized to reduce sediment loads and prevent clogging of the permeable surface.

Slopes should be flat or gentle to facilitate infiltration. The design surface infiltration rate should be significantly greater than the design rainfall intensity to avoid surface water ponding. The infiltration rate of the soils in the subgrade (or, in its case, the underdrain) should be adequate to support drawdown of the entire runoff capture volume within 24 to 48 hours. Special care must be taken during construction to avoid undue compaction of the underlying soils which could affect the soils' infiltration capability.

Operations and maintenance

The permeable surfaces require specialized vacuuming at least once a year to remove fine particulates from the infiltration spaces. This maintenance must be carried out with high-power vacuums. Without this maintenance, the facility will become impervious over time. Additionally, some settling may occur over time, requiring additional aggregate base, washed sand, and/or paver replacement and repair.

Approximate construction cost	60 €/m^2	14-82 €/m^2
Approximate maintenance cost	1 €/m^2/year	0.08-3 €/m^2/year
Approximate lifespan (CNT, 2006)	30 years	20-40 years
More information and references	(ARC, 2001), (CP, 2008), (SCSMC, 2010), (SFPUC, 2009), (Woods-Ballard *et al.*, 2007).	

2.3.5. Soakaways

Description

A soakaway, also called dry well, is an underground stormwater storage structure with no outlet other than percolation to the soil. Soakaways collect stormwater and allow it to infiltrate into the surrounding soil for groundwater recharge, much like infiltration trenches. However, while infiltration trenches tend to be long narrow at the surface, soakaways are vertical holes dug into the ground. There are two main types of soakaways:

- **Unlined soakaways:** Consist of an earth pit filled with gravel or riprap. Such pits resist collapse but their storage capacity is limited because their interior column is filled with crushed stone. These soakaways are prone to sediment clogging, but are less expensive to construct.
- **Lined soakaways:** Are typically contained by a reinforced concrete cylinder with perforated sides and bottom, allowing greater storage volume. Lined soakaways differ from infiltration basins in that they are underground and tend to be smaller.

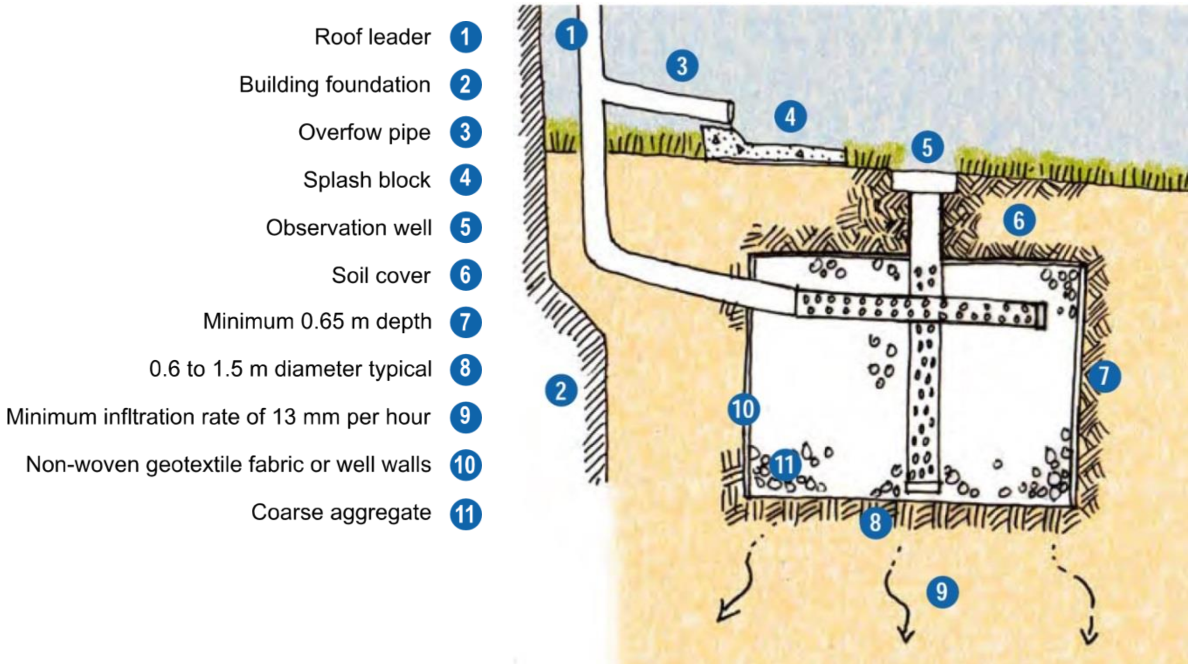


Figure 2.23. Parts of a soakaway. Adapted from (SFPUC, 2009).

Benefits

- Reduces runoff volume and rate and attenuates peak flows.
- Improves water quality - good for removing fine sediment and adsorbed pollutants.
- Enhances groundwater recharge and contributes to stream base flow.
- Minimal space requirements.
- Visually unobtrusive.
- Easy to construct and operate.

Limitations

- Not suitable when infiltration is not feasible (see Section 3.1.).
- Potentially expensive in dense urban areas because they are underground.

Performance summary	Picture

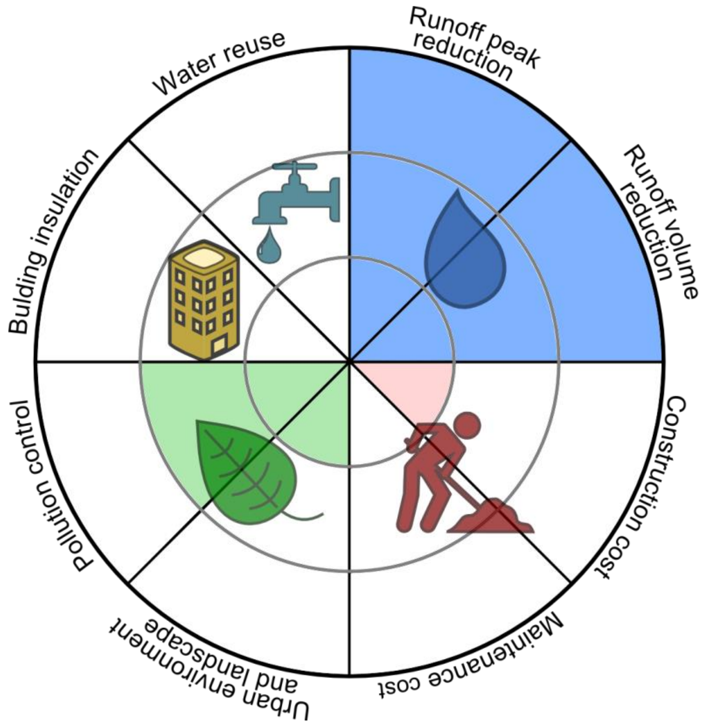


Figure 2.24. Construction of a soakaway in Barcelona (Spain).

Design considerations

Soakaways are best-suited to the infiltration of stormwater from small areas such as roofs of residential housing. They are also commonly located next to roads. In general, they are not appropriate for sites that use or store chemicals or hazardous materials, unless those materials are prevented from entering the soakaway, and only pre-treated runoff should be considered for infiltration to sensitive groundwater resources. A geotechnical investigation should ascertain how the stormwater runoff will move in the soil both horizontally and vertically, accounting for any geological conditions that could inhibit water movement or could produce flooding of other urban areas.

Soil conditions are critical to the success of soakaways. Because of this, an infiltration test or bore-log feasibility test must be performed. The soakaways should discharge from full to half-volume within 24 hours so that sufficient capacity is available to receive runoff from subsequent storms.

Operations and maintenance

The longevity of Soakaways can be increased by careful geotechnical evaluation prior to construction, and by designing and implementing an inspection and maintenance plan. Soakaways should only be constructed after the entire area draining to the facility has been stabilized. Care should be taken during construction to divert sediment-laden runoff away from the well. Good construction practice should minimize over-compaction, sediment generation, and smearing.

Approximate construction cost	150 €/m^3 stored volume	107-242 €/m^3
Approximate maintenance cost	5 €/m^3 stored volume/year	0.1-24.2 €/m^3/year
Approximate lifespan (estimation)	30 years	20-50 years
More information and references	(CP, 2008), (SCSMC, 2010), (SFPUC, 2009), (Woods-Ballard *et al.*, 2007).	

2.3.6. Infiltration trenches

Description
An infiltration trench is a shallow trench in permeable soil that is lined with filter fabric and backfilled with washed rock. The trench surface may be covered with grass, stone, sand, or plants. They collect runoff during a storm event, store it in the void spaces within the stones, and release it into the soil by infiltration. By diverting runoff into the soil, an infiltration trench not only treats the water quality volume, but also helps to preserve the natural water balance on a site and can recharge groundwater and preserve baseflow. Infiltration systems are limited to areas with highly porous soils where the water table and/or bedrock are located well below the bottom of the trench. Using the natural filtering properties of soil, infiltration trenches can remove a wide variety of pollutants from stormwater through sorption, precipitation, filtering, and bacterial and chemical degradation.

Ideally a pre-treatment device (such as a filter strip or grassed area) should be incorporated to increase the longevity of the system. It is also an option to add a geotextile layer just below the surface to trap silt and stop it from clogging the gravel deeper in the trench. Inspection manholes should be located at regular intervals along the length of the device.

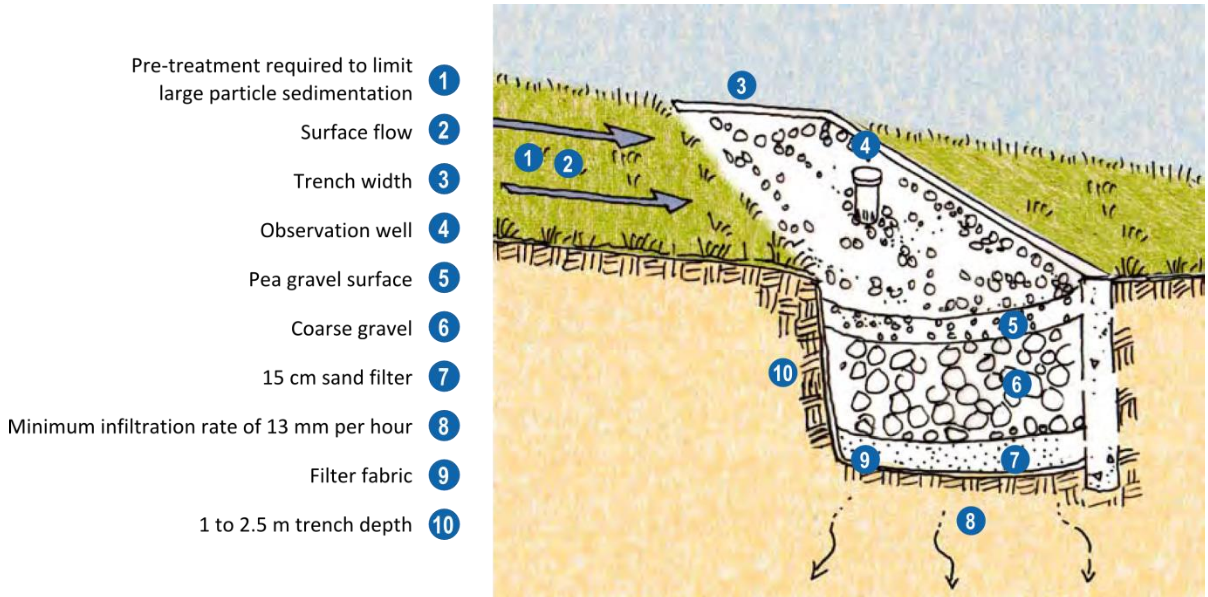


Figure 2.25. Parts of an infiltration trench. Adapted from (SFPUC, 2009).

Benefits	Limitations
• Improves water quality by removing sediment, nutrients, organic matter, and trace metals. • Can significantly reduce runoff rates and volumes. • Enhances groundwater recharge and contributes to stream base flow. • Can be incorporated easily into site landscaping and fit well besides roads.	• Limited to relatively small catchments. • Not suitable when infiltration is not feasible (see Section 3.1.). • High historic failure rate due to poor maintenance, wrong siting or high debris input. • Build-up of pollution/blockages is difficult to see.

Performance summary	Picture

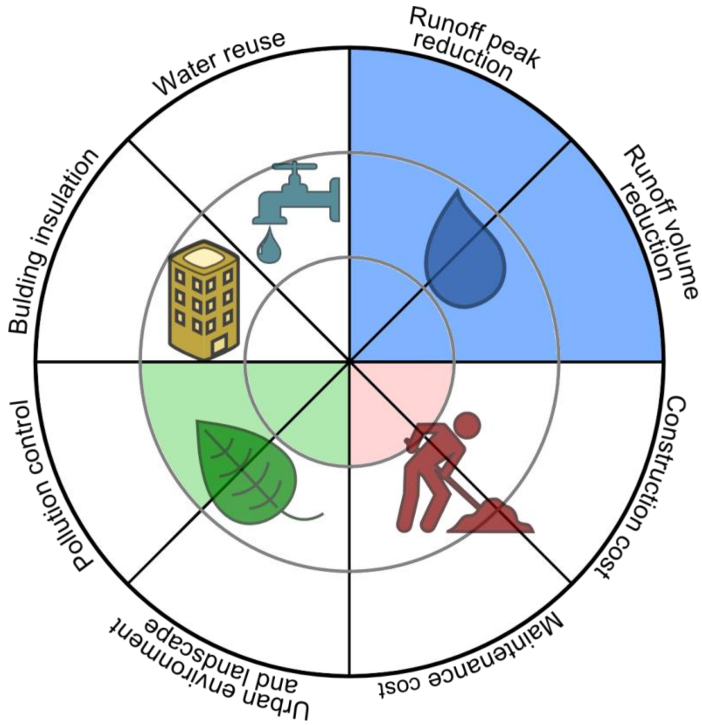


Figure 2.26. Infiltration trench in Hamburg (Germany).

Design considerations

Infiltration trenches are typically located in open spaces next to roads (preceded by filter strips) and car parks. Infiltration trenches can drain areas up to 4 hectares. They cannot be subject to vehicular traffic that will compact the soil, thus reducing permeability.

They are not recommended on steep slopes, or in areas where pollutant spills are likely. In addition, infiltration trenches must be carefully sited to avoid the potential of groundwater contamination.

Appropriate pre-treatment measures to prevent clogging and failure should be installed upstream from an infiltration trench. However, some clogging and vegetation accumulation is inevitable and there should be easy access by vehicles for maintenance.

Operations and maintenance

Infiltration trenches can be prone to clogging with sediment and require pre-treatment as well as regular observation and maintenance to ensure proper functioning. The three main maintenance activities are inspections for clogging, removing sediments and replacement of pea gravel layer as needed.

Approximate construction cost	120 €/m^3 stored volume	82-130 €/m^3
Approximate maintenance cost	3 €/m^3 stored volume/year	0.35-48 €/m^3/year
Approximate lifespan (estimation)	30 years	20-50 years
More information and references	(ARC, 2001), (CP, 2008), (SCSMC, 2010), (SFPUC, 2009), (Woods-Ballard *et al.*, 2007).	

2.3.7. Geocellular systems

Description

Geocellular systems are modular plastic structures with a high void ratio that can be used to create an underground infiltration or storage structure. Geocellular systems with a void ratio about 95% are more efficient, versatile and easy-to-install than stone-filled soakaways, which have a void ratio of about 30%. The systems can be designed to withstand traffic loads, so they can be installed under roads and car parks as well as recreational areas and other public open space. Geocellular systems can contribute to stormwater management in two different ways:

- **By facilitating infiltration:** Through the provision of a storage structure that is wrapped in permeable geotextile and which allows the stormwater to infiltrate into the ground.
- **By creating storage volumes:** Through the provision of a structure that is wrapped in a suitable robust impermeable geomembrane that provides storage for stormwater runoff. This option is appropriate where ground conditions are not suitable for a soakaway. In this case, it works like a detention structure and can be designed as either on-line or off-line.

Runoff can enter in these systems through infiltration from a permeable surface above or through a perforated inlet/distributor pipe. In this case, runoff must be filtered to avoid sedimentation.

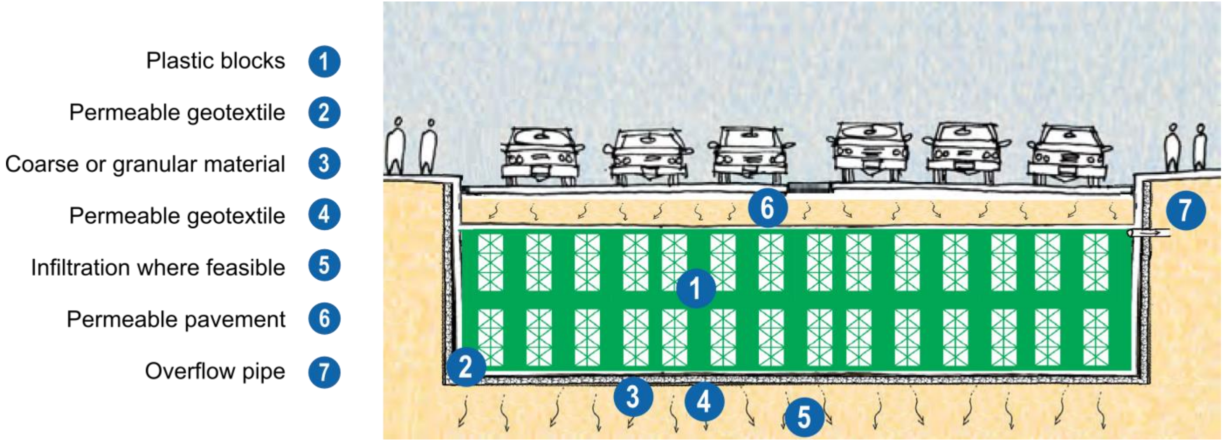


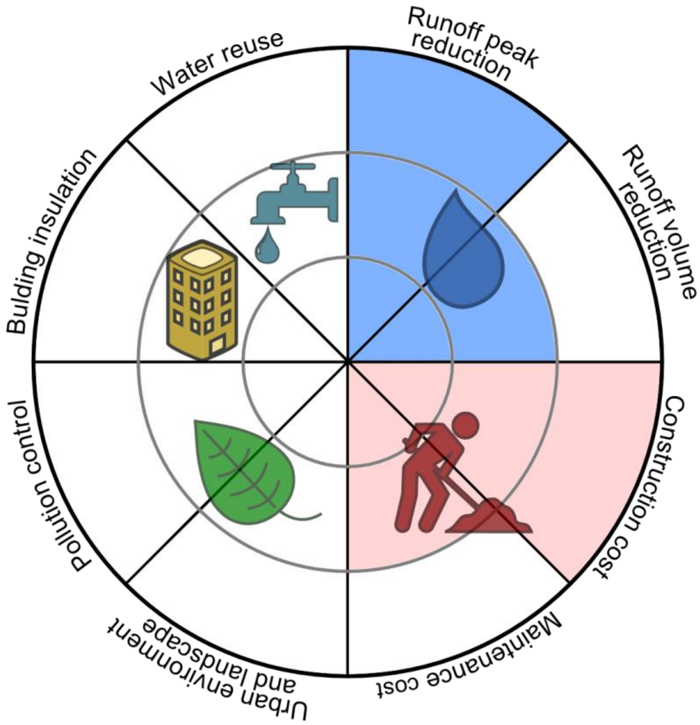
Figure 2.27. Geocellular system in soakaway mode under a permeable pavement. Adapted from (SFPUC, 2009).

Benefits

- Modular and very flexible.
- High void ratios (about 96%) providing high storage capacity.
- Lightweight, easy to install and robust.
- Capable of managing high flow events.
- Long-term physical and chemical stability.
- Infiltration can significantly reduce runoff rates and volumes.
- In soakaway mode, enhances groundwater recharge and contributes to stream base flow.
- Attenuates peak flow.

Limitations

- Provides no water quality improvements.
- May cause structural problems to other buildings.
- Potentially high excavation and installation costs.
- Not beneficial to urban environment or landscape.
- Structures can float when water table is high.
- In soakaway mode, infiltration feasibility needs to be checked (Section 3.1.).

Performance summary	Picture
	 *Figure 2.28. Construction of a geocellular system in Oleiros, Spain.*

**Volume reduction when facilitates infiltration.*

Design considerations

Geocellular systems generally can be used for any site requiring surface water storage. They offer great flexibility to the designer because of their modular nature and their ability to be used for either infiltration or storage.

Modular geocellular systems must be designed as structural components, using structural design theory and considering all the loads that they have to withstand. They must be properly designed, since they may cause structural problems to other buildings and there have been a number of recorded failures.

To achieve water quality treatment, these systems will need to form part of a management train, with appropriate sediment management and pollution control devices installed.

Operations and maintenance

Access may be provided for inspection and maintenance of the modular system itself via gaps in the components. Regular inspection and maintenance is required to ensure the effective long-term operation of underground modular storage systems. All inlets, outlets, vents and overflows must be periodically checked to ensure that they are in good condition and operating as designed.

Approximate construction cost	350 €/m^3 stored volume	200-700 €/m^3
Approximate maintenance cost	0.8 €/m^3 stored volume/year	0.3-2.5 €/m^3/year
Approximate lifespan (estimation)	25 years	15-30 years
More information and references	(CIRIA, 2012), (Faram *et al.*, 2004), (SCSMC, 2010), (Woods-Ballard *et al.*, 2007).	

2.3.8. Bioretention areas

Description

Bioretention areas are vegetated shallow depressions that rely on vegetation and either native or engineered soils to capture, infiltrate, transpire and remove pollutants from runoff, thereby reducing stormwater volume, attenuating peak flow and improving stormwater quality. They feature plants adapted to the local climate and soil moisture conditions that can tolerate periodic inundation. In bioretention areas, pore spaces, microbes, and organic material in the engineered soils help to retain water in the form of soil moisture and to promote the adsorption of pollutants into the soil matrix. Plants utilize soil moisture and promote the drying of the soil through transpiration. If no underdrain is provided, stored water in the bioretention area is infiltrated into the underlying soils over a period of days.

For areas with low permeability native soils or steep slopes, bioretention areas can be designed with an underdrain system to route the treated runoff to the storm drain system rather than depending on infiltration. In this situation, treatment is achieved mainly through filtration and adsorption in the vegetation and soils.

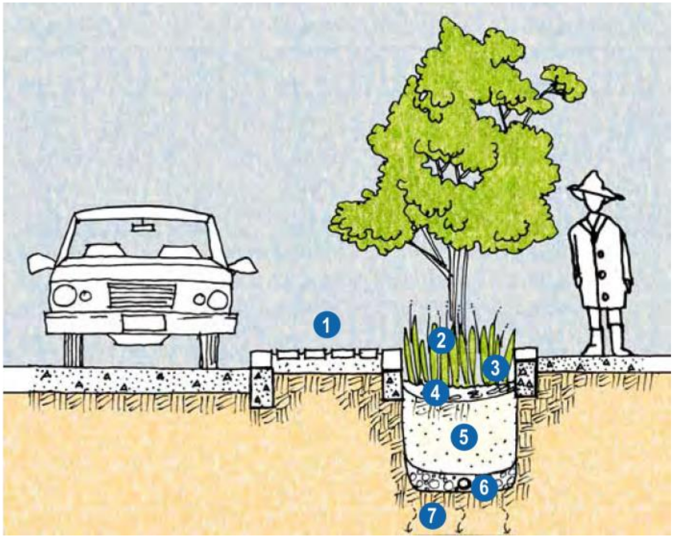
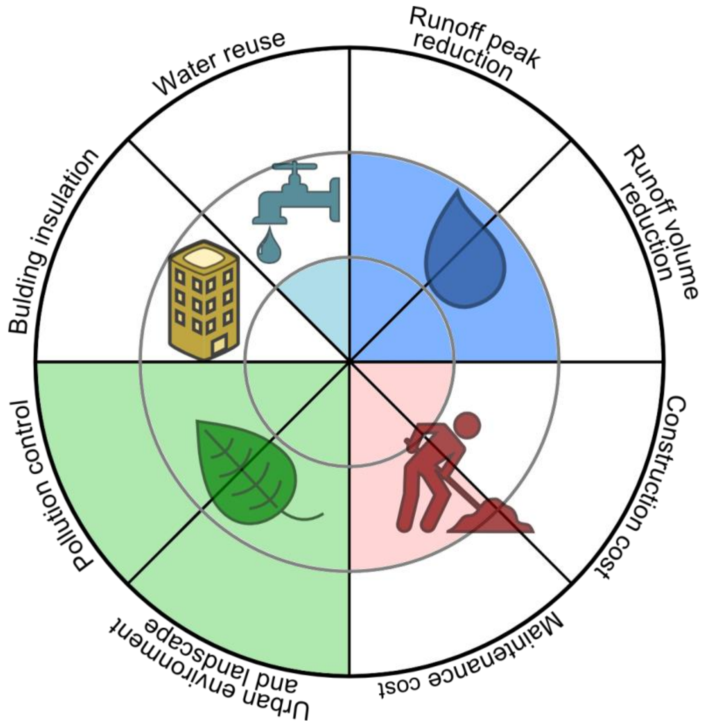


Figure 2.29. Parts of a biorretention area. Adapted from (SFPUC, 2009).

Benefits	Limitations
• Easy and inexpensive to install. • Wide range of scales and site applicability. • Reduces runoff volume where infiltration is feasible and attenuates peak flows. • Improves water and air quality. • Increases effective permeable surfaces in highly urbanized areas. • Creates habitat and increases biodiversity in the city. • Provides aesthetic amenity and can be planned as landscaping features. • Facilitates groundwater recharge (infiltration-based systems only). • Facilitates evapotranspiration.	• Requires relatively flat site and sufficient hydraulic head for filtration. • Vegetation requires maintenance and can look overgrown or weedy; seasonally it may appear dead. • Not suitable for areas with steep slopes. • Requires extensive landscaping. • In soakaway mode, infiltration feasibility needs to be checked (Section 3.1.).

Performance summary	Picture



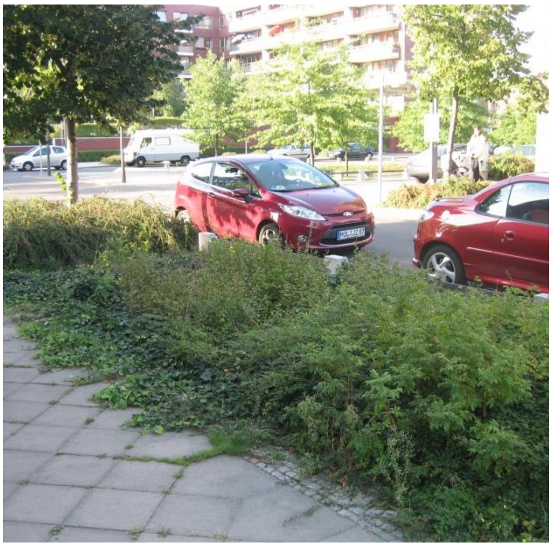


Figure 2.30. Bioretention area in Berlin (Germany).

Design considerations

There are numerous design applications, both on- and off-line, for bioretention areas. These include use on single-family residential lots, as off-line facilities adjacent to parking lots, along highway and road drainage swales, within larger landscaped pervious areas, and as landscaped islands in impervious or high-density environments. Bioretention is appropriate for use in commercial, institutional, residential, industrial, and transportation applications.

Bioretention areas are designed primarily for stormwater quality. They can provide limited runoff quantity control, particularly for smaller storm events. However, bioretention areas will typically need to be used in conjunction with another structural control to provide flood protection. It is important to ensure that higher flows safely bypass a bioretention area. With this purpose, an overflow structure and non-erosive overflow channel may be provided for flows that exceed the storage capacity to a stabilized downstream area or watercourse.

Operations and maintenance

Regular inspection and maintenance is critical to the effective operation of bioretention facilities as designed. Bioretention areas will require supplemental irrigation during the first 2-3 years after planting. Drought tolerant species may need little additional water after this period, except during prolonged drought, when supplemental irrigation may become necessary for plant survival. In some instances, where it is desired to maintain fast-growing annual herbaceous plant cover, annual mowing may be appropriate.

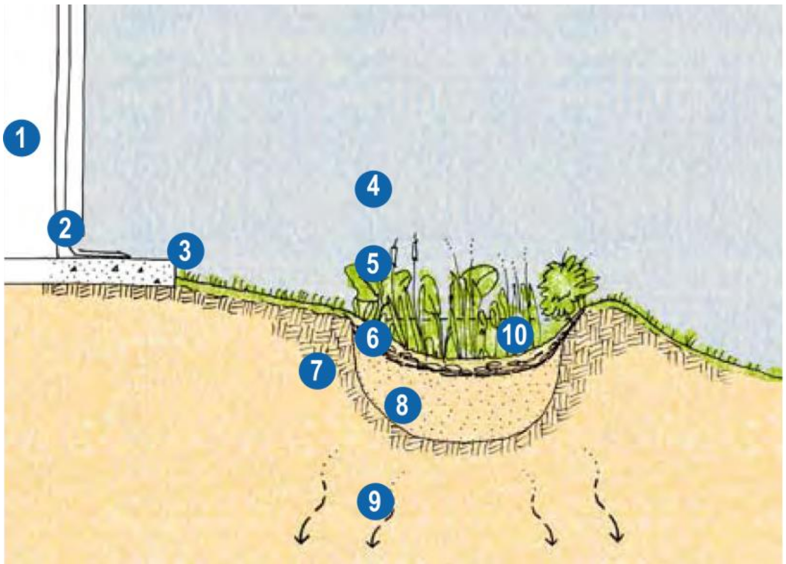
Approximate construction cost	75 €/m^2	4.5-328 €/m^2
Approximate maintenance cost	8 €/m^2/year	0.3-12.5 €/m^2/year
Approximate lifespan (CNT, 2006)	30 years	25-50 years
More information and references	(ARC, 2001), (CLADPW, 2010), (SCSMC, 2010), (SFPUC, 2009), (Woods-Ballard *et al.*, 2007).	

2.3.9. Rain gardens

Description

Rain gardens are the simplest type of biorretention areas and are usually used on single-family residential lots and around public buildings (they can also be powerful educational instruments). They are vegetated depressions that provide storage, infiltration, and evapotranspiration. Rain gardens remove pollutants by filtering stormwater through plants adapted to the local climate and soil moisture conditions.

In rain gardens, pore spaces, microbes, and organic material in the native or engineered soils help to retain water in the form of soil moisture and to promote the adsorption of pollutants into the soil matrix. Plants utilize soil moisture and promote the drying of the soil through transpiration. Stored water in the rain gardens is infiltrated into the underlying soils over a period of days. As part of a disconnection strategy, roof downspouts may be directed to rain gardens to store and filter stormwater.



1. Water from paved or landscaped surfaces and roof (maximum contributing area of 4000 m^2)
2. Splash block
3. Suitable length from foundation
4. Minimum 0.6 m rain garden width
5. Dense, wet- and dry-tolerant vegetation
6. Ponding depth, 15 to 30 cm
7. Mulch, 5 to 7.5 cm depth
8. 45 cm bioretention planting soil
9. Native soils suitable for infiltration
10. Berm

Figure 2.31. Parts of a rain garden. Adapted from (SFPUC, 2009).

Benefits

- Easy and inexpensive to install.
- Wide range of scales and site applicability.
- Reduces runoff volume where infiltration is feasible and attenuates peak flows.
- Improves water quality and air quality.
- Increases effective permeable surfaces in highly urbanized areas.
- Creates habitat and increases biodiversity in the city.
- Good retrofit capabilities.
- Provides aesthetic amenity. Can be planned as landscaping features.
- Facilitates groundwater recharge.
- Facilitates evapotranspiration.

Limitations

- Requires sufficient hydraulic head for filtration.
- Vegetation requires maintenance and can look overgrown or weedy; seasonally it may appear dead.
- Not suitable for areas with steep slopes.
- Requires landscaping and management.
- Susceptible to clogging if surrounding landscape is poorly managed.
- Infiltration feasibility needs to be checked (See Section 3.1.).

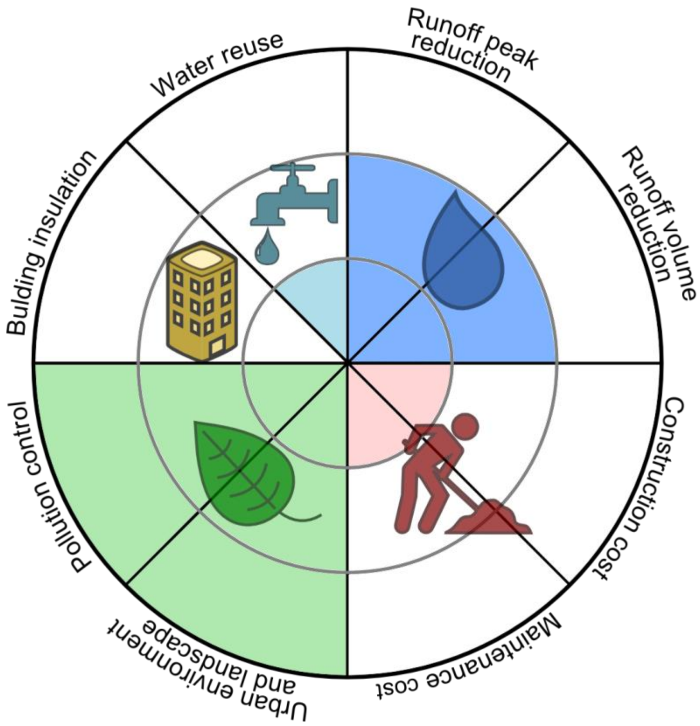
Performance summary	Picture
	 Figure 2.32. Rain garden in Washington DC (USA).

Figure 2.32. Rain garden in Washington DC (USA).

Design considerations

Rain gardens are mainly used on single-family residential lots and around public buildings. They should be integrated into the site plans and aesthetic considerations should be taken into account in their siting and design. Elevations must be carefully worked out to ensure that the desired runoff flow enters the rain garden with no more than the maximum design depth.

Rain gardens are mainly designed to improve stormwater quality, removing stormwater pollutants. They can provide limited runoff quantity control, particularly for smaller storm events. Rain gardens will typically be used in conjunction with another structural control to provide flood protection. It is important to ensure that a rain garden safely bypasses higher flows.

Operations and maintenance

Regular inspection and maintenance is critical to the effective operation of rain gardens. They will require supplemental irrigation during the first 2-3 years after planting. Drought tolerant species should need little additional water after this period, except during prolonged drought, when supplemental irrigation may become necessary for plant survival. In some instances, where it is desired to maintain fast-growing annual herbaceous plant cover, annual mowing may be appropriate.

Approximate construction cost	50 €/m^2	30-130 €/m^2
Approximate maintenance cost	2.5 €/m^2/year	1.5-4.9 €/m^2/year
Approximate lifespan (CNT, 2006)	30 years	25-50 years
More information and references	(ARC, 2001), (CLADPW, 2010), (NYSDEC, 2010), (SCSMC, 2010), (SFPUC, 2009), (Woods-Ballard *et al.*, 2007).	

2.3.10. Filter strips

Description

Filter strips are vegetated strips of land designed to treat sheet flow runoff from adjacent impervious surfaces or intensive landscaped areas. They are typically linear facilities that run parallel to the impervious surface and are commonly used to receive runoff from walkways and driveways. Filter strips are covered with vegetation, including grasses and groundcover plants, which filter and reduce the velocity of stormwater. As the stormwater travels across the strip, it may infiltrate into the soils below. Filter strips are generally very effective in trapping sediment and particulate-bound metals, nutrients, and pesticides.

There are two different filter strip designs: a simple filter strip and a design that includes a permeable berm at the bottom. The presence of the berm increases the contact time with the runoff, thus reducing the overall width of the filter strip required to treat stormwater runoff. Filter strips are typically on-line components, so they must be designed to withstand the full range of storm events without eroding.

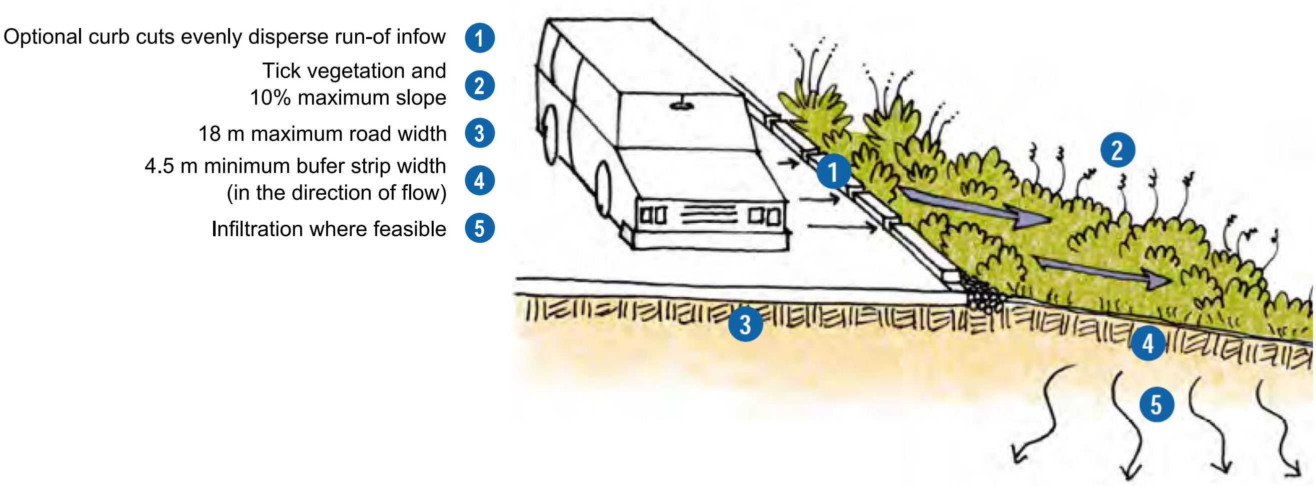


Figure 2.33. Parts of a filter strip. Adapted from (SFPUC, 2009).

Benefits	Limitations
• Improve water quality. • Effective pre-treatment option. • Attenuate peak flows and can recharge groundwater. • Good for roadside shoulders. • Attractive landscape feature. • Easy to construct and minimal maintenance required. • Easy to customize to varying site conditions.	• Large land requirement. • Not appropriate for industrial or contaminated sites. • Not suitable for steep sites. • Limited ability to treat large drainage areas. • Minimal stormwater volume reduction. • May require irrigation in dry season, depending upon species. • Persistent stormwater pollutants may accumulate in sediments, such as metals, oil and grease. • In soakaway mode, infiltration feasibility needs to be checked (Section 3.1.).

Performance summary	Picture

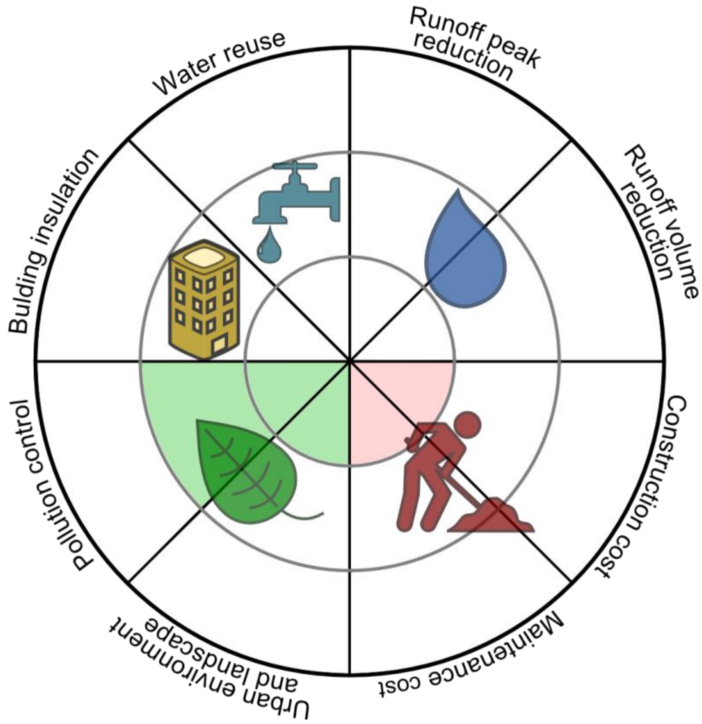


Figure 2.34. Filter strip leading to wet swale in Scotland.

Design considerations

Vegetated filter strips are well-suited to treating runoff from roads and highways, roof downspouts, small parking lots, and pervious surfaces. They are also appropriate for the "outer zone" of a stream buffer, or as pretreatment for another stormwater SuDS that provides detention or storage. In addition, they can be attractive features that tend to be viewed as landscape amenities rather than as stormwater infrastructure.

Buffer strips should be sited on gentle slopes between 1 and 10%. Steeper slopes may trigger erosion during heavy rain events, thus eliminating water quality benefits. On slopes greater than 5%, fibre rolls, check dams, or other means should be used to slow flows and reduce erosion potential. If the buffer strip slope is less than 0.5%, or if the underlying soil has infiltration rates of less than 12 mm per hour, an underdrain system should be installed to facilitate drainage. The underdrain would be sited at the toe of the buffer strip and connected to the collection system or other SuDS.

Operations and maintenance

Filter strips require similar maintenance to other vegetative practices. Maintenance is very important for filter strips, particularly in terms of ensuring that flow does not short circuit the practice. Recent research indicates that grass height and mowing frequency have little impact on pollutant removal; consequently, mowing may only be necessary once or twice a year for safety and aesthetics. Weed suppression must be done much more frequently than mowing.

Approximate construction cost	6 €/m^2	0.5-27 €/m^2
Approximate maintenance cost	0.1 €/m^2/year	0.06-0.6 €/m^2/year
Approximate lifespan (CNT, 2006)	25 years	20-50 years
More information and references	(ARC, 2001), (CP, 2008), (CLADPW, 2010), (SCSMC, 2010), (SFPUC, 2009), (Woods-Ballard *et al.*, 2007).	

2.3.11. Filter drains

Description

Filter drains are gravel filled trenches that collect and convey storm water and also treat pollution. The trench is filled with free draining gravel and often has a perforated pipe in the bottom to collect the water. Filter drains are best located adjacent to impermeable surfaces such as cars parks or road/highways. They are widely used to drain roads and are often located on the edge of main roads.

The perforated pipe is not required along the entire length of the trench, only near the end of the device. Ideally a pre-treatment device (such as a filter strip or grassed area) should be incorporated to increase the longevity of the system. It is also an option to add a geotextile layer just below the surface to trap silt and stop it from clogging the gravel deeper in the trench. Inspection manholes should be located at regular intervals along the length of the device.

Excess flows during extreme rainfall events may be dealt with by overland flooding passing to swales or by an overflow pipe which connects to swales or other parts of the drainage system.

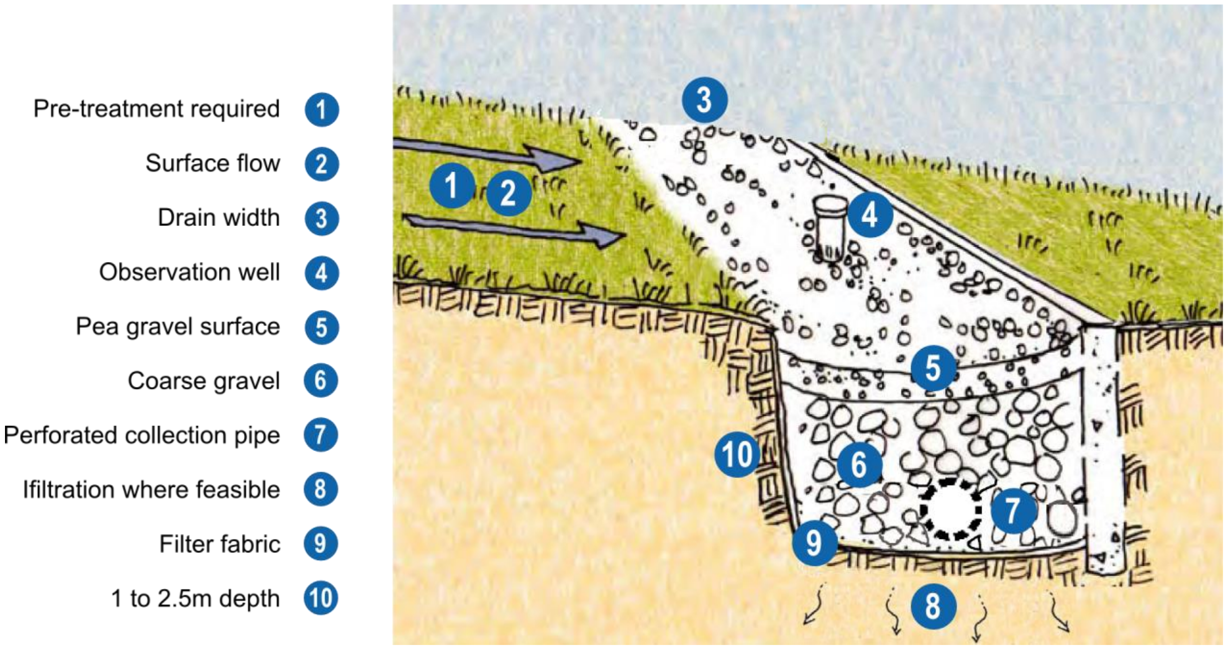


Figure 2.35. Parts of a filter drain. Adapted from (SFPUC, 2009).

Benefits	Limitations
• Improves water quality by removing sediment and with the sediment, nutrients, organic matter and trace metals. • Can be incorporated easily into site landscaping and fit well besides roads. • Can significantly reduce runoff peak flow. • Can provide a significant reduction in the pollution load discharged to the receiving body.	• A very common feature on highways but will have a high failure rate if maintenance is poor. • Build-up of pollution/blockages is difficult to see. • Limited to relatively small catchments. • In soakaway mode, infiltration feasibility needs to be checked (Section 3.1.).

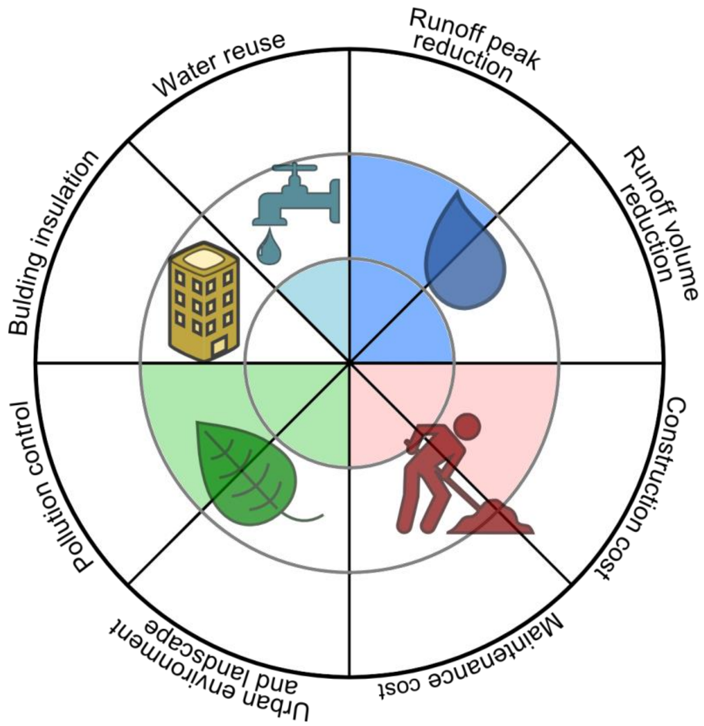
Performance summary	Picture
	

Figure 2.36. Filter drain in Crevillent, Spain.

Design considerations

There are three elements to the design of filter drains:

- Design of filter material to percolate water: The rate of percolation is a compromise between pollutant removal and the need to restrict the risk of flooding in the catchment.
- Design of material to store water: The greater the void ratio the more storage is available in the trench.
- Design of the pipe system to convey water.

Operations and maintenance

Regular inspections are required to monitor sediment build-up and clogging. These inspections can involve:

- Digging up sections of the trench to check for clogging.
- Use of inspection manholes.
- Surveys within the perforated pipe.

Remedial work will also be required at intervals to scarify the surface and/ or remove sediment from the device. This can be done by replacing the filter material or through cleaning and replacement.

Approximate construction cost	175 €/m^3 stored volume	146-205 €/m^3
Approximate maintenance cost	0.9 €/m^3 stored volume/year	0.3-1.5 €/m^3/year
Approximate lifespan (estimation)	30 years	20-50 years
More information and references	(HRWallingford, 2013), (Wilson *et al.*, 2009), (Woods-Ballard *et al.*, 2007).	

2.3.12. Vegetated swales

Description

Vegetated swales are broad, shallow channels designed to convey and either filter or infiltrate stormwater runoff. Swales are vegetated along their bottom and sides and are used to reduce stormwater volume through infiltration, improve water quality through infiltration and vegetative filtering, and reduce runoff velocity by increasing flow path lengths and channel roughness.

Vegetated swales can be designed as part of the stormwater conveyance system and can potentially eliminate the need for kerbs, gutters and storm drains. They are also well suited to treat runoff from roads and highways because of their linear nature. Swales can be connected to many other treatment measures, such as wet ponds, infiltration basins, and wetlands. They can significantly reduce runoff volume in very permeable soils.

Vegetated swales are designed with limited longitudinal slopes to force the flow to be slow, thus allowing particles to settle and limiting the effects of erosion. Berms and/or check dams installed at right angles to the flow path promote settling and infiltration.

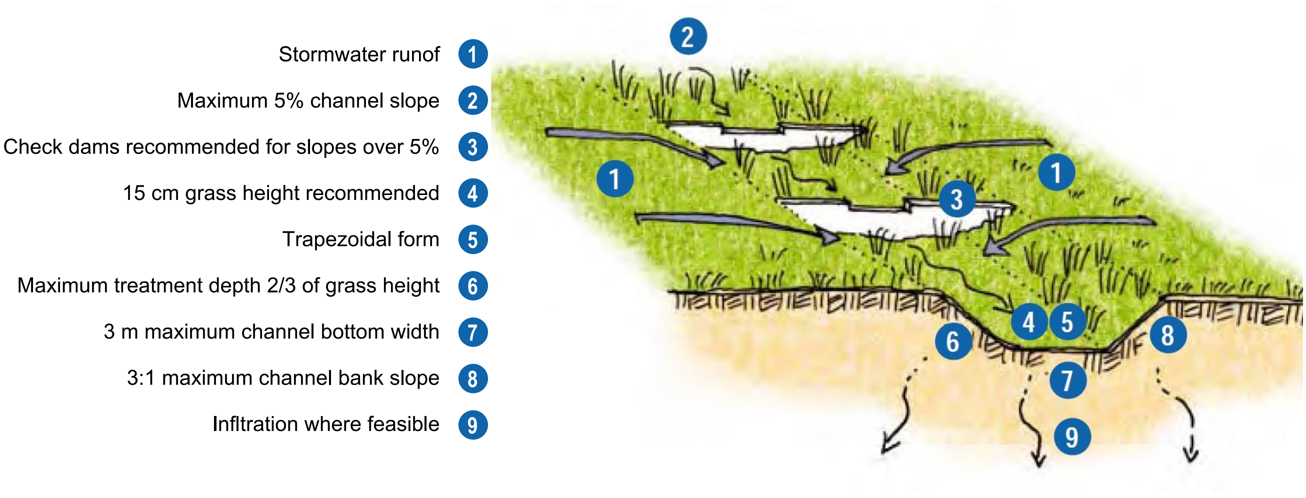


Figure 2.37. Vegetated swale. Adapted from (SFPUC, 2009).

Benefits

- Improves water quality by removing sediment, particulate matter, and trace metals.
- Can be easily incorporated into landscaping.
- Creates habitat and increases biodiversity in the city.
- Can provide a good removal of urban pollutants.
- Attenuates peak flows and can recharge groundwater.
- Low construction and maintenance costs.
- High volume reduction can be achieved in very permeable soils.

Limitations

- Not suitable for steep areas.
- Limited to relatively small drainage areas.
- Limit opportunities to use trees for landscaping.
- Little removal of dissolved pollutants and bacteria.
- Vulnerable to erosion when flow velocities are high.
- Risks of blockage in connecting pipework.
- Limited volume reduction in poor draining soils.
- In soakaway mode, infiltration feasibility needs to be checked (Section 3.1.).

Performance summary	Picture

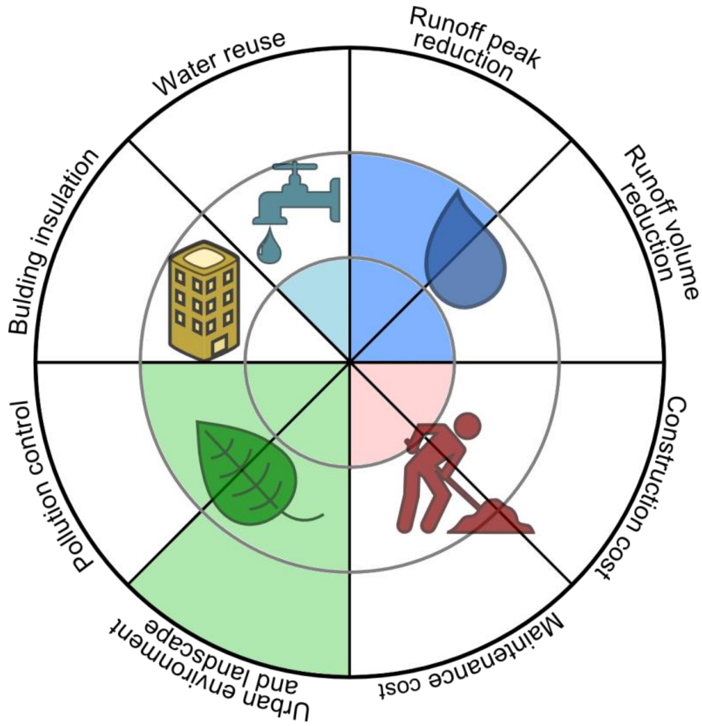


Figure 2.38. Vegetated swale in Leicester (England).

Design considerations

Vegetated swales can be an important part of the stormwater system and can potentially eliminate the need for conventional drainage systems. They are also suitable to treat runoff from roads and highways because of their linear nature. Swales can be paired with many other treatment measures, such as wet ponds, infiltration basins, and wetlands.

Vegetated swales should promote low flow velocities to allow suspended particulate load in the stormwater runoff to settle out, thus providing effective pollutant removal. The treatment effectiveness is correlated to the residence time of the runoff in the swale, and therefore, vegetated swales can be considerably longer than other SuDS infrastructures.

Operations and maintenance

If properly designed and regularly maintained, vegetated swales can last indefinitely. The primary maintenance objective for vegetated swales is to maintain the hydraulic and removal efficiency of the channel with a dense, healthy vegetative cover. This requires regular vegetation maintenance and trash removal. During construction, it is important to stabilize the swale before the vegetation has been established, either with a temporary grass cover, or the use of natural or synthetic erosion control products.

Approximate construction cost	15 €/m^2	2.7-18 €/m^2
Approximate maintenance cost	0.1 €/m^2/year	0.03-0.16 €/m^2/year
Approximate lifespan (CNT, 2006)	30 years	20-50 years
More information and references	(ARC, 2001), (CP, 2008), (CLADPW, 2010), (NYSDEC, 2010), (SCSMC, 2010), (SFPUC, 2009), (Woods-Ballard *et al.*, 2007).	

2.3.13. Infiltration basins

Description

Vegetated infiltration basins are flat-bottomed, shallow landscaped depressions used to collect and hold stormwater runoff, allowing pollutants to settle and filter out as the water infiltrates into the ground. Stormwater temporarily forms pools on the surface of the basin, then infiltrates. Pollutant removal is accomplished by natural mechanisms within the soil including filtration, absorption and adsorption, and chemical and biological uptake.

They are either excavated or created with bermed side slopes. An inlet pipe, swale or sheet flow over impervious area conveys the stormwater into the basin, where it is temporarily stored until it infiltrates into the ground. Basins often provide complete infiltration for small storm events. They can be sized to infiltrate large storms in areas where soils drain well or they can overflow to an approved discharge point.

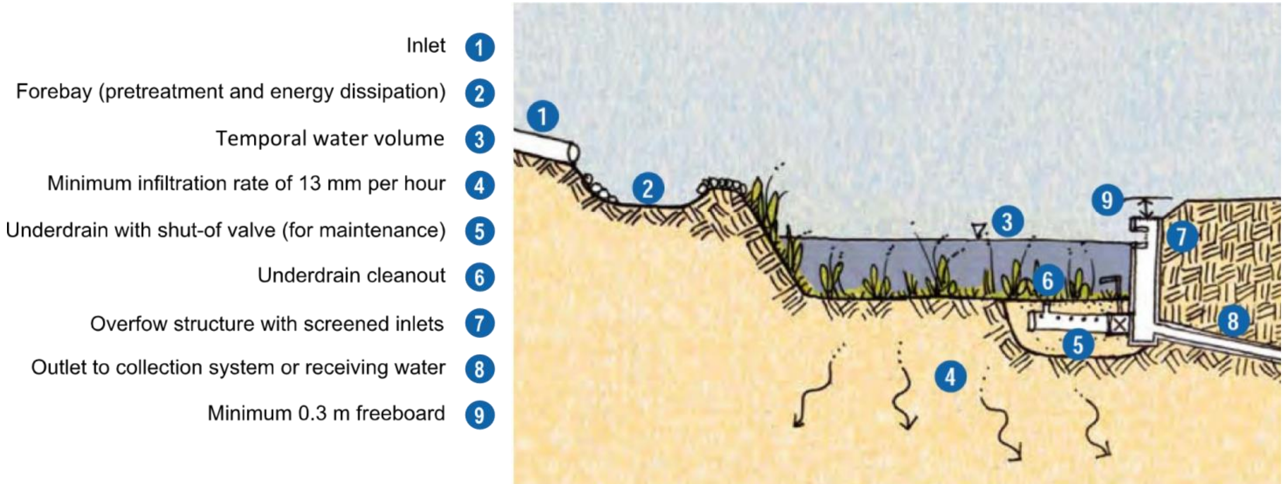


Figure 2.39. Infiltration basin. Adapted from (SFPUC, 2009).

Benefits

- Improves water quality by removing sediment, nutrients, organic matter, and trace metals.
- Infiltration can significantly reduce runoff rates and volumes.
- Enhances groundwater recharge and contributes to stream base flow.
- Can be incorporated easily into site landscaping.
- Creates habitat and increases biodiversity in the city.
- Simple and cost-effective to construct.
- Low maintenance costs.
- Changes in performance can be easily observed.
- They can function as regional facility treating large volumes of water.

Limitations

- Requires a large, flat area.
- Infiltration feasibility needs to be checked (See Section 3.1.).
- Potentially high failure rates due to improper sitting, poor design and lack of maintenance, especially if pre-treatment is not incorporated.

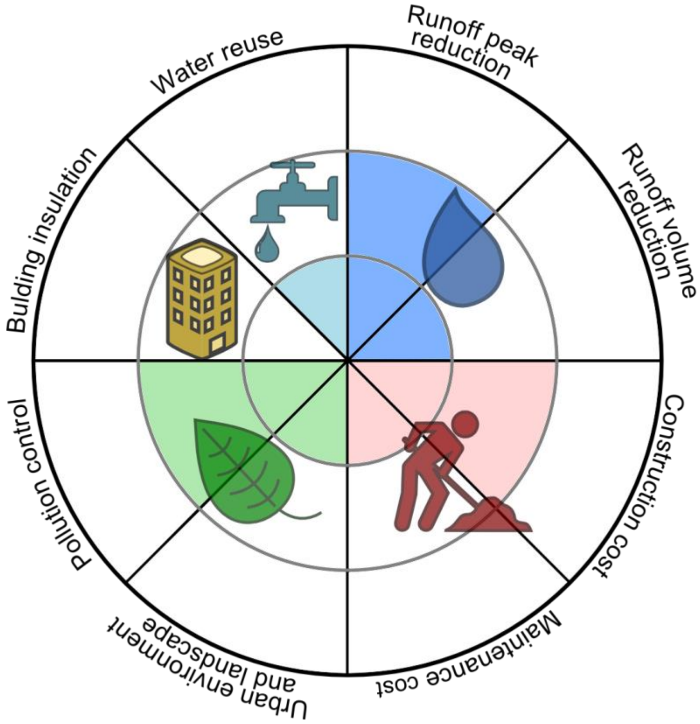
Performance summary	Picture
	

Figure 2.40. Infiltration basin in Cincinnati (USA).

Design considerations

Basins can have a formal or informal design that can be used to improve urban landscape. The most important constraint for infiltration basins sitting is the infiltration capacity of the soils and the availability of land.

Infiltration basins have high removal efficiency for fine sediment and associated pollutants. However, coarse sediment and oils will clog the basin and should be removed using appropriate pre-treatment practices, such as vegetated swales, before runoff reaches the basin.

Infiltration basins are generally between 0.3 and 1 m deep with earth side slopes no steeper than 3H:1V to provide bank stability and allow for mowing. The bottom of the basin should be as flat as possible to provide uniform ponding and infiltration across the basin bottom. A key part of an infiltration basin is its vegetation. Deep-rooted plants on the basin bottom reduce the risk of clogging and increase the infiltration capacity by creating small conduits through which water can infiltrate. Dense vegetation also impedes soil erosion and scouring of the basin floor.

Operations and maintenance

Proper soil conditions, sufficient pre-treatment measures (such as vegetated swales) and well-designed operations and maintenance programs are the key to implementing successful and long-lasting infiltration basins. The main maintenance requirements are visual inspections, trash removal, inlets and outlets cleaning and vegetation management.

Approximate construction cost	65 €/m^3 storage volume	18-485 €/m^3
Approximate maintenance cost	4 €/m^3 storage volume/year	0.35-48.5 €/m^3/year
Approximate lifespan (estimation)	50 years	25-75 years
More information and references	(CP, 2008), (CLADPW, 2010), (SCSMC, 2010), (SFPUC, 2009), (Woods-Ballard *et al.*, 2007).	

2.3.14. Detention basins

Description

Detention basins are surface facilities intended to store stormwater runoff temporarily to reduce downstream water quantity impacts and provide flood protection. They temporarily detain stormwater runoff, releasing the flow over a period of time. Generally, detention basins are designed to fill and empty within 48 hours of a storm event. They also facilitate some settling of pollutant particles. They are designed to drain completely following a storm event and are normally dry between rain events. If designed with vegetation, basins can also create wildlife habitat and improve air quality. Detention basins may be constructed as on-line or off-line facilities:

- **On-line:** have surface runoff routed through them during storm events. They have a restricted outflow that causes the basin to fill, thus attenuating flow.
- **Off-line:** usually receive runoff via a flow diverter or overflow in the main channel by which flows in excess of a threshold value are diverted from the main flow path into the detention basin and temporally stored. The water from the detention basin is passed back into the main system when the inflow falls below the diversion threshold.

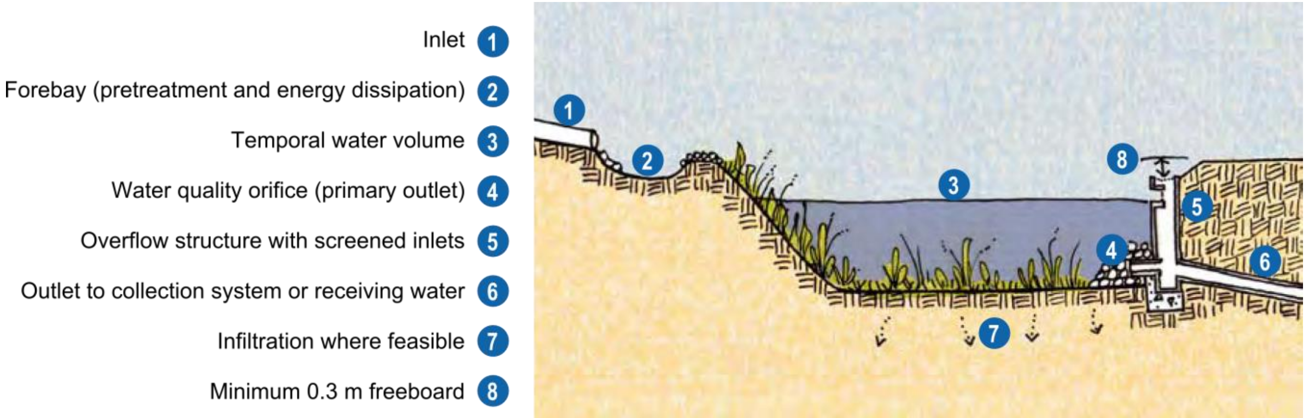


Figure 2.41. Detention basin. Adapted from (SFPUC, 2009).

Benefits	Limitations
• Attenuates peak flows. • Reduces flooding. • Can cater for a wide range of rainfall events. • Improves water quality by removing particulate matter and sediment. • Removes trash and debris from the flow. • Low construction and maintenance costs. • Simple to design and construct. • Good for sites where infiltration is not an option. • Multi-purpose detention basins create habitat and increase biodiversity in the city. • Multi-purpose detention basins provide open space and aesthetic amenity.	• Do not remove soluble pollutants. • Little reduction in runoff volume. • Detention depths may be constrained by system inlets and outlet levels. • Minimum drainage area of 2 ha.

Performance summary	Picture

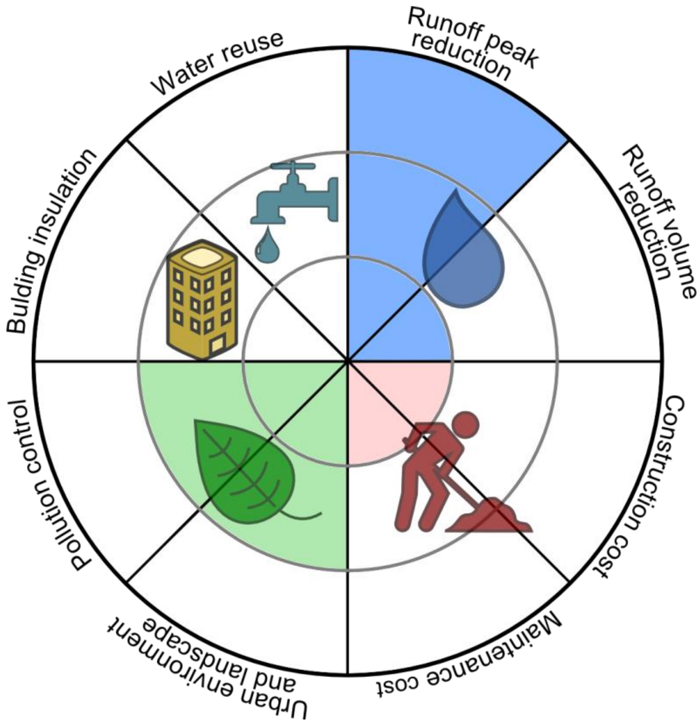


Figure 2.42. Detention basin in Dunfermline East Expansion (Scotland).

Design considerations

Detention basins are generally applicable to most types of development and can be used in both residential and non-residential areas. They usually consist of a depressed area of land, or an area that is surrounded by earth berms (or small dams), where stormwater is directed and stored during storm events. They may be constructed to serve more than one purpose, and can be used as playgrounds or sport fields. When constructed for dual purposes, the detention basin should be usable for the function other than stormwater detention for most of the time; it should have relatively low flooding frequency.

Vegetation within the detention zone (up to the elevation of the design storm) appears to increase pollutant removal and decrease re-suspension of accumulated sediment. Plants selected for this zone should be able to withstand both wet and dry periods.

Operations and maintenance

The principal maintenance of detention basins is periodic sediment removal, vegetation management, and vector abatement if needed. Regular mowing in and around detention basins is required only along maintenance access routes, amenity areas, across embankments and across the main storage area.

Approximate construction cost	22 €/m^3 storage volume	17-34 €/m^3
Approximate maintenance cost	0.5 €/m^3 storage volume/year	0.17-1.3 €/m^3/year
Approximate lifespan (CNT, 2006)	50 years	25-75 years
More information and references	(ARC, 2001), (CP, 2008), (CLADPW, 2010), (SCSMC, 2010), (SFPUC, 2009), (Woods-Ballard *et al.*, 2007).	

2.3.15. Retention ponds

Description

Retention ponds are constructed basins that have a permanent pool of water throughout the wet season and potentially throughout the year. The primary removal mechanism is settling while stormwater runoff resides in the pool. Where algae are present, they also aid stormwater treatment. Nutrient uptake occurs through biological activity in the sediment and water. Wet ponds differ from constructed wetlands in that they are typically deeper, ranging from 1.2 to 1.8 m, and have less vegetative cover.

Retention ponds are one of the most cost-effective and widely used stormwater treatment practices. The typical configuration of a retention pond includes a forebay, a permanent storage, and variable storage areas. The forebay is a small inlet pool that provides a pre-treatment allowing settling of coarse and medium grained sediment. Permanent storage refers to the permanent pool of water remaining in the wet pond between storm events and during dry weather. If intended as permanent water feature, supplemental water and the installation of an impermeable liner may be required to maintain the permanent pool during the dry season. Variable storage refers to the remaining storage capacity in the wet pond that will vary based on stormwater influx. The stormwater in the variable storage area will generally drain from the pond 24 to 48 hours after the end of a storm event.

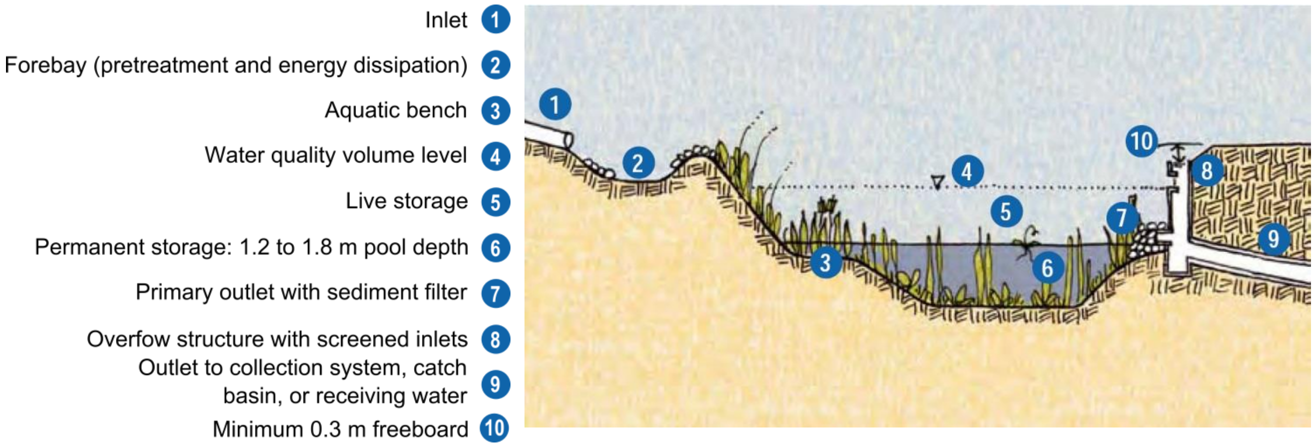


Figure 2.43. Retention pond. Adapted from (SFPUC, 2009).

Benefits

- Effective at removing stormwater pollutants.
- Suitable for all types of storms.
- Reduces stormwater peak flows
- Creates a wetland habitat and increase biodiversity in the city.
- Provide open space and aesthetic amenity.
- Good in areas unsuitable for infiltration or with high groundwater table.
- Easily customizable to various sizes and dimensions.
- Suitable for large drainage areas.
- May add value to local properties.

Limitations

- Require a relatively large land area.
- May require supplemental water source during dry seasons.
- Do not reduce significantly runoff volume.
- Anaerobic conditions can occur without a regular inflow.
- Colonization by invasive species may increase maintenance costs.
- Not suitable for steep sites.

Performance summary	Picture

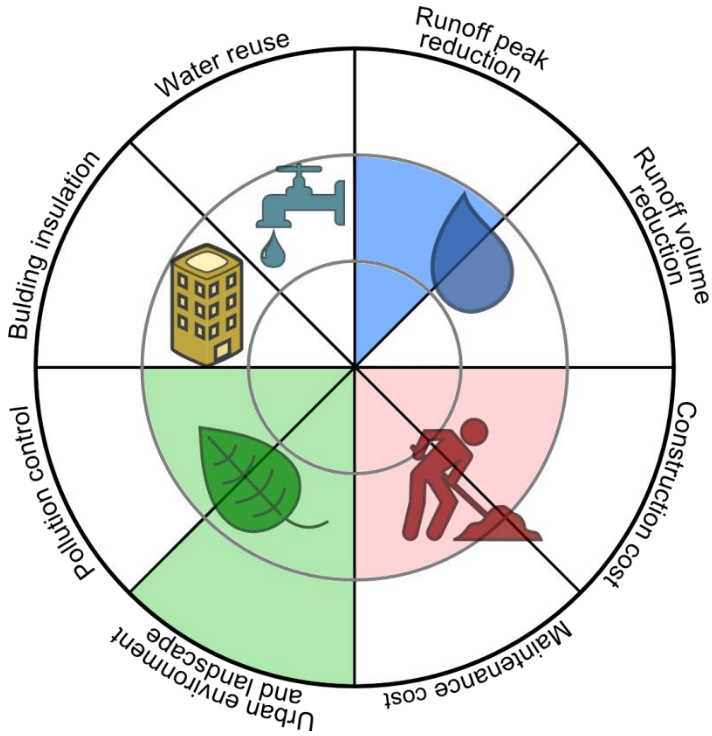


Figure 2.44. Retention pond in Dunfermline East Expansion (Scotland).

Design considerations

Generally, retention ponds are applicable to most types of new development and redevelopment, and be used in both residential and non-residential areas. Land-take requirements may limit their suitability for high-density development areas. Retention ponds must be sited on a relatively flat area with less than 2% slope. Because they are not designed to reduce runoff by infiltration, they can be used in almost all soil types. There may be child safety issues when ponds are located close to houses.

In Mediterranean climates, retention ponds may either be allowed to evaporate in the dry season, or may be supplemented with an alternative source of influent water. Retention ponds may intersect the groundwater table, which will help support vegetation. This should be avoided in areas where either the stormwater or the groundwater could be contaminated.

Operations and maintenance

Maintenance of ponds is relatively straight forward for landscape contractors and typically only a small amount of extra work is required for a retention pond. More intensive maintenance work such as silt and/or vegetation removal is only required intermittently but it should be planned to be sympathetic to the requirements of wildlife in a pond. Intensive silt and vegetation removal should only be carried out to limited areas at any one time to minimise the impact on biodiversity.

Approximate construction cost	45 €/m^3 storage volume	13.5-70 €/m^3
Approximate maintenance cost	1.5 €/m^3 storage volume/year	0.4-5 €/m^3/year
Approximate lifespan (CNT, 2006)	50 years	25-75 years
More information and references	(SFPUC, 2009), (Wilson *et al.*, 2009), (Woods-Ballard *et al.*, 2007).	

2.3.16. Constructed wetlands

Description

Constructed wetlands are shallow marsh systems designed to both improve stormwater quality and provide some control of runoff volumes. As stormwater runoff flows through the wetland facility, pollutant removal is achieved through settling and contaminant uptake by marsh vegetation. Wetlands are among the most effective stormwater practices in terms of pollutant removal and also offer aesthetic value and wildlife habitat.

They have a shallow and relatively constant depth of standing or slow-flowing water and contain both emergent vegetation and open water. Vegetated areas foster microbial communities that transform and remove stormwater pollutants, while open water areas aid in pathogen removal and hydraulic circulation.

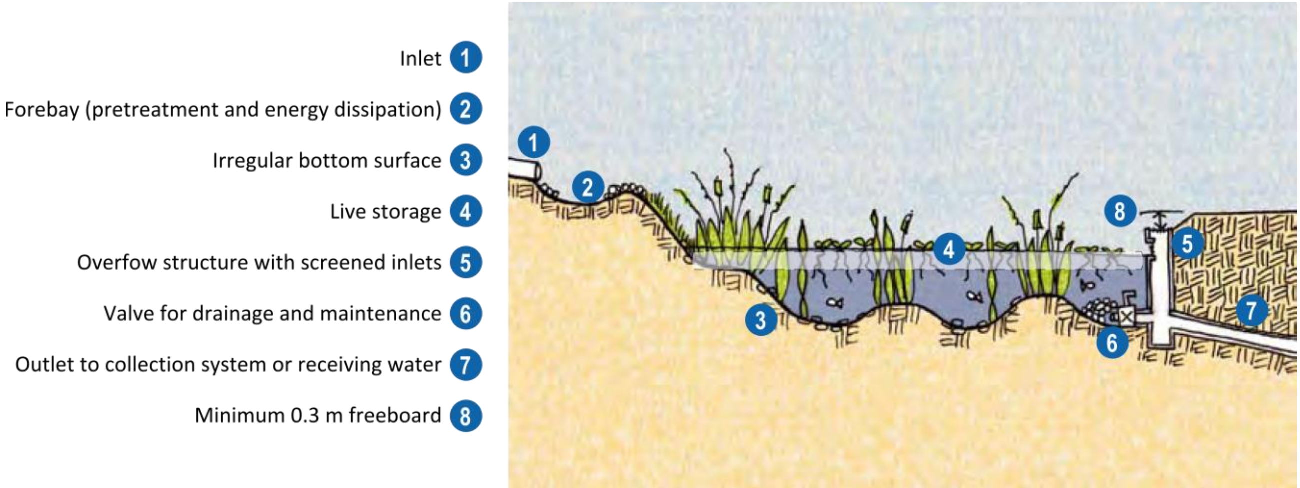


Figure 2.45. Surface wetland. Adapted from (SFPUC, 2009).

Benefits

- Effective at removing stormwater pollutants (sediment, nutrients, organic compounds, pathogens, heavy metals).
- With storage above the normal water level, it may reduce stormwater peak flows.
- Can reduce runoff volume if stormwater is stored and used.
- Can be designed to treat and store water for local non-potable use.
- Create a wetland habitat and increase biodiversity in the city.
- Provide open space and aesthetic amenity.
- Good in areas unsuitable for infiltration or with high groundwater table.
- Easily customizable to various sizes and dimensions.

Limitations

- Require a relatively large land area.
- May require supplemental water source during dry season.
- Seasonal variation in water quality improvement.
- Vegetation may appear dead in winter and summer.
- Colonization by invasive species may increase maintenance costs.
- Performance vulnerable to high sediment inflows.
- In general, little reduction in runoff volume.
- Not suitable for steep sites.

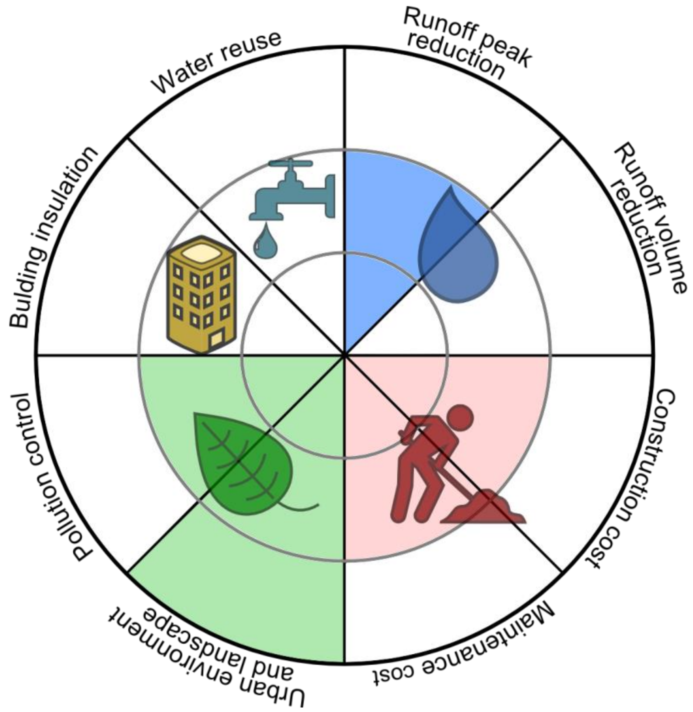
Performance summary	Picture
	

Figure 2.46. Constructed wetland in Leicester (England).

Design considerations

Constructed stormwater wetlands differ from natural wetland systems in that they are engineered facilities designed specifically for the purpose of treating stormwater runoff and typically have less biodiversity than natural wetlands both in terms of plant and animal life. However, as with natural wetlands, constructed wetlands require a continuous base flow or a high water table to support aquatic vegetation.

Wetlands can be used for both site and regional controls. High land take requirements may impede its use in high-density developments and the need for a perennial base flow may also be a constraining factor. Because they are not designed to reduce runoff by infiltration, constructed wetlands can be used in almost all soil types. In Mediterranean climates, wetlands may either be allowed to evaporate in the dry season, or may be supplemented with an alternative source of influent water. Wetlands may intersect the groundwater table, which will help support wetland vegetation. This should be avoided in areas where either the stormwater or the groundwater could be contaminated.

Operations and maintenance

Maintenance requirements for constructed wetlands are particularly high while vegetation is being established. Wetland facilities should be inspected after major storms during the first year of establishment to assess bank stability, erosion damage, flow channelization, and sediment accumulation within the wetland. A sediment marker should be located in the forebay to determine when sediment removal is required, since accumulated sediments will gradually decrease wetland storage and performance.

Approximate construction cost	40 €/m^3 storage volume	35-47 €/m^3
Approximate maintenance cost	1.3 €/m^3 storage volume/year	1-1.75 €/m^3/year
Approximate lifespan (CNT, 2006)	50 years	25-75 years
More information and references	(ARC, 2001), (CLADPW, 2010), (SCSMC, 2010), (SFPUC, 2009), (Woods-Ballard *et al.*, 2007).	

3. WATER QUANTITY AND QUALITY FROM DRAINAGE SYSTEMS

3.1. HYDRAULIC PERFORMANCE OF DRAINAGE SYSTEMS

When drainage systems are designed, their hydraulic performance is analyzed to determine their appropriate size and characteristics for a proper stormwater management. Different principles guide this hydraulic design (Woods-Ballard *et al.*, 2007) (Figure 3.1):

- **Flow management:** Urban drainage systems must ensure that people and property have a high level of protection from stormwater flooding. It is also important to ensure that stormwater management in an urban area reduces if possible, or at least does not increase, flood risk in downstream areas. Furthermore, drainage systems must also be designed to manage flooding during extreme events without increasing flood risk. Different design objectives will ensure flood protection:
    - **Conveyance:** Pipes and channels must be able to transport enough water in order to ensure urban flood protection and to avoid drainage system flooding. This design objective is very important when pipes are designed, especially in conventional drainage systems. Some SuDS, including swales and filter drains must have a conveyance function.
    - **Attenuation:** Some components in drainage system store runoff to reduce peak discharge. The volumes of storage must be designed to achieve a proper level of protection downstream. After the storm event, they should completely drain at a rate controlled by the outlet structure. This objective defines detention volume for structural detention facilities, detention basins and geocellular systems, and it is also very important in the design of most SuDS.
    - **Pumping:** In some cases, pumping stormwater is required to protect urban areas from flooding. These pumping facilities will determine the hydraulic performance of the drainage system. Pumping is usually the highest energy consumption process within the urban water cycle.
    - **Infiltration:** Infiltration systems must be constructed in soils with enough infiltration capacity andbe permeable and unsaturated. Furthermore, provision of sufficient storage capacity is essential for an infiltration system to perform properly.
- **Water quality improvement:** Appropriate stormwater management should effectively mitigate the pollution risks in receiving watercourses placing a further influence the hydraulic design of the infrastructures. In order to remove pollutants effectively, the following design objective can be considered:
    - **Retention:** Some facilities are designed to contain a permanent pool of water which is used to provide water quality treatment through biodegradation, as explained in Section 3.2. Retention ponds and constructed wetlands incorporate this permanent volume.

- **Filtering:** The runoff rate is especially important for system components whose primary mode of pollutant removal depends on the rate of flow of runoff through a filter media, like swales, filter strips, bioretention areas, filter drains and screening devices.

- **Infiltration:** Infiltration can also improve water quality. The provision of sufficient storage capacity is essential for an infiltration system to perform properly. Infiltration capacity is very important to design soakaways, infiltration trenches, infiltration basins, rain gardens and other type of SuDS where infiltration is feasible.

- **Attenuation to avoid excessive CSO discharge:** In combined systems, some detention structures can be designed to enable a reduction in the peak discharge in order to avoid excessive discharge from Combined Sewer Overflows. This attenuation volume is crucial in detention structures. Furthermore, attenuation volume is not designed to improve runoff water quality by itself, although it may often deliver benefits thanks to sedimentation within the storage.

- **Dilution:** When polluted stormwater is mixed with cleaner water, the concentration of pollutants decreases due to the dilution process. Dilution of pollutants can be important before releasing this water into the environment and it must be taken into account in the hydraulic design of drainage structures.

- **Other principles:** There are other objectives that can influence the hydraulic design of the drainage system:

  - **Water reuse:** The size of rain harvesting systems is defined according to the volume of water needed for reuse. Water reutilization is explained further in Section 3.3.

  - **Amenity objectives:** Sustainable drainage system design requires to give specific attention to their visual impact and their interaction with the local environments and residents.

  - **Ecologic objectives:** Maximizing the ecological value of drainage systems can make an important contribution to biodiversity enhancement at a development site and can facilitate the movement of wildlife through the creation of green corridors within the urban area.

Drainage system and component selection will depend on the objectives to be addressed since they define the criteria that must be followed to design each drainage system. Furthermore, selection is highly dependent on local conditions and regulations. Selection graphs and tables (SFPUC, 2009; Woods-Ballard *et al.*, 2007) can be very useful to summarize the local conditions needed for each kind of infrastructure and to support the decision-making process.

Drainage systems are normally designed by analyzing their hydraulic performance for rainfall events with target return periods. These rainfall events are estimated according to local climate conditions. An initial assessment of the runoff rates entering into drainage systems can be made using the Rational Method, which involves characterizing the permeability of the drainage area. For volume assessments, hydrographs methods are required (Woods-Ballard *et al.*, 2007). For these events, the design must ensure that all design criteria are satisfied. The entire drainage system must be analyzed together, since problems in one part can produce poor performance in others. Furthermore, the design of some drainage system components such as constructed wetlands and rain harvesting systems also requires a long term water balance.

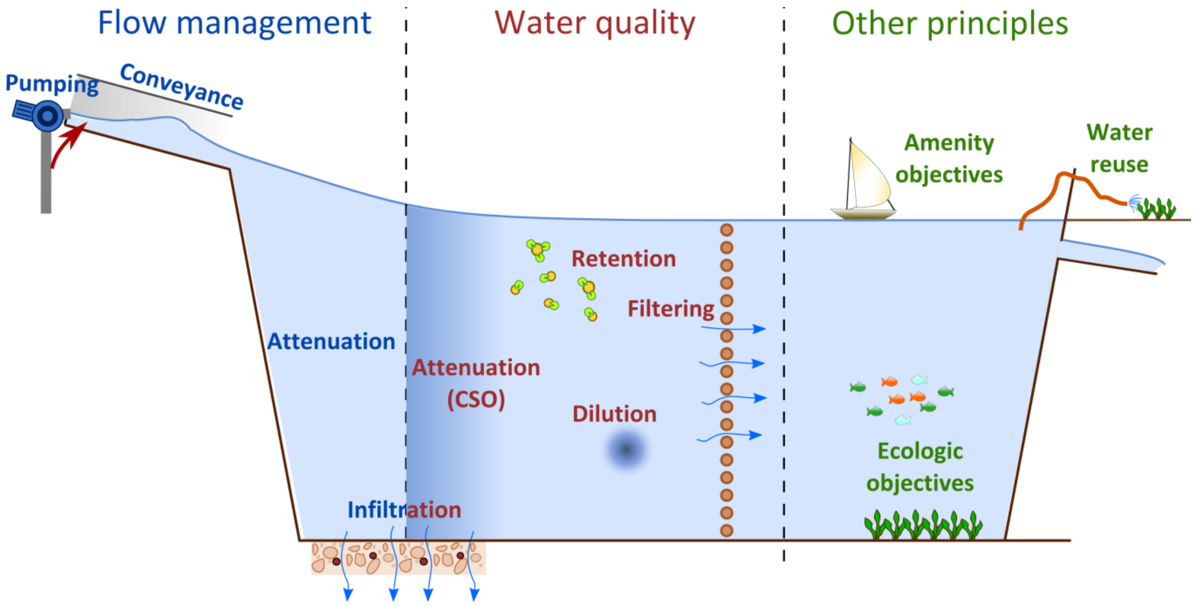


Figure 3.1. Summary of criteria that can influence the hydraulic design of drainage systems.

The following tools and guides can be useful to design drainage system infrastructures based on the objectives previously described:

- **Urban Hydrology for Small Watersheds** (USDA, 1986): Presents simplified procedures to calculate storm runoff volume, peak rate of discharge, hydrographs, and storage volumes within stormwater management systems. These procedures are applicable in small, especially urbanized watersheds.

- **Storm Water Management Model (SWMM)** (USEPA, 2013a): Free dynamic rainfall-runoff simulation model used for either single event or long-term simulation of runoff quantity and quality from primarily urban areas. New releases allow modeling of the hydrologic performance of SuDS such as permeable pavements, green roofs, infiltration trenches and vegetated swales.

- **Integrated Urban Drainage Modeling Guide** (WAPUG, 2009): Detailed technical guidance that explains how to choose and use integrated urban drainage models.

- **Virginia Runoff Reduction Method** (VDCR, 2012): This method focuses on determining the required capacity of SuDS to reduce the overall volume of runoff as well as pollutant removal. Two spreadsheets are available for stormwater design, one for new development and one for redevelopment.

- **San Francisco BMP Sizing Calculators** (SFPUC, 2013): Two spreadsheets available to guide SuDS design, one for separate sewers that is focused on water quality and one for combined sewer, focused on water quantity.

- **Stormwater and SuDS Manuals**: Different manuals provide guidelines to design stormwater systems and each type of SUDS. They also provide some formulations and procedures to define size and characteristics quickly. Some examples are: (CLADPW, 2010; CSQA, 2003; CP, 2008; NYSDEC, 2010; Puertas-Aguado *et al.*, 2008; Woods-Ballard *et al.*, 2007).

When the hydraulic design of infiltration-based drainage systems (for instance infiltration trenches, soakaways…) is under consideration, the infiltration capacity of the soil must be checked to ensure that the infrastructure will work properly. Some of the aspects that can influence infiltration are (SFPUC, 2013; Woods-Ballard *et al.*, 2007):

- Subsoil characteristics: Infiltration systems must be set back from the seasonal high groundwater table and far enough from any impermeable soil layers or bedrock.

- Infiltration rates: The infiltration capacity of the soil must be high enough to ensure that water is infiltrated properly. Field investigations are required to confirm soakaway rates and these systems are clearly not suitable for poor draining soils. A geotechnical investigation should ascertain how the stormwater runoff will move in the soil both horizontally and vertically, accounting for any geological conditions that could inhibit water movement or could produce flooding of other urban areas.

- Groundwater/sediment pollution: In general, SuDS and in particular infiltration systems are not suitable for areas with contaminated groundwater or sediment so they may not be appropriate in industrial sites or sites where chemical spills are likely to occur. They are not appropriate for sites that use or store chemicals or hazardous materials unless those materials are prevented from entering the infiltration system.

- Sensitive groundwater: Infiltration systems may increase the risk of groundwater pollution; only pre-treated runoff should be considered for infiltration to sensitive groundwater resources.

- Structural foundations: Infiltration systems are not suitable for locations where infiltrating water may put structural foundations at risk.

- Terrain slope: Infiltration does not work properly in steep areas.

In general, SuDS tend to provide better reduction of runoff volumes and rates for smaller storms, which occur more frequently than larger storms. Volume reduction can lead to reduced frequency of discharges or much smaller discharge volumes, which produces lower treatment costs, as explained in Section 4.

Table 3.1 shows a first approximation of global inflow volume reduction of the system components in Section 2. These values can be applied to infrastructures correctly designed and managed.

Values presented in Table 3.1 can be used to obtain a first approximation for annual runoff volume reduction in each infrastructure. These values are extremely dependent on system design and weather conditions. The more torrential the rainfall, the lower the annual volume reductions that will be achieved. In order to obtain an accurate estimation of runoff volume reduction in each infrastructure, a continuous model is needed. It must represent water balance in these infrastructures during a representative period, analyzing the interception, evapotranspiration and infiltration processes.

Regarding peak runoff reduction, some drainage infrastructures also produce attenuation of runoff. A qualitative evaluation of runoff rates reduction in each type of drainage infrastructure reduced is shown in the flood protection part of the summary graph presented in Section 2. In order to obtain how the outflow hydrographs from drainage infrastructures behave in a specific storm, a detailed modeling of the system should be made, for instance with some of the tools previously described.

Type of drainage infrastructure	% Runoff volume reduction	Source
Conventional drainage networks	**Not substantial reduction**	Estimation
Structural detention facilities	**Not substantial reduction**	Estimation
Rain harvesting systems	[1]	-
Water butts	[1]	-
Green roofs	**50 %**	(USEPA, 2012)
Permeable pavements	**Clay: 60%** **Sandy soils: 99%**	(USEPA, 2012)
Soakaways	**85%**[2]	Estimation
Infiltration trenches	**85%**[2]	Estimation
Geocellular systems	[3]	-
Bioretention areas	**50%**	(ISBMPD, 2011)
Rain gardens	**85%**[2]	Estimation
Filter strips	**Not substantial reduction**	Estimation
Filter drains	**Not substantial reduction**	Estimation
Vegetated swales	**40%**	(ISBMPD, 2011)
Infiltration basins	**85%**[2]	Estimation
Detention basins	**30%**	(ISBMPD, 2011)
Retention ponds	**Not substantial reduction**	(ISBMPD, 2011)
Constructed wetlands	**Not substantial reduction**	(ISBMPD, 2011)

[1]*Depending on water reused in each system. Guidelines for estimation this volume are explained in Section 3.3.*
[2]*If they are correctly designed, they should infiltrate all runoff volume except during very heavy rainfall events.*
[3]*Only volume reduction when is designed for infiltration. Volume reduction is very dependent on detention volume and infiltration capacity.*

Table 3.1. Approximated annual runoff volume reduction for each type of drainage infrastructure.

3.2. WATER QUALITY IN DRAINAGE SYSTEMS

In addition to changes in local hydrology, urbanization also causes an increase in types and quantities of pollutants in surface and ground waters. Runoff from urban areas has been shown to contain many different types of pollutants, including oils and greases, Polynuclear Aromatic Hydrocarbons (PAH's), heavy metals, sediments (soil particles) and agricultural pollutants such as herbicides, pesticides and nutrients (WSDE, 2012). Rainwater mobilizes all of these pollutants which are washed into drainage system and sometimes into rivers or into groundwater. All these contaminants can seriously damage the environment and the beneficial uses of receiving waters.

To minimize the impact of pollutants on receiving water bodies, a water quality management train is required, as explained in Section 2. The main pollutant removal mechanisms that occur in stormwater systems are (Woods-Ballard *et al.*, 2007) (Figure 3.2):

- **Filtration and biofiltration:** The runoff is filtered using a variety of filtration media, for instance gravels (filter drains, permeable pavements, soakaways, infiltration trenches), soils (bioretention areas, rain gardens), surface vegetation (vegetated swales, filter strips) or aquatic vegetation (constructed wetlands).

- **Sedimentation:** Storing runoff allows sediment particles to fall out of suspension. Most pollution in runoff is attached to sediment particles and therefore removal of sediments results in significant reduction in pollutant loads. Some examples of SuDS where this process occur are detention basins, structural detention facilities, retention ponds and constructed wetlands.

- **Adsorption:** occurs when pollutants attach or bind to the surface of soil or aggregate particles. Some examples where this process occurs are filter drains, permeable pavements, soakaways, infiltration trenches, constructed wetlands, retention ponds and rain gardens.

- **Biodegradation:** Retention ponds and wetlands promote plants and microbial activity to degrade organic pollutants such as oils and greases. This process will depend on environmental conditions such as temperature and the supply of oxygen and nutrients.

- **Volatilization:** comprises the transfer of a compound from solution in water to the soil atmosphere and then to the general atmosphere. In SuDS, It occurs primarily with organic compounds petroleum products and pesticides. This process might be important in bioretention areas, green roofs and permeable pavements.

- **Uptake by plants:** In ponds and wetlands, uptake by plants is an important removal mechanism for nutrients.

- **Nitrification:** Ammonia and ammonium ions can be oxidized by bacteria in the ground to form nitrate, which is a highly soluble form of nitrogen. Nitrate is readily used as a nutrient by plants.

- **Photolysis:** The breakdown of organic pollutants by exposure to ultra-violet light.

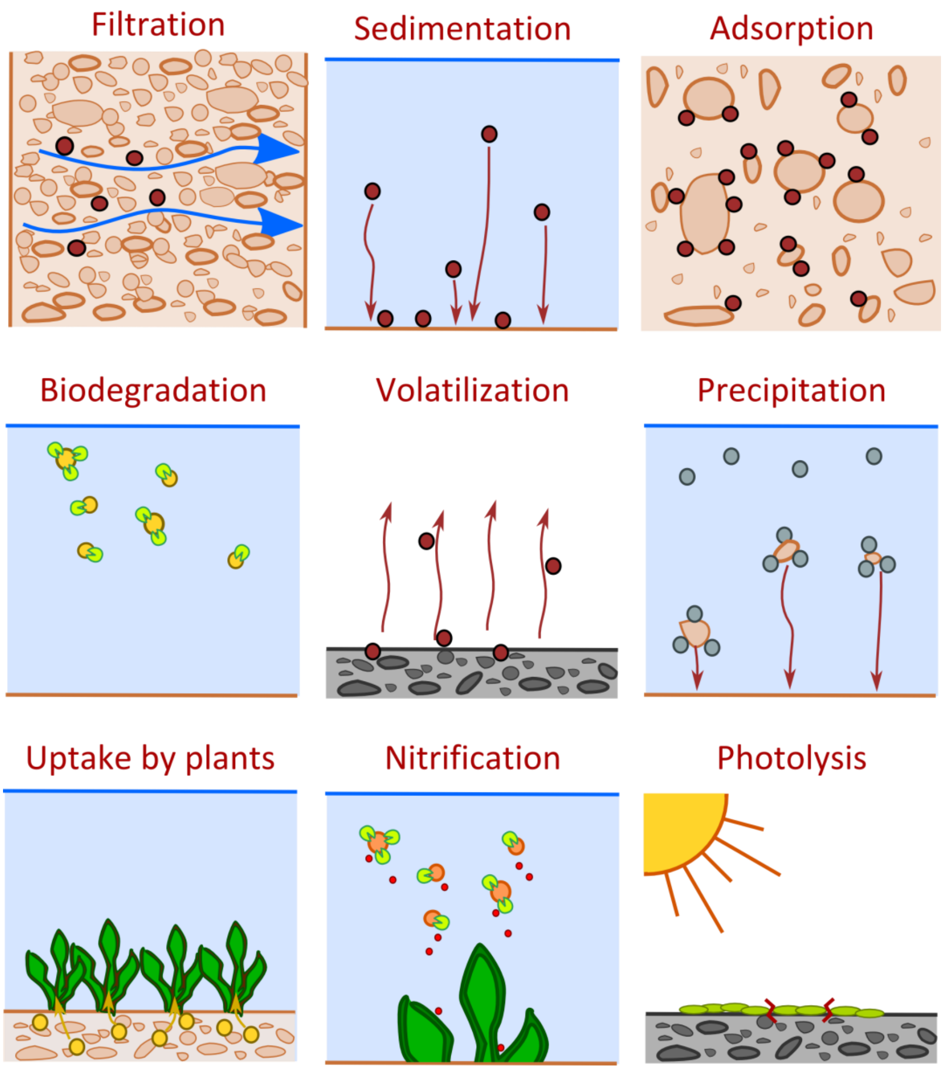


Figure 3.2. Schemes of the main pollutants removal mechanisms.

As explained in the previous chapter, these water quality treatment options must influence stormwater infrastructures sizing and design, especially when SuDS are used. There are available some tools and manuals that can be useful to analyze water quality processes in detail and estimate outflow water quality after each treatment:

- **CIRIA The SuDS Manual** (Woods-Ballard *et al.*, 2007): This manual provides general guidance to design stormwater management trains and explains how to take into account water quality processes in the design of each type of infrastructure.

- **California Stormwater Best Management Practice Handbook** (CSQA, 2003): provides guidance to design stormwater infrastructures for water quality protection.

- **Georgia Stormwater Management Manual** (ARC, 2001): General guidance is provided to estimate pollutant removal efficiency of stormwater infrastructures individually and in series.

- **SUSTAIN model** (USEPA, 2013b): Software that provides process-based simulation of flow and pollutant behavior for a wide range of structural SuDS. It provides guidance to optimize stormwater management trains.

In order to obtain quantitative results on quality performance of drainage systems it is important to analyze each case and storm in detail since stormwater quality is highly variable during a storm, from storm to storm at a site, and between sites even of the same land use (NYSDEC, 2010). Furthermore, water quality processes are not linear, so a water treatment train will produce different results depending on the order of the treatment processes.

As a simplification of these processes, Table 3.2 shows a qualitative indication of pollutant removal efficiencies for each drainage infrastructure explained in Section 2. Three main pollutants groups are addressed: total suspended solids, nutrients and heavy metals.

Type of drainage infrastructure	Total suspended solids	Nutrients	Heavy metals
Conventional drainage networks	Low	None	Low
Structural detention facilities	Medium	None	Low
Rain harvesting systems	High	Low	Medium
Water butts	Low	Low	Low
Green roofs	High	Low	Medium
Permeable pavements	High	High	High
Soakaways	Medium	Low	Medium
Infiltration trenches	High	Low	High
Geocellular systems	Low	None	Low
Bioretention areas	High	Low	High
Rain gardens	High	Low	High
Filter strips	Medium	Low	Medium
Filter drains	High	Low	High
Vegetated swales	High	Low	Medium
Infiltration basins	High	Medium	High
Detention basins	Medium	Low	Medium
Retention ponds	High	Medium	High
Constructed wetlands	High	Medium	High

Table 3.2. Quantitative evaluation of pollutants removal efficiency of each drainage infrastructure. Adapted from (Woods-Ballard et al.*, 2007).*

Water quality performance of treatment trains cannot be generalized, since they will vary with climatic conditions and inflow concentrations. Where risks posed to the environment are likely to be high, then a larger number of components should be included within the management train. Table 3.3 gives an indication of the minimum number of components likely to be appropriate for different contributing and receiving catchment characteristics assuming all effectively remove pollutants (Woods-Ballard *et al.*, 2007). However, for larger sites, an increased number of components will generally be required to meet all design criteria.

Runoff catchment characteristics	Receiving water sensitivity		
	Low	Medium	High
Residential roofs only	**1**	**1**	**1**
Residential roads **Parking areas** **Commercial zones**	**2**	**2**	**3**
Industrial areas **Highways** **Lorry parks**	**3**	**3**	**4**

Table 3.3. Minimum number of infrastructures components in the water quality management train for different contributing and receiving catchment characteristics. (Woods-Ballard et al.*, 2007).*

When these management trains are designed all types of pollutants likely to be present in the stormwater must be addressed, since some components will be more effective than other in removing, for example, nutrients or sediments. A proper management train must include components with a significant removal efficiency of all the types of pollutants that reach the train from the catchment area.

On one hand, in separate sewer systems, water quality improvements using drainage infrastructures avoid treating stormwater in regional facilities and water can be directly released into the environment. Improved water qualities deliver economic benefits and energy savings, as explained in Section 4.2. On the other hand, in combined sewer systems, a better stormwater quality avoid problems of wastewater treatment plants due to additional pollutants that stormwater can contain, such as heavy metals and oils. Furthermore, if discharges from Combined Sewer Overflows are produced, pollution will be lower if stormwater quality has been improved in the drainage system infrastructure.

3.3. STORMWATER REUTILISATION

Stormwater reutilization with rainwater harvesting systems is an ancient technique which is currently enjoying a revival in popularity due to the inherent quality of rainwater and the interest in reducing the consumption of treated water (TWDB, 2005). As explained in Section 2, with these systems, the water collected is used for non-potable purposes such as flushing toilets, washing machines and irrigation. Rainwater harvesting systems can also be used to provide potable water, but a sophisticated water treatment system may be necessary to ensure compliance with potable water quality standards. Water butts are the simplest type of rainwater harvesting systems and are typically used for irrigation purposes.

A first approximation of water reused volume can be obtained with a monthly water balance in these systems, as shown in Figure 3.3.

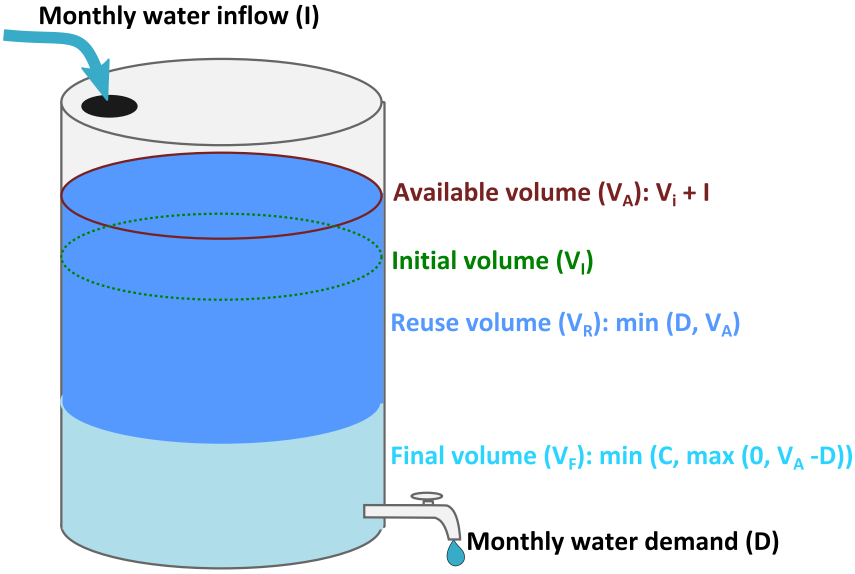


Figure 3.3. Monthly water balance in rain harvesting systems.

In this balance, monthly water inflow (I) can be estimated with the following formula (Woods-Ballard *et al.*, 2007):

$$I = R \cdot A \cdot C \cdot e \qquad \textit{Equation 3.1}$$

Where I is the monthly water inflow (m^3), R is the monthly average rainfall (m), A is the catchment area of the rain harvesting system (m^2), C is the drainage coefficient, which indicates the proportion of the runoff that reaches the collection tank (recommended values is 0.9 for conventional roofs) and e is the filter efficiency, which represents the proportion of the collected water that is available for use (recommended value of 90%). Drainage coefficient and filter efficiency will depend on each rain harvesting system distribution and the mechanism to collect the water in the roof.

Monthly water demand (D) should be estimated for irrigation and household uses. Household water demand is more stable and depends on the number of inhabitants of the house. The volume of water needed will also depend on its use, for instance, for toilets use, 5-10 toilet flushes can be considered per person and per day (SFPUC, 2012).

Irrigation demand is usually more seasonal and can be estimated using evapotranspiration formulations (Allen *et al.*, 1998; UCCE, 2000).

This simple water balance can be used for a first approximation of rain harvesting systems. A more detailed analysis can be made using the following tools and manuals:

- **Rain harvesting manuals:** Several manuals provide guidelines to design and maintain rain harvesting systems. Some examples are (CBC, 2007) and (TWDB, 2005).

- **NCSU Rainwater Harvesting Model** (NCSU, 2013): This computer model is available online to assist in determining the appropriate cistern size for a given situation. The model uses rainfall data and anticipated usage to establish cistern inputs and outputs.

- **Rainwater Harvesting Calculators**: Spreadsheets developed by public entities to estimate the annual performance of a rainwater harvesting cistern based on the estimation of the runoff to the cistern, cistern size and the site's non-potable demand. Some examples are the spreadsheets for San Francisco (SFPUC, 2012) and for Texas (TWDB, 2010).

In addition to rainwater harvesting systems, other drainage arrangements also provide an opportunity for stormwater reutilization. They allow stormwater to infiltrate, potentially recharging aquifers and improving water quality. This water can later be used later for urban water supply or irrigation. Some examples are soakaways, infiltration trenches, infiltration basins and rain gardens.

4. COSTS AND BENEFITS RELATED WITH STORMWATER MANAGEMENT

4.1. WASTEWATER TREATMENT COST (COMBINED SYSTEMS)

In a combined drainage system, stormwater goes into the sewerage system, which also collects wastewater from houses and industries and it usually delivers it to facilities for treatment before it is discharged to water bodies or land, or reused (USEPA, 2004). Some drainage systems (especially with SuDS) reduce runoff volumes entering the wastewater network and improve their quality, what decreases water treatment costs (Philip, 2011b). Hence, wastewater collection and treatment costs may influence the selection between different drainage system options.

Some of the most common wastewater treatment methods are (USEPA, 2013c):

- Aerated basin: Treatment pond provided with artificial aeration to promote the biochemical oxidation of wastewaters
- Activated sludge without nutrients removal: Reactor where microorganisms are cultivated and are in contact with the wastewater to eliminate the organic pollutants.
- Activated sludge with nutrients removal: Activated sludge process that includes microorganism to eliminate nitrogen and phosphorus.
- Trickling filter: Aerobic treatment system that utilizes microorganisms attached to a medium to remove organic matter from wastewater. They are also called biofilters.
- Rotating biological contactors: A variation of trickling filters consisting of parallel discs where microorganisms grow in the surface and produce the biological degradation of wastewater pollutants.
- Tertiary treatment: When the previous treatments are completed with an advanced treatment. In general, the purpose of these treatments is eliminating nutrients like nitrogen and phosphorus.

In this section, guidance for estimating wastewater treatment cost is provided in order to introduce runoff reduction economic benefits in the drainage system infrastructures analysis. In general, this cost can be estimated with the following formula:

$$C = V_w \cdot c_{trea} \qquad \textit{Equation 4.1}$$

Where C is the total cost of wastewater treatment (monetary units/year), c_{trea} is the unitary cost of wastewater treatment (monetary units/m^3) and V_w is the annual volume of water which flows into the wastewater network (m^3/year). This volume of water can be estimated for each drainage system option according to the guidelines provided in Section 3.1.

The unitary treatment cost (c_{trans}) can be provided by the wastewater management department or company, although sometimes this data is not public and may be very dependent on local management aspects. Operating and maintenance cost of Wastewater Treatment Plants (WWTP) include labour, electricity, chemicals, laboratory analysis, repairs, equipment replacement, and administrative costs, including insurance and sludge disposal (CAPE COD Commission, 2013). When this cost is estimated, the following aspects must be taken into account:

- Treatment processes applied in the wastewater management plant.
- Treatment plant capacity, a higher volume of water treated shall produce lower unitary costs.
- Year of construction, since newer plants and technologies are more efficient.

In order to obtain approximate unitary treatment cost (c_{trea}), the results of a study made with data from 341 WWTP has been used (Molinos Senante, 2012). These WWTP treat mainly wastewater from urban areas and are located in the Valencian Community in Spain. According to the equations obtained in this study, the unitary treatment cost can be obtained from the annual volume of water treated in the plant, the type of treatment processes and the plant age:

$$c_{trea} = A \cdot V_{WWTP}{}^{B} \cdot e^{C \cdot t + D} \qquad \textit{Equation 4.2}$$

Where c_{trea} is the unitary cost of wastewater treatment (€/m^3), V_{WWTP} is the annual capacity of the WWTP (m^3/year), t is the WWTP age (years), A, B, C and D are constants obtained directly from data adjustment. The value of these constants is shown in Table 4.1.

Type of main treatment	A	B	C	D
Primary and secondary treatments				
Aerated basin	169.48	-0.546	0.0009	0.5483
Activated sludge without nutrients removal	2.1165	-0.2872	0.0174	1.4396
Activated sludge with nutrients removal	2.518	-0.2847	0.007	1.6534
Trickling filter	17.361	-0.4229	0.1006	0.5650
Rotating biological contactors	28.952	-0.5507	0	2.1679
Tertiary treatments				
General tertiary treatment	3.7732	-0.2777	0	0.5733

Table 4.1. Constants to compute WWTP unitary costs.

For instance, the estimated unitary treatment cost of an aerated basin WWTP with an age of 7 years, an annual capacity of 147,500 m^3 is 0.44 €/m^3. If this plant had a tertiary treatment, this cost would be 0.245 €/m^3 higher.

The previous recommendations can be applied when wastewater is treated in a WWTP. In other cases, like individual and small cluster wastewater treatment systems, the unitary treatment cost must be computed analyzing these local processes.

In addition to the benefits from reducing the volume of runoff and water quality improvement, other environmental benefits are also obtained when peak flow is reduced. Larger wet weather events can overwhelm a combined sewer system by introducing more stormwater than the collection system or wastewater treatment plant is able to handle. In these situations, rather than backing up sewage and stormwater into basements and onto streets, the system is designed to discharge untreated sewage and stormwater directly to nearby water bodies through outfalls that release raw sewage and other pollutants (Combined Sewer Overflows) (Garrisson and Hobbs, 2011). Therefore decreasing runoff peaks may reduce the probability of environment pollution, which implies a benefit as explained in Report on Ecosystem services (E^2STORMED project).

4.2. STORMWATER TREATMENT COST (SEPARATE SYSTEMS)

As explained in the previous section, some drainage system components (especially SuDS) reduce runoff volumes and improve their quality. This quantity reduction and quality improvement can also reduce stormwater treatment cost in separate drainage systems. So, this cost reduction should be taken into account when different drainage system options are analyzed.

Many separate sewer systems discharge high volumes directly to receiving water bodies with little or no treatment (Philip, 2011b). In these cases, the reduction of treatment costs produced by lower runoff volumes and pollution is not significant. However, this release of water and contaminants produces an environmental impact on receiving water bodies. This impact is clearly dependent on runoff quantity and quality, and the economic value can be estimated, as explained in Report on Ecosystem Services (E^2STORMED project).

When SuDS are used, stormwater treatment is mainly made with on-site infrastructures. Stormwater quality is improved with bioretention areas, sand filters, detention basins, etc. When different drainage system options are analyzed, the cost of these treatments must be included in the operation and maintenance cost of the infrastructures.

Besides the treatment made in the infrastructures presented in Section 2, some other treatments can be applied to stormwater before being released into the receiving bodies. Some options are (NSWEPA, 1997):

- **Mesh screen**: Physically traps and removes larger objects from the stormwater.
- **Sedimentation tank**: Helps to remove larger-sized pollutants through sedimentation (the natural settlement of solids). Detention facilities described in Section 2 can be used for this purpose if they are designed for sediments management.
- **Litter booms** (Figure 4.1): Are floatation structures with suspended curtains that can be used to contain floating trash (SCVURPPP, 2007). Booms are best suited to slow-moving waters. Since more pollutants sink than float, they are only useful for trapping highly buoyant materials and can miss most of the gross solids load. Booms were initially designed as oil slick retention devices, and are still often designed using absorbent materials to collect oil and grease from the water’s surface.

- **Alum treatment systems**: It is an innovative solution where stormwater runoff is chemically treated by injecting liquid alum into storm sewer lines on a flow-weighted basis during rain events (ARC, 2001).

It is extremely difficult to generalize stormwater treatment costs since it mainly depends on local treatment processes and characteristics. When no local data is available, the U.S. Center for Neighborhood Technology recommends a cost for stormwater treatment of 0.0185 €/m^3 (CNT, 2006), based on treatment costs in Chicago (Torres, 2004). This value can be used at a screening level to compare the effect of runoff reduction in different drainage infrastructures when stormwater is regionally treated. This regional treatment can be avoided if stormwater is treated at source, for instance with Sustainable Drainage Systems.

Figure 4.1. Picture of a litter boom (SCVURPPP, 2007).

4.3. STORMWATER TRANSPORT COST

In combined and separate systems, sometimes stormwater need to be pumped to reach the treatment plant or to be released in the environment. This pumping may produce significant energy consumptions and costs (CAPE COD Commission, 2013). Therefore, reducing runoff volumes will result in important savings of electricity. The main factors that have influence on pumping costs are:

- Runoff volume of water to be pumped.
- Size of the pump.
- Height difference between inflow and outflow points.
- Efficiency of the pump and motor.
- Stormwater/wastewater network age and state.
- Energy source: electricity or fuel.

In order to estimate this pumping cost, a simplification can be made considering only the electricity or fuel necessary to pump each cubic meter. Therefore, the total cost of stormwater transport will be obtained multiplying this value by the produced runoff volume.

Guidance for estimating energy consumption in this pumping process is provided in the Report on Energy in the urban water cycle (E^2STORMED project). When the electricity consumption is obtained, the pumping cost can be easily estimated with the electricity or fuel cost.

4.4. Flood protection benefits

A significant proportion of flooding is due to local problems from sources such as surface stormwater runoff. Damage caused by local flooding is significant and includes: loss of life, damage to domestic and business premises, loss of livestock and damage to agriculture, infrastructural damage and loss of revenue (DEFRA, 2009). Therefore, drainage systems that contribute to reduce these flood events produce important social and economic benefits.

Although both conventional drainage systems and SuDS protect urban areas, they manage floods in a different way. SuDS manage more water above-ground than conventional drainage systems, keeping water out of sewers. Conventional systems are designed to move water downstream as quickly as possible. SuDS store surface water and allow it to infiltrate into the ground or gradually release it downstream, where possible, to the natural drainage system (DEFRA, 2009).

Flood protection benefits can be obtained using economic risks calculations for pluvial flooding. This risk is estimated relating different pluvial flood events defined by a return period (inverse of probability of exceedance) with the estimated economic consequences of these events. In the case of stormwater flood risk, the most significant events are usually the events with a relatively low return period (5-100 years), since these are the events that in general might be properly managed by the urban drainage system.

In order to estimate the expected economic consequences in each flood event, different methodologies can be used (Escuder-Bueno *et al.*, 2011; QG, 2002). According to them, economic damages are usually estimated as a function of:

- Flood water depth.
- Reference cost (monetary units/m^2) for each urban land use and infrastructure. It is estimated supposing that this land use is completely destroyed.
- Damages-depth curves: They define a relation between water depth and percentage of damages for each urban land use.

As a simplification, these consequences can be estimated analyzing the number of properties protected by the analyzed drainage system during each event and multiplying it by the average economic damages per property during flood events. Average economic damages per property during flood events (*D*) depend on many local and national aspects, like construction typologies and materials, local standard of living, etc. For England, a value between 27,615 € and 34,895 € is recommended (HGL, 2009). There is also an online tool available (NFIP, 2013) that estimates average economic damages per household in United States as a function of water depth.

Results of flood economic consequences are used to represent flood risk by means of Frequency-Damages (FD) curves. These curves show the annual exceedance probability (inverse of return period) of each event versus its flood economic consequences. The area under the curve is the economic risk (monetary units per year) of pluvial flooding. If FD curves are computed for the cases with and without a drainage infrastructure, flood protection economic benefits are directly obtained with the difference between these two curves (Figure 4.2).

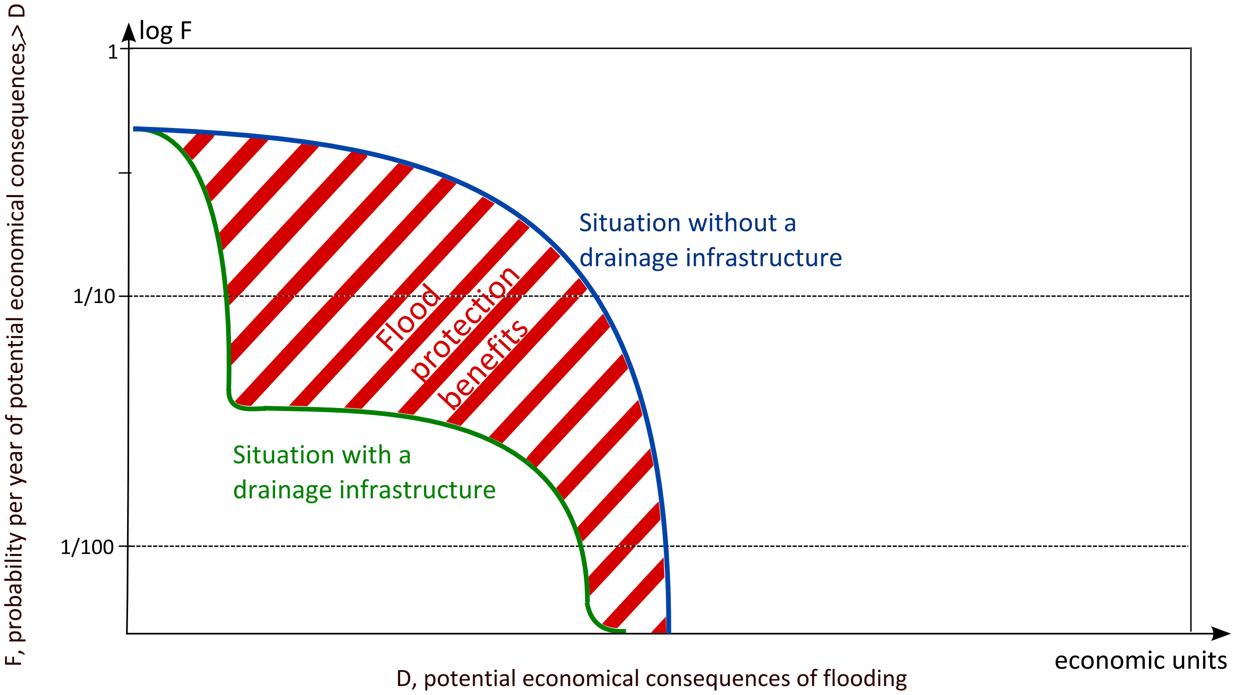


Figure 4.2. FD curves for representing flood economic risk. Adapted from (Escuder-Bueno et al.*, 2011).*

Figure 4.2 shows only the part of the FD curves more significant for pluvial flood events. In a more detailed analysis, flood risk must be analyzed in an integrated way, taking into account all the measures that can contribute to flood protection, like embankments, dikes and large dams, and considering flood events with a higher return period.

Methodologies for estimation of pluvial flood consequences (Escuder-Bueno *et al.*, 2011) also include other social consequences whose economic quantification is more complex, like loss of life. These consequences must be included in a detailed flood analysis, since they can be significant in high-magnitude flood events.

4.5. OTHER BENEFITS AND COSTS

Besides the benefits and costs explained in the previous sections, there are other issues that can influence decision-making on stormwater management. Some of these issues can also be economically quantified, for example:

- **Water reuse benefits:** Some SuDS incorporate systems to reuse stormwater for non-potable purposes such as irrigation and industrial use. The economic benefits of this reutilization can be estimated multiplying the annual volume of water reutilized (Section 3.3.) by the cost of this water if it was provided by the water supply system.

- **Building insulation improvement:** Green roofs improve buildings insulation, which reduces the energy consumption for heating and air conditioning systems. Economic benefits of this improvement can also be quantified, as explained in the Report on Energy in the urban water cycle (E^2STORMED project).

- **Ecosystem services:** Some SuDS can also improve urban landscape and environment. They achieve this through (CNT, 2010; Philip, 2011b; Woods-Ballard *et al.*, 2007):

    - Encouraging natural groundwater recharge.
    - Reducing the concentrations of pollutants in stormwater, thus protecting the quality of the receiving water body.
    - Contributing to the enhanced amenity and aesthetic value of developed areas.
    - Providing habitats for wildlife in urban areas and opportunities for biodiversity enhancement.
    - Reducing the urban heat island effect. This effect is produced by the rapid removal of stormwater from urban areas that reduces evapotranspiration. When combined with the heating effect of sealed surfaces this results in a hotter urban microclimate. Urban heat island effect compromises human health and comfort by causing respiratory difficulties, exhaustion, heat stroke and heat-related mortality.
    - Improving urban air quality.

  These environmental benefits can also be economically quantified, as explained in the Report on Ecosystem Services (E^2STORMED project).

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ANNEX 1.
INFRASTRUCTURES COSTS REVIEW

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CONSTRUCTION COST

Drainage infrastructures costs are very site specific and therefore, general unitary construction costs can only be used for a first approximation and cannot be considered as definitive values. More detailed construction costs can be obtained developing a construction project for each infrastructure. Besides the manuals listed in Section 3.1., there are many whole life cost models for drainage infrastructures (SEPA, 2013; WERF, 2009), that can be useful for estimating costs in this process.

In this table, a comparison is made of proposed infrastructures cost from different stormwater manuals and references. Finally, an average value and a range for each type of infrastructure are proposed based on these values. These values are used as guidance in the E^{2}STORMED Decision Support Tool.

Type of drainage infrastructure	Source				Estimated average and range
	(Royal Haskoning DHV, 2012)	(CNT, 2006)	(SFPUC, 2009)	(SCSMC, 2010)	
Conventional drainage networks	-	-	-	-	200 €/m (50-400) Estimation
Conventional roof	-	40 €/m² (20-82)	-	-	60 €/m² (20-82)
Standard pavement	-	35 €/m² (23-101)	-	-	50 €/m² (23-101)
Structural detention facilities	647 €/m³ (602-690)	311 €/m³ (115-612)	-	-	400 €/m³ (115-690)
Rain harvesting systems	1333 €/property	-	200-400 €/m³	200 €/m³	250 €/m³ (200-400)

Type of drainage infrastructure	Source (Royal Haskoning DHV, 2012)	(CNT, 2006)	(SFPUC, 2009)	(SCSMC, 2010)	Estimated average and range
Water butts	763 €/m³ (444-1082)	220 €/m³ (145-508)	180-240 €/m³	290-437 €/m³	250 €/m³ (145-1082)
Green roofs	129 €/m² (64-135)	123 €/m² (48-132)	148 €/m²	41-205 €/m²	145 €/m² (48-205)
Permeable pavements	395 €/m³ (322-468)	43 €/m² (14-82)	16-65 €/m²	14-29 €/m²	60 €/m² (14-82)
Soakaways	146 €/m³	-	107-242 €/m³	-	150 €/m³ (107-242)
Infiltration trenches	88 €/m³ (82-94)	-	135-1350 €/m³	-	120 €/m³ (82-1350)
Geocellular systems	-	-	-	-	350 €/m³ (200-700) Estimation
Bioretention areas	-	65 €/m² (4.5-190)	66 -260 €/m²	25-328 €/m²	75 €/m² (4.5-328)
Rain gardens	-	40 €/m² (30-130)	65 €/m²	-	50 €/m² (30-130)
Filter strips	6 €/m²	12 €/m² (0.25-27)	2.5-5.7 €/m²	-	6 €/m² (0.25-27)

Type of drainage infrastructure	Source (Royal Haskoning DHV, 2012)	(CNT, 2006)	(SFPUC, 2009)	(SCSMC, 2010)	Estimated average and range
Filter drains	175 €/m³ (146-205)	-	-	-	175 €/m³ (146-205)
Vegetated swales	18 €/m²	-	2.7-4.9 €/m²	-	15 €/m² (2.7-18)
Infiltration basins	21 €/m³ (18-23)	-	80-485 €/m³	-	65 €/m³ (18-485)
Detention basins	27 €/m³ (23-29)	27 €/m³ (17-34)	26 €/m³	-	22 €/m³ (17-34)
Retention ponds	47 €/m³ (35-58)	-	13.5-27 €/m³	-	45 €/m³ (13.5-70)
Constructed wetlands	41 €/m³ (35-47)	-	35 €/m²	-	40 €/m² (35-47)

MAINTENANCE COST

Drainage infrastructures costs are very site specific and therefore, general unitary maintenance costs can only be used for a first approximation and cannot be considered as definitive values. There is also a relation between construction and maintenance costs: better construction standards will produce lower maintenance costs. More detailed maintenance costs can be obtained developing a maintenance plan for each infrastructure. Besides the manuals listed in Section 3.1., there are many whole life cost models for drainage infrastructures (SEPA, 2013; WERF, 2009), that can be useful for estimating costs in this process.

In this table, a comparison is made of proposed maintenance cost from different stormwater manuals and references. Finally, an average value and a range for each type of infrastructure are proposed based on these values. These values are used as guidance in the E^{2}STORMED Decision Support Tool.

Type of drainage infrastructure	Source				Estimated average and range
	(Royal Haskoning DHV, 2012)	(CNT, 2006)	(SFPUC, 2009)	(SCSMC, 2010)	
Conventional drainage networks	-	0.77 €/m	-	-	1 €/m (0.1-5)
Conventional roof	-	0.4 €/m^2 (0.16-1.2)	-	-	0.4 €/m^2 (0.16-1.2)
Standard pavement	-	0.45 €/m^2 (0.4-0.5)	-	-	0.45 €/m^2 (0.4-0.5)
Structural detention facilities	-	0.8 €/m^3 (0.4-1.6)	-	-	1.5 €/m^3 (0.4-3)
Rain harvesting systems	140 €/property	-	-	-	70 €/m^3 (20-300) (Estimation)
Water butts	-	0 €/m^3	-	-	1 €/m^3 (0-5) (Estimation)

Type of drainage infrastructure	Source (Royal Haskoning DHV, 2012)	(CNT, 2006)	(SFPUC, 2009)	(SCSMC, 2010)	Estimated average and range
Green roofs	0.5 €/m² (0.2-0.7)	12 €/m² (10-16)	45 €/m²	-	15 €/m² (0.2-45)
Permeable pavements	1.1 €/m² (0.7-1.5)	0.3 €/m² (0.08-1.8)	0.75 €/m²	0.08-0.5 €/m²	1 €/m² (0.08-3)
Soakaways	0.1 €/m³	-	5.3-24.2 €/m³	-	5 €/m³ (0.1-24.2)
Infiltration trenches	0.9 €/m³ (0.35-1.5)	-	4-48 €/m³	-	3 €/m³ (0.35-48)
Geocellular systems	-	-	-	-	0.8 €/m³ (0.3-2.5) (Estimation)
Bioretention areas	-	6.5 €/m² (0.3-8.2)	8 €/m²	-	8 €/m² (0.3-12.5)
Rain gardens	-	2.5 €/m² (1.5-4.9)	-	-	2.5 €/m² (1.5-4.9)
Filter strips	0.1 €/m²	0.6 €/m²	0.06 €/m²	-	0.1 €/m² (0.06-0.6)
Filter drains	0.9 €/m³ (0.35-1.5)	-	-	-	0.9 €/m³ (0.35-1.5)

Type of drainage infrastructure	Source				Estimated average and range
	(Royal Haskoning DHV, 2012)	(CNT, 2006)	(SFPUC, 2009)	(SCSMC, 2010)	
Vegetated swales	0.1 €/m²	-	0.03 -0.16 €/m²	-	0.1 €/m² (0.03-0.16)
Infiltration basins	0.35 €/m² (0.1-0.5)	-	4-30 €/m³	-	4 €/m³ (0.3-48.5)
Detention basins	0.35 €/m² (0.1-0.5)	0.27 €/m³ (0.17-0.34)	0.7-1.3 €/m³	-	0.5 €/m³ (0.17-1.3)
Retention ponds	1.5 €/m² (0.7-2.2)	-	0.4-1.3 €/m³	-	1.5 €/m³ (0.4-5)
Constructed wetlands	0.1 €/m²	-	1-1.75 €/m²	-	1.3 €/m³ (1-1.75)

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E²STORMED PROJECT

Improvement of energy efficiency in the water cycle by the use of innovative storm water management in smart Mediterranean cities

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