Effects of Low Impact Development (LID) and Green Infrastructures (GI) in the control of quality and quantity of stormwater

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Abstract

Urban areas worldwide face escalating stormwater management challenges due to climate change and rapid urbanization. This thesis evaluates the effectiveness of Low Impact Development (LID) and Green Infrastructure (GI) practices in controlling both quantity and quality of urban stormwater runoff through comparative analysis of European and Pakistani implementations.

The research focuses on four main technologies: bioretention systems, permeable pavements, grass swales or bioswales, and green roofs. It analyzes their design criteria, hydrological performance, and ability to remove pollutants. The study draws on case studies from European projects such as the Augustenborg eco-district in Sweden, the Copenhagen Cloudburst Management Plan in Denmark, and the Marsala wetlands in Italy, as well as Pakistani initiatives like the Sialkot floating wetlands, QAAP rainwater harvesting, and CDA recharge wells.

Key findings demonstrate that bioretention systems achieve 70-95% TSS removal and 40-60% runoff reduction, while green roofs provide 60% stormwater retention. European projects show sustained city-wide benefits with 20-year monitoring (Augustenborg: 20% runoff reduction; Copenhagen: 100-year storm management), while Pakistani pilots demonstrate promising localized results (QAAP: 24% peak flow reduction, 3-year payback; Sialkot: >90% chromium removal) but face monitoring gaps (1-3 years vs. 10-20 years in Europe).

The comparative analysis reveals that European success stems from integrated policy frameworks (Water Framework Directive, Floods Directive), standardized design guidelines, comprehensive monitoring protocols, and dedicated funding mechanisms. Pakistani implementations face fragmented legislation, limited monitoring capacity, and uncertain maintenance funding, despite demonstrating cost-effectiveness through shorter payback periods and innovative low-cost solutions.

Chapter 1: Introduction

Modern urban areas face a growing crisis as traditional infrastructure struggles to cope with the escalating threat of extreme weather. Climate change has led to a significant increase in the **frequency and intensity** of major storms, resulting in an upswing of devastating flood events. These incidents cause substantial and ends up in damage of billions of dollars in property loss annually. These events are no longer anomalies but a growing threat to cities worldwide. From 1990 to 2022 alone, floods have affected over 3.2 billion people. The human cost is tragic, with more than 218,000 deaths recorded during this same period. This highlights a critical public safety issue, as urban populations are increasingly vulnerable to sudden and powerful storm events. The economic devastation is equally staggering, with floods causing over $1.3 trillion in global economic damages between 1990 and 2022. In the United States alone, recent estimates suggest the annual cost of flooding ranges from $179.8 billion to $496.0 billion, which is equivalent to 1-2% of the country's GDP. These numbers reflect not only the direct property damage to homes and commercial assets but also the indirect costs of lost business output, infrastructure repairs, and emergency response efforts.

1.1) Background and Context

Urban flooding is primarily caused by following key factors.

Excess Runoff: This happens because cities are covered in **impervious surfaces** like concrete and asphalt, which block rainwater from naturally soaking into the ground. Instead, the water rushes across the surface, creating a massive volume of runoff.

Outdated Drains: A lot of a city's plumbing—the pipes and sewer systems—are old and undersized. They were built for a time when there was far less concrete and less intense rain, so they simply can't handle the huge volume of water coming at them during a modern storm.

Extreme Weather: On top of that, climate change is causing more **frequent and intense storms**. This dumps an overwhelming amount of rain in a short period, which even newer systems often can't handle, leading to widespread flooding.

1.2 The Objectives of this Thesis

The core objective of this thesis is to evaluate the effectiveness of **Low Impact Development (LID)** and **Green Infrastructure (GI)** in mitigating the negative environmental impacts of urban stormwater runoff. This study specifically aims to analyze these strategies through the dual lens of **quantity** and **quality** control.

The research will focus on two key areas:

- **Stormwater Quantity Control:** This objective involves assessing how LID and GI practices—such as green roofs, permeable pavements, and rain gardens—reduce the volume and peak flow rate of stormwater. The goal is to understand how these systems prevent urban flooding, minimize erosion of natural waterways, and promote groundwater recharge by mimicking the pre-development hydrological cycle.
- **Stormwater Quality Control:** This objective focuses on analysing the ability of these green strategies to improve water quality. The thesis will examine how practices like bioretention cells and vegetated swales naturally filter out common urban pollutants, including sediment, heavy metals, nutrients, and hydrocarbons, before they can contaminate local rivers, lakes, and coastal ecosystems.

Additionally, this thesis aims to evaluate the role of Low Impact Development (LID) practices in enhancing urban resilience through decentralized stormwater management. By investigating methods such as bioretention systems, permeable pavements, and swales, the study will explore how these strategies not only reduce surface runoff and mitigate flooding but also promote groundwater recharge and sustainable water reuse. The research seeks to quantify the effectiveness of LID practices in various urban contexts, examining how site-specific factors such as soil type, catchment size, and vegetation selection influence both hydrological performance and pollutant removal efficiency. Understanding these interactions is essential for guiding urban planning and engineering designs that integrate ecological and infrastructural benefits.

Chapter 2: Low Impact Development (LID) and Green Infrastructure (GI)

2.1 Low Impact Development (LID)

Low Impact Development (LID) represents a modern and practical approach to stormwater management that aims to counter the negative impacts of urbanization. The main goal is to preserve the site's natural hydrological conditions as they existed prior to development, using decentralized and small-scale practices. By focusing on water balance, LID incorporates natural drainage solutions across urban landscapes to slow down, filter, infiltrate, and capture rainfall and surface runoff. This strategy not only improves stormwater quality but also helps recharge local groundwater systems and supports opportunities for water reuse.

The main working principles of LID as follows

- Using a distribution approach to mange the storm water as much as possible to existing source
- Practices to ensure minimizing the impacts of development and get maximum ecological benefits
- Integration of management strategies in very early stages of construction sites in a particular area
- Deployment of environmentally friendly ideas
- Promotional efforts to support and maintain natural hydrological features
- Promotion of sustainability in order to reduce financial instability

The main objective of the practice is to reduce the surface run off, ground water recharge, increase the infiltration, natural precipitation and removal of impurities to increase the quality of water by the techniques of filtration, infiltration and using other biological methods.

2.2 Green Infrastructures (GI)

Green infrastructure has been defined as "A strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services, while also enhancing biodiversity."

Usage of green infrastructure (GI) for stormwater management of water quantity and quality is increasingly common as an alternative to enhance stormwater system flexibility and reduce its maintenance related costs and approach towards less or completely vanish carbon footprint. GI help to divert water from traditional stormwater systems to engineered designed to mimic natural processes to detain, retain, infiltrate, or filter water away from urban areas to reduce the effects of harm or destruction.

The working principle of GI is a kind of similar to LID but on macro scale exposure

- Filtration of storm water by usage of ecological treatment
- Enhancing detention and storage of storm water for multiple usage
- Usage of Natural Hydrological Cycle to manage urban flooding
- Catchment based water management interconnecting the GI with Grey infrastructures

The main goals of such practices to control the volume of excessive water to achieve the targets in case of emergency to Reduce peak flow, Runoff delay, Pollutants or impurities removal, reduction of water velocity and stop erosion of water bodies.

Chapter 3: Design, Functional Classification, and Performance Evaluation of LID and GI Systems

LID and GI practices based on the problem related solutions in sense of controlling the excessive Urban flooding water volumes and improve runoff water quality. As we already know the sudden human urbanization and disturbance of natural cycles brought unpredictable consequences and world experiencing notable damages and consequences of such disasters. These lethal incidents brought the attention of policymakers to start the immediate actions to tackle such emergencies to reduce the expected frequency and severity of these incidents to ensure the growing concerns for both public safety and economic stability. Thanks to researchers, with their intense attention research bring crucial factors those contribute to urban flooding and future solutions to mitigate disasters based on such factors. Now from here these factors with be discussed and related solution and theirs design criteria.

Surface Runoff is the term used to describe the portion of rainfall or precipitation that flows over the land surface without getting absorbed into the soil towards rivers,lakes,drains or other water bodies.

Figure.1 Example of Surface Runoff

Our city centre or any urban area is so dense with the paved paths and only left with few spaces for soil to absorb the rain water. In the case of rainfall, due to continuous development the water doesn't have any place to get soaked by the natural soil absorption ,this phenomenon cause that water to spill over the paved surfaces by following the slopes towards the drainage areas. This idea work fine with conventional drainage system but as observed through the past few decades growing urbanization took place of all natural ecological spaces and force the rainwater to follow drains but previously developed systems are unable to hold the continuously increasing loads put by urbanization and become the root cause for the surface runoff. The continuous coming pressure develops the velocity and with, so intensity hit the on the way structures and vanish them in couple of hours. We can get roughly idea of surface water speed by the following

Manning's equation:

$$V = \frac{1}{n} R^{2/3} S^{1/2}$$

Where:

- V = velocity (m/s)
- n = Manning roughness coefficient (dimensionless, e.g., 0.013 for concrete, 0.035 for grass)
- R = hydraulic radius (m), approx. flow depth for shallow sheet flow
- S = slope (m/m)

Figure.1.1 Mannings Equation

Here we calculate the impact of that runoff speed on Humans and small building structures.

$$F = \rho \cdot Q \cdot V$$

Where:

- F = Force (N)
- ρ = Density of water ($1000\,\mathrm{kg/m^3}$)
- Q = Flow rate (m^3/s)
- V = Velocity (m/s)

Example Calculation:

- **Assumptions:** Flow rate (Q) = 0.05 m^3/s, Velocity (V) = 3 m/s
- **Calculation:**

$$F = 1000\,\mathrm{kg/m^3} \times 0.05\,\mathrm{m^3/s} \times 3\,\mathrm{m/s} = 150\,\mathrm{N}$$

This force is equivalent to the weight of a 15 kg object.

Figure.1.2: showing example of Water force on Human Bodies and small objects

So that much force if exerted on a human body continuously can be dangerous and cause to the small buildings the effect erosion of foundations, undermine the structural stability and cause the collapse of building. The term known as **INFILTRATION** to ensure the reduction of surface runoff. Now a sight on possible solutions and in practices techniques to cater the surface runoff.

3.1) Bioretention

It is a stormwater management strategy that uses soil, plants, and microbes in depressed areas like rain gardens to treat runoff from impervious surfaces. From its name its shown a practice to stop water from following, with the proven experiments now a days different kind of bioretention devices available. The main benefit includes the runoff control by infiltration and ground water recharge plus removal impurities and pollutants from runoff and delay the time of peak flow into the sewer system.

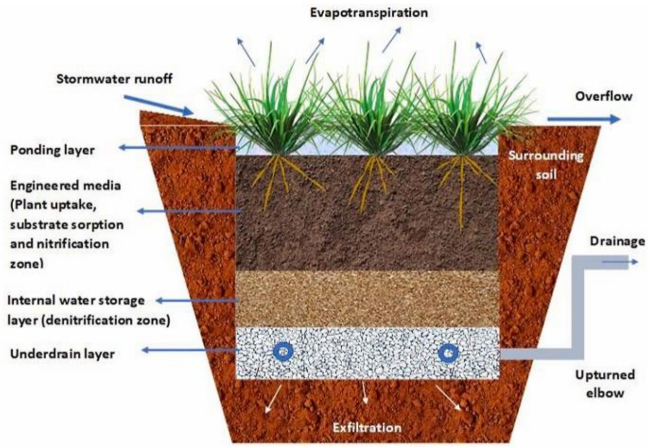


Fig.3.1.1 shows schematic setup of Biorenteion system

Construction of a bioretention area: Stormwater is firstly and above guided into the designed treatment area, which conventionally constructed of a sand bed (which uses as a transition to the actual soil), a filter media layer (which consists of layered engineered materials of various composition), and plants and vegetation at top the filter media. Various soil amendment such as water treatment residue, Coconut husk, biochar etc have been proposed over the years after careful observation. These materials were reported to have enhanced performance in terms of pollutant removal. Runoff passes first over or through a sand bed, which slows the runoff's velocity, distributes it evenly along the length of the ponding area, which consists of a surface organic layer and the underlying planting soil. Stored water in the bioretention area planting soil exfiltrates over a period of days into the underlying soils.

3.1.1 Site selection

To execute the idea the first and foremost step is carefully selecting the site to ensure long term results. To maximize the beneficial part as some studies and observation state that practice is micro scaled and can be used for small to medium size catchment ranges from 2-3hectares without overflowing the treatment area. Sites with the separation of 1.2 meters is recommended between bottom of bioretention and ground water level and ensure the pollutants removal without exposing them to the underground reservoirs ,on the other hand in case of deep groundwater scales limit this application from usage.

3.1.2 Sizing and Hydrology

The hydrologic features of the contributing drainage area and the intended level of stormwater treatment determine the size of a bioretention facility. To properly capture and treat the Water Quality Volume (WQV), which is the first flush of rainfall (usually the first 25–40 mm), the surface area of the bioretention cell should normally be equal to 5–7% of the impervious drainage area.

3.1.3 Soil Media

The composition of the soil media among of the main filtering and treatment element of a bioretention system, is essential to the system's operational setting. The layer of soil as a whole is distributed as 50–60% sand, 20–30% topsoil or loam, and 10–20% compost or organic matter is ideally recommended. Permeability, pollutant removal, and vegetation support are all optimally balanced in this layer. The depth of 0.5 to 1.0 meters is the recommended, also proportionate according to the type of vegetation and site-based conditions. Maintaining the hydraulic conductivity between 25 and 100 mm/hr is important because too high infiltration rates can decrease contact time and decrease the efficiency of pollutant removal, on contrary lower rates may result in prolonged ponding and vegetation stress.

3.1.4 The vegetation

Vegetation performs a multipurposes, like absorbing stormwater, removing pollutants, preventing erosion, and improving overall aesthetics. It’s very important to carefully choose the plant species as in bioretention area experience variable conditions and to ensure the plants withstand with conditions like drought and flooding

3.1.5 Maintenance Considerations:

Long-term performance of bioretention systems can be achieve particularly on regular and organized maintenance. A survey should be held at period over the year to detect sediment buildup, clogged inlets, erosion, or vegetation failure particularly following significant storm events. Maintaining hydraulic function requires routine trash and debris removal, and depending on site conditions, accumulated sediment in pretreatment areas and inflow points should be removed every two to five years.

Table 3.1.1 below shows the results obtained from the different locations of experiments and give insights about the runoff reduction and removal efficiency of BIORETENTION.

The average pollutant removal efficiencies and runoff reduction across all the studies in the table. Here are the results:

Percentage runoff reduction and pollutant removal by bioretention systems

Reference	Experiment site	Runoff [%]	TSS [%]	TN [%]	TP [%]	Zn [%]	Pb [%]	Cu [%]
Sun X, Davis AP, 2007 [62]	Lab experiment, USA	–	–	–	–	88–97	88–97	88–97
Brown and Hunt, 2008 [63]	Rocky Mount, NC	90	92	80	72	–	–	–
Hunt et al., 2008 [64]	Charlotte, NC		60	32	31	60	32	77
Brown and Hunt, 2011 [65]	Rocky Mount, NC	95	58	58	–	–	–	–
Debusk and Wynn, 2011 [66]	Blacksburg, VA	97	99	99	99	–	–	–
Hathaway and Hunt, 2011 [67]	Wilmington, NC	–	100	–	–	–	–	–
Trowsdale and Simcock, 2011 [68]	New Zealand	–	90	–	–	–	–	–
Khan et al., 2012 [69]	Alberta, Canada	–	99	92	95	–	–	–
Chen, 2013 [70]	Lenexa, KS	–		56	–	–	–	–
Olszewski and Davis, 2013 [71]	Silver Spring, MD	79	–	–	–	–	–	–
Bakacs et al., 2013 [72]	New Jersey, USA	–	84–95	–	–	–	–	–
Geronimo et al., 2014 [73]	South Korea	–	–	49–55	85–86	–	–	–
Guo et al., 2014 [74]	Singapore	–	93.4	59.8	92.7	–	–	–
Houdeshel et al., 2015 [75]	Utah, USA	–	–	22	60	–	–	–

Table 3.1.1:showing removal of pollutants individually at each experiment site

3.2) Permeable pavements

Permeable pavements are smart and sustainable moment in reduction of excessive water and its part of Low Impact Development(LID).It is designed on the theory of infiltration and that can be done by installing the surfaces as contrary to the traditional surfaces those bulk up with the high priced and overrated materials those almost make the surface runoff impossible to soaked by the soil and results in excessive runoff and putting extreme burden on the sewerage system. By continuously pumping of the ground water, the water tables are significantly going down and alarming the dangerous consequences of water scarcity. In most places all over the world communities are trying best to reduce the waste of water and try best to give opportunity to water tables to refill and can be used in future.

The working mechanism consists of three steps as follows

- Rainwater passes through the permeable surface layer and enters the sub-base and this step ensuring the infiltration
- In very next step the in designed aggregates layer capture the suspended solids in pores and improve the quality of water through this filtration process.
- The granular subbase performs two kind of process from allowing the gradually infiltration and can be step up the storage or controlled drainage via underdrains according to the system build requirements.

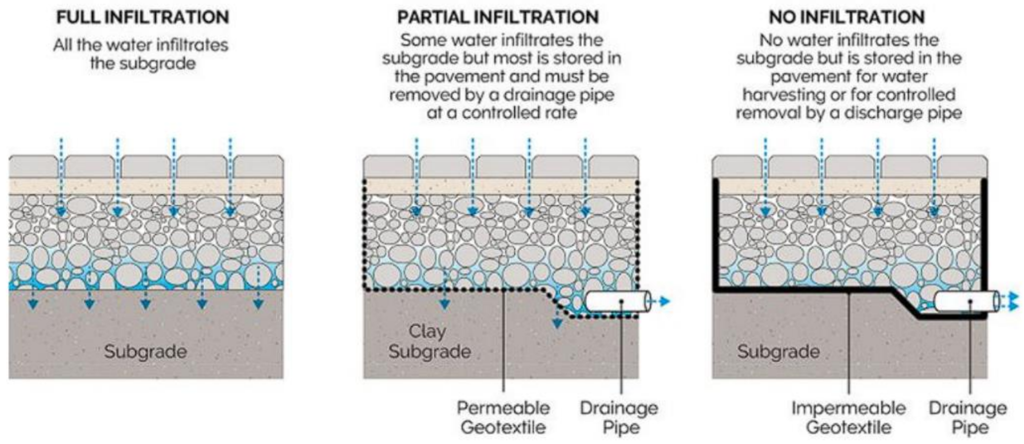


Figure 3.2.1: Different type of pavements according to working principal

From this given diagram we can understand the construction plan and its variety of design opinations according to the specific site needs. Currently different types of designs are available in the market according to the specific applications and structural requirements, here are some common types:

3.2.1 Permeable Interlocking concrete pavers

PICP a prefabricated concrete block is placed at site by putting the enlarged joints and opening and then these openings are filled with aggregates. Water infiltrates those joints and goes inside the aggregates layer and filter the water out and then water runs towards the soil below. In this specific design only joints act for the infiltration while blocks play no role expect structural stability. These kinds of designs are so common and widely used in parking areas, pathways.

3.2.2 Porous Asphalt

It comes with reduced fine aggregates and porous asphalt acts as combiner and leave the voids inside for the passage of water. It seems similar to traditional asphalts, but it performs with infiltration, and its use is limited for light weight traffic. Here is look of porous asphalt

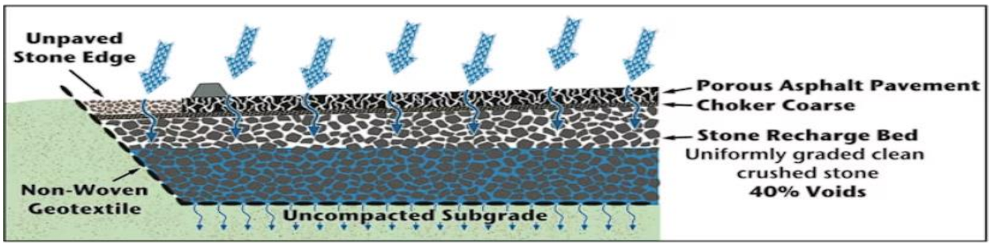


Figure 3.2.3 demonstrates the porous concrete working principle

Other types are Previous concrete, Grid Pavements and Green/Vegetated Permeable Pavements which are somehow related to above with some altered specifications.

3.2.3 Structural Design

In design process of Permeable pavements structural design means figuring out of means those utilize them. ASTM test methods require for the compressive and flexural strength of previous concrete which is done by the body of Previous concrete industry. These tests are necessary for the modelling of fatigue under loads. The design requires to map expected loads (while interoperating in ESALS or specific axel configurations) into layer thickness and material specifications while looking for the mechanical behaviour of the open graded surfaces and bases. Porous asphalt (Hansen 2008) and permeable interlocking pavements (Smith 2011) use flexible pavement design methods adopted from the 1993 AASHTO *Guide for Design of Pavement Structures* (AASHTO 1993).

3.3) Grass Swales or Bio Swales

These are stable turf, parabolic or trapezoidal open channels which are designed to convey runoff, control runoff, and improve storm water through various processes.

Swales are low lying, depressions in the ground. They can be naturally occurring or man-made. **Bioswales** are a vegetated version of swales that are specifically designed to control and regulate stormwater runoff. They can be considered stormwater runoff conveyance systems, and they provide an alternative to storm sewers.

An essential part of managing stormwater is these swales. They help in lowering runoff and flooding. Wastage of excess water flowing into drains and sewers, they make sure that rainwater can naturally seep into the ground. The ground can naturally filter this water because of the aggregate layers, replenishing groundwater aquifers. The outer layer of Bioswales is harvest with the plantation which helps to enrich the filtration process.

Figure 3.3.1 showing BIOSWALE

3.3.1 Design for runoff volume reduction

Primary purpose of Swales is to gather storm water runoff from urban cities while deign life of most commonly 10 years and designed in a way to handle both regular and extreme rainfall events and avoid the flooding scenarios. Soil plays a vital role in infiltration capacity and influence greatly while dealing with high peaks of runoff, in case of soil present with highly permeability permit maximum portion of water to get soaked underground, on the contrary side there needs to be install additional measures. Volume reduction provided by check dams is well-documented especially for storms up to 30 mm (Davis et al., 2012; Shafique et al.,

Table 1. Swale design for stormwater conveyance and volume reduction.

Design Component	Common Design Guidance	Supporting Literature
Main channel	Increase the cross-sectional area to provide higher conveyance capacity. This can be achieved by a trapezoidal channel. If right-of-way space is limited, a longer section of triangular channel with side slopes 6:1 (H:V), or shallower is better.	Chow (1959); Winston et al. (2017)
Vegetation type	Select a blend of species with tall and stiff grass blades	Temple et al. (1987); Fiener and Auerswald (2005)
Grass density	Non-clumping grasses with high density to prevent concentrated flow. Aim for grass cover of good-excellent for selected species (3000–9000 stems/m^2).	Ree (1949); Temple (1982); Bäckström et al. (2006)
Channel roughness	Manning's roughness coefficient (n) between 0.26 and 0.35 for different grass types. Significantly lower at high flows when water depth exceeds grass height.	Kirby et al. (2005); Bäckström (2002); Barling and Moore (1994)
Check dams	Add earthen or rock structures located at the downstream end of swale or at drop inlet. Maximum height 60cm.	Kaighn and Yu (1996); Dunn et al. (1995); Winston et al. (2018)
Underdrains (optional)	Install perforated pipe systems in permeable soils with a minimum infiltration rate of 1cm/h (0.5 in/h) and maintain sufficient separation from groundwater table	Abida and Sabourin (2006)
Construction technique	Minimize compaction in the main swale channel to maintain soil permeability	Ahmed et al. (2015)

2018; Winston et al., 2018; Yu et al., 2001).Factors like channel roughness, height of grass and density of vegetation ensures flow retardance to achieve pollutant removal and hydraulic performance. The advised height of grass with stiff stemmed between 100-150mm helps to lower down the speed, maximize the capturing of sediments and keep float the vegetation above the water levels in case of low to moderate flows (Bäckström, 2002; Deletic and Fletcher, 2006). Fiener and Auerswald (2005). The hydraulic resistance is shown by the Mannings Roughness coefficients which ranges from 015 to 0.35 along mainly to roadsides areas and it decrease significantly water levels if it shows trend of high stream and reducing the swales maximum conveyance capacity

3.3.2 Water quality treatment design

Physical, chemical, and biological processes must be integrated into the traditional hydraulic capacity analysis when designing swales for water quality treatment. With careful consideration of the local climate, swales must be designed to filter, infiltrate, and biologically assimilate pollutants in addition to transporting them. For example, in cold climates, swales can become clogged and lose their ability to remove pollutants when de-icing salts are used and street sweeping is reduced during the winter (Monrabal-Martinez et al., 2019). Swales pocess a well-established ability to treat water quality around the world (Bäckström, 2002; Barrett et al., 1998; Gavrić et al., 2019a; Lucke et al., 2014; Stagge et al., 2012; Winston et al., 2012; Yousef et al., 1987; Yu et al., 2001). However, other factors like rainfall intensity, antecedent dry period, incoming pollutant loads, and the imperviousness of the contributing catchment affect how well they perform (Gong et al., 2019). Since coarse particles can be efficiently removed by filtration and sedimentation processes, swales usually serve as a sink for pollutants when influent concentrations are high and pollutants are particle-bound (Bäckström, 2002, 2003; Barrett et al., 1998; Fardel et al., 2019). However, because of the possibility of resuspension and mobilization of previously deposited contaminants, they can also become a source of pollution when influent concentrations are low (Bäckström, 2003; Fardel et al., 2019; Luell et al., 2021).

3.3.3 Cost and economic considerations

The costs of implementing stormwater control measures (SCMs) are high and include design, permitting, construction, land acquisition, feasibility studies, and continuing maintenance. Choosing cost-effective solutions is essential because municipalities and transportation agencies frequently have limited funding (Wossink and Hunt, 2003; Blecken et al., 2017).

Because of site-specific factors like soil type, topography, and land availability, reported costs in the literature vary greatly (Barrett, 2005). According to comparative studies, bioretention systems are the most costly overall, wetlands have high construction costs but lower operating costs, and grass swales are typically the most economical choice with moderate construction and operating costs (Yu et al., 2013; Houle et al., 2013).Detailed cost data for bioswales and wet swales are limited, bioswales are expected to have higher life-cycle costs due to engineered media, underdrains, and intensive maintenance, while wet swales fall into a moderate cost range, mainly related to vegetation management (Li, 2015).

3.3.4 Climate change considerations

Although the main focus of stormwater design has been on drainage failure and flooding risks (Rosenberg et al., 2010; Semadeni-Davies et al., 2008; Waters et al., 2003), little is known about how climate change affects the sustainability and performance of SCMs (Fletcher et al., 2013). Climate change is results as increased rainfall amounts, frequency, and intensity. In order to achieve this, Hathaway et al. (2014) assessed how future climate scenarios would affect the hydrologic performance of two bioretention cells and concluded that higher rainfall amounts could result in an increase in overflow volume. As a result, they suggested a larger footprint to accommodate more storage. Zhang et al. (2019) assessed the treatment performance of two low-impact development practices under future climate change scenarios and suggested larger footprints for future SCM designs.


Figure 3.3.3 showcasing some examples of Green/Bio swales

3.4) Green Roofs

A Green Roof is a sustainable practice in which intentionally roof is covered with the vegetation and growing medium is placed over the waterproofing membrane to capture the rainwater in order to reduce runoff and storing it to fulfil the local needs of water usage and energy purposes.

The rapid urbanization over the decades world observed increase in construction sites and mass shift from rural to urban area population transfer. Currently, almost half of the world population lives in cities, with up to 67% living in cities by 2050 (United Nations, 2019). Beside the socio-economic benefits, urbanization leads to numerous environmental problems such as urban flood and urban heat island effect where urban dense areas experience higher temperature than surroundings due to mainly modification of land surfaces. By observation and studies it demonstrate that buildings occupy cities 50 percent surface area (Dunnett and Kingsbury, 2008), in such scenarios,

Primary purpose of GRs in the quantitative sense is to volume retention due to evapotranspiration; volume detain and store in green roof layers and it's also interesting to watch how GRs perform seasonally over the long period of time.

Components of Green Roofs and Terrace Assemblies

Green Roof Assemblies are typically composed of two systems: a) Roof base assembly and b) above membrane vegetated Roof System. The Roof Base assembly includes the water proofing membrane, rigid insulation, protection board, and structural system. The typical modern vegetated roof system requires a minimum of eight (8) functional layers. The system

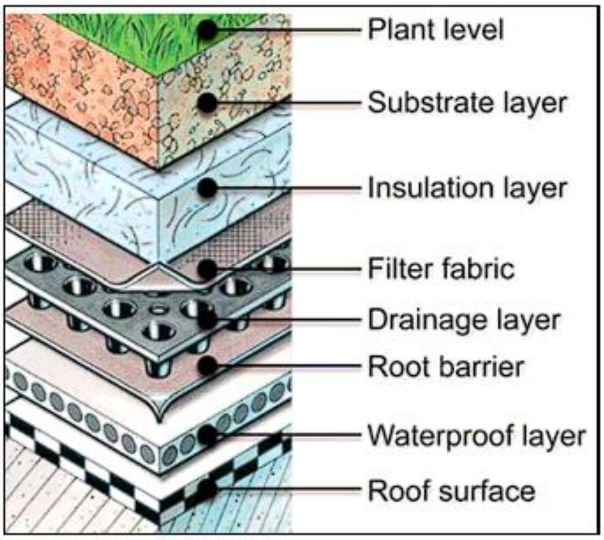


Figure 3.4.1 Layering of Green Roof

include the vegetation, engineered fill, insulation, filter fabric, drainage layer, root barrier, waterproofing membrane, and structural support (See Figure 4). Each of these components (layers or courses) is described above.

3.4.1 Drainage and Filter Layers:

In GRs a filter fabric is necessary to keep fine particles from clogging drainage voids and a dedicated drainage layer to move excess water away from the substrate in a green roof system. These layers are crucial for maintaining the roof's structural integrity and the health of the plants.

Drainage Layer: The drainage layer can be chosen up of the following:

Crushed stone or gravel

Drainage boards made of modular plastic Geocomposite mats with specialization

The ideal drainage layer thickness for large green roofs is usually between 20 and 50 mm. Under design storm conditions, the vertical discharge capacity must be engineered to surpass the anticipated peak infiltration from the substrate (EPA; Megamanual).

Filter Fabric:

The filter layer, generally a geotextile, must:

- Allow vertical water migration
- Retain substrate fines, preventing clogging of drainage voids

3.4.2 Stormwater retention and detention capacity

Green roofs have a dual hydrological role by providing both retention and detention of stormwater. Retention refers to the capacity of the system to store water within its components, including the substrate, drainage layer, and vegetation canopy. Detention refers to the term of delayed release of stored water, which mitigates peak runoff and reduces the burden on urban drainage networks, retention rates vary significantly depending on factors like substrate depth, antecedent moisture, vegetation type, and rainfall intensity, empirical studies note that event-based retention generally averages about 60% (Zheng et al., 2021; Stovin, 2015). This important observation highlights the importance of site-specific design considerations when evaluating green roof performance.

Substrate Storage Calculation

The water storage capacity of the substrate can be estimated by using the available water capacity (AWC) and the substrate depth. For example,

$$\text{Storage volume per m}^2 = \text{substrate depth} \times \text{AWC} \times 1000$$

Worked Example:

Let’s have a rough idea by taking Substrate depth: 0.10 m, AWC: 0.231 m^3/m^3

$$0.10 \times 0.231 \times 1000 = 23.1\ \text{L/m}^2$$

Thus, a 0.10 m deep substrate can store approximately 23.1 L/m^2 of plant-available water before runoff occurs.

Event-Based Retention Estimation

Event retention can also be estimated using empirical retention percentages. For a 10 mm rainfall event (10 L/m^2) and an average retention of 62% (Zheng et al., 2021):

$$\text{Retained water} = 10 \times 0.62 = 6.2\ \text{L/m}^2$$

$$\text{Runoff} = 10 - 6.2 = 3.8\ \text{L/m}^2$$

Note: This calculation provides a first approximation physical value and Retention abilities generally increases with deeper substrates, higher AWC, and drier antecedent conditions, whereas high-intensity rainfall events can reduce storage efficiency.

3.4.3 Integrated Design Considerations

For accurate stormwater management, combination of substrate storage, drainage layer storage, canopy interception, and evapotranspiration to determine the residual peak runoff. Roof overflow and drainage systems must be designed to safely convey the remaining water in compliance with local standard codes.

One important factor in preserving plant health and preventing extended waterlogging or mosquito breeding is the amount of time needed for the substrate to drain. Complete drainage within 24 to 48 hours is typically advised by guidance for temperate climates.If the substrate cannot drain adequately within this interval, design strategies may include:

- Increasing drainage layer depth or adding underdrains
- Selecting substrate mixes and plant species tolerant of extended saturation (EPA; Minnesota Manual)

Root barrier and waterproofing

In this part of construction, a specific attention need and its suggested use special membranes those designed for the GRs and available in markets which are based on manufacturer data and FLL guidelines. The inclusion of details and boards between the membrane and substrate needs thoroughly attention. In order to locate any membrane failure

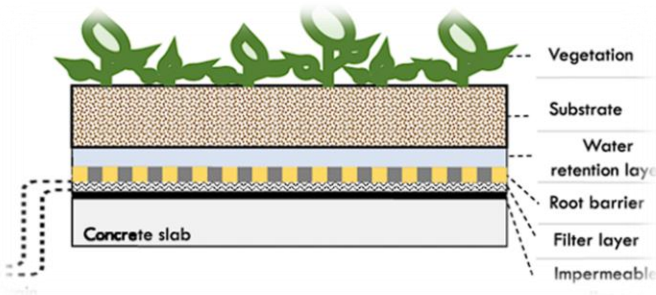


Figure 3.4.2 Showing Roots barrier layers

without removing the substrate entirely, it is also necessary to specify inspection access points. Avoid membranes with leachable compounds that could harm runoff quality

Pollutant Removal Efficiency of Green Roofs: Green roofs not only retain and detain stormwater, but they also significantly improve water quality by lowering pollutant loads in roof runoff. Filtration, sorption, plant uptake, and microbial degradation within the substrate and vegetation layers are some of the methods used to accomplish this.

Total Solids Suspended (TSS): With removal rates of 70–95% frequently reported, green roofs are effective at lowering sediment and particulate matter in runoff (Getter & Rowe, 2006). By acting as efficient particle traps, the filter fabric and substrate layers stop sediment from entering drainage systems. Here are detailed removal efficiencies according to the studies done:

Reference	TSS(%)	TN(%)	ZN(%)	PB(%)	CU(%)	Nitrate (NO_3^-) (%
Getter & Rowe, 2006 (MSU, USA)	70–95	-	-	-	-	-
balkhair et al., 2019 (Desalination & Water Treatment, arid climate)	77.0	57.8	92.4	-	72.7	variability in pollutant removal efficiencies
Rowe, 2011 (review of multiple green roof studies)	-	-	40-90	40-90	40-90	variability in pollutant removal efficiencies
Vijayaraghavan, 2016 (review) IDEAS/RePEc	-	10-50	30-80	-	20-60	Often low

Table 3.4.3 summarizing removal efficiency of pollutants according to different studies

Conclusion:

- **TSS removal:** Most consistent and reliable across all studies (≥70%).
- **Heavy metals (Zn, Cu, Pb):** Generally well-removed (40–97%), but some substrates and early rain events can cause leaching.
- **Nitrogen species (TN, NO_3^-):** Highly variable; often low removal or temporary export, especially in early stages of green roof operation.
- **Overall:** Green roofs are effective in reducing suspended solids and certain metals, but nitrogen management requires careful consideration of substrate and fertilization practices.
-

Chapter 4: Legal and Policy Framework for Stormwater Management

Stormwater regulation is part of a comprehensive and integrated water and environmental law system in Europe. Directive like Floods Directive and the Water Framework Directive (WFD) have set challenging goals over the 20 years to reduce flooding risks and water quality control. These initiatives when practice together with strategies that support green infrastructure and sector-specific regulations such as the Urban Wastewater Treatment Directive provide the favourable stage for the application of natural stormwater management techniques

While on the other side of the Pakistan case, legal framework for stormwater management has evolved in a fragmented manner, and introduction of new municipal laws, environmental protection rules and formation of building regulations authorities and related rules are very encouraging. Recently additional development such as the 2025 Green Building Code represent progress, stormwater management in Pakistan still lacks behind and required unified national vision, consistent enforcement, and adequate financial resources. This chapter critically reviews the legal and policy context in both Europe and Pakistan, comparing their strengths and gaps while highlighting opportunities for reform.

4.1) European Union Legislative Framework

The EU has progressively developed a suite of directives and policies that integrate stormwater management into the broader agenda of environmental protection and climate resilience. These instruments reflect a shift from purely technical, end-of-pipe drainage solutions to integrated, catchment-based approaches.

The Water Framework Directive (2000/60/EC)

The Water Framework Directive (WFD) is the main pillar of Eu water legislation. As it quotes that

‘ ‘The key objectives of the WFD are set out in Article 4 of the Directive. It requires Member States to use their River Basin Management Plans (RBMPs) and Programmes of Measures (PoMs) to protect and, where necessary, restore water bodies in order to reach good status, and to prevent deterioration. Good status means both good chemical and good ecological status.’ ’

It establishes the principle of river basin management, requiring Member States to achieve "good ecological and chemical status" for water bodies by integrating measures across sectors (European Parliament & Council, 2000.Stormwater runoff is addressed indirectly through requirements to control diffuse pollution, hydro morphological pressures, and chemical contaminants.

The Floods Directive (2007/60/EC)

Member states are required by the Floods Directive to adopt flood risk management plans, create hazard and risk maps, and carry out risk assessments (European Parliament & Council, 2007). The directive places a clear emphasis on readiness, protection, and prevention. Two practical examples by Eu countries had done work in this sense, for example In Germany ,use of GI techniques to control the flooding build retention basins and Green roofs to delay the runoff and break the peak of flooding. And same in Netherland ,introduction of spaces for flood water shows the preparedness in the region.

Urban Wastewater Treatment Directive (Recast 2024/3019/EU)

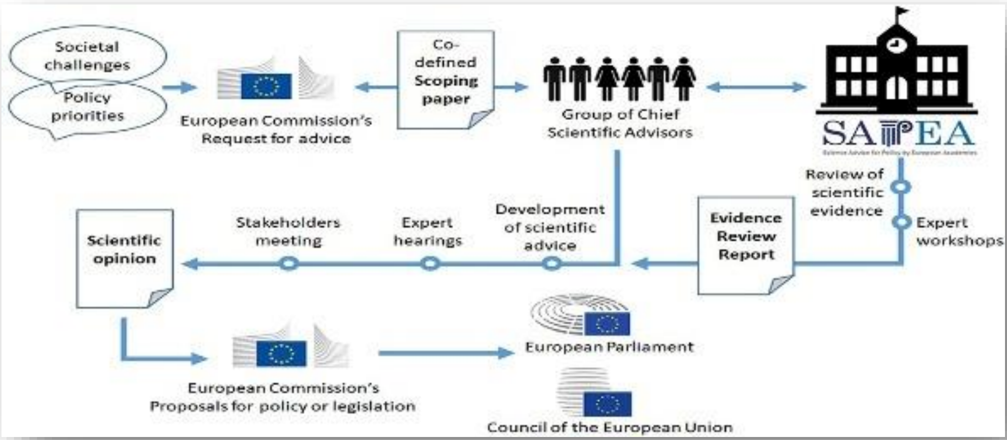
EU commission mentioned that

"relevant points in separate sewers have been identified where urban runoff is expected to be polluted in such a way that its discharge into receiving waters can be considered to be a risk to the environment or human health or prevents the fulfilment of any of the requirements or environmental objectives referred to in point (c)."

Sewage treatment was the main focus of the 1991 original Urban Wastewater Treatment Directive, but the 2024 revision greatly broadens its purview. Given their influence on receiving waters, urban wastewater and stormwater overflows must now be planned for holistically (European Parliament & Council, 2024).

EU Green Infrastructure Strategy and Supporting Policies

Nature-based solutions are promoted as affordable substitutes for traditional infrastructure by the EU Green Infrastructure Strategy (European Commission, 2013), which is a guiding framework instead of a directive. By presenting GI as a means of providing several ecosystem services, such as biodiversity support, climate regulation, and recreational space, the approach strengthens the economic and political justification for stormwater management. Further supporting the incorporation of GI in urban development and connecting it to more general sustainability objectives is the EU Biodiversity Strategy for 2030.



4.2) Pakistan Legislative and Policy Framework

In Pakistan, stormwater management has traditionally been presented less as an integrated environmental challenge and more as a municipal service issue. Consequently, laws are scattered throughout local government acts, building regulations, and environmental protection statutes.

National Green Building Code (2025)

On July 30, 2025, the Federal Cabinet of Pakistan officially approved the Green Building Code and Rainwater Harvesting Provisions, marking a major step toward environmental protection and climate resilience. It's in this sense is the first federal policy to specifically incorporate stormwater into building regulations. To achieve dual goals smartly of lowering urban flooding and augmenting the water supply, the code requires rainwater harvesting systems in new construction (Government of Pakistan, 2025). Although implementation is still in its early phases, this development shows that national policy is beginning to recognize the importance of water scarcity and climate resilience.

Recent Prime Minister Shehbaz Sharif's vision aligned with the UN Sustainable Development Goals (SDGs), the codes mandate eco-friendly, energy-efficient, and water-conserving practices in new construction.

Green Building Code: This applies to buildings with four or more floors, requiring green roofs, renewable energy integration, energy-efficient lighting, eco-friendly materials, and use of BIM for sustainable design and management which is interesting step towards the GI installation.

Rainwater Harvesting Code: Mandates systems in residential, commercial, and industrial buildings for rainwater collection, filtration, reuse, and groundwater recharge to combat water scarcity as Pakistan is among the group of countries those suffer with extreme water scarcity.

With interesting role by the Pakistan Engineering Council (PEC) Byelaws, these codes aim to foster sustainable infrastructure, reduce energy consumption, conserve water, and improve the quality of life for citizens while contributing to global climate action.

Environmental Impact Assessment Regulations

According to the law of Environmental Impact Assessments (EIAs) or Initial Environmental Examinations (IEEs) in accordance with Pakistan's Environmental Protection Act (1997), all the Projects must undergo. According to the revised version of 2022 regulations, urban drainage and rainwater harvesting are to be reviewed (Pakistan EPA, 2022). With the help of this legal framework regulators have a clear opportunity to carefully review stormwater control measures before approving a project. According to the reviews and with the interviews with the regulators express that the lack of technical guidelines, uneven enforcement across provinces, and limited institutional capacity limit this approach's efficacy and require the proper formation of legislative committees to commit proper regulations.

Provincial and Municipal Laws

In Pakistan instead of national common law, authorities are divided into provisional and local bodies, and these individual bodies are responsible for drainage and sanitation services. As an example, and quoted by the Punjab Local Government Act (2019) empowers councils to manage urban drainage systems (Government of Punjab, 2019). At the municipal level as the Karachi Building & Town Planning Regulations (2002) force the developers to introduce the inclusion of stormwater drainage systems in building designs (Sindh Building Control Authority, 2002). These institutions are responsible for the formation of stormwater regulation, mostly they emphasize structural drainage infrastructure (Grey Structures) over ecological solutions which reduce the biodiversity. Practical implementation is mostly limited due to inadequate technical capacity, weak enforcement mechanisms, and a lack of coordination between planning and environmental agencies..

Implementation Challenges

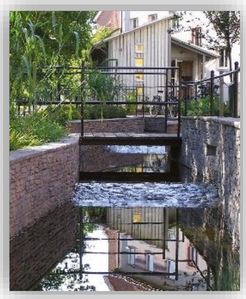
Pakistan still lies among the third world countries and has a lot of problems in spite of these laws. Numerous municipalities are deficient in financial resources, enforcement capabilities, and technical know-how. Stormwater is frequently regarded as secondary to wastewater treatment and drinking water supply. Since there is no specific national stormwater strategy, efforts are still dispersed and reactive, usually sparked by severe floods rather than pre-emptive planning.

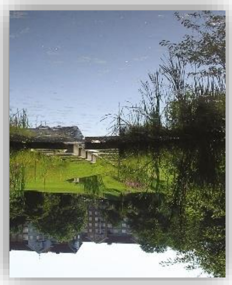
Chapter 5: Case Studies on the Application of LID and GI in Europe and Pakistan

In recent decades, the application of Low Impact Development (LID) and Green Infrastructure (GI) practices has gained global recognition as sustainable strategies for urban stormwater management and an alternative to the conventional drainage systems that primarily emphasize rapid conveyance. LID and GI are designed in a way to integrate natural processes such as infiltration, filtration, evapotranspiration, and biological retention to manage runoff at its source. Across Europe, cities such as Malmö, Copenhagen, and numerous urban districts in France, Italy, and Poland have implemented large-scale projects those ranging from green roofs and rain gardens to constructed wetlands and permeable pavements and related research cases those demonstrate success in reducing peak runoff, mitigating flooding, and achieving pollutant removal rates often exceeding 70–90% for sediments and heavy metals. In Pakistan, as a whole large-scale adoption is still in early stages, but emerging initiatives by individuals' bodies in various areas as Islamabad, Lahore, Rawalpindi, and Sheikhupura demonstrate the feasibility of these approaches in South Asian contexts. Case studies reveal these strategies have hydrologic benefits and significant potential for pollutant control with help of properly design and maintenance. LID and GI in practice examples proves that they have potential in advance sustainable water management and improving urban resilience to climate-induced challenges.

5.1) Augustenborg eco-district, Malmö (Sweden) blue-green network

In Europe one of the most well-known examples of LID and GI practice is The Augustenborg Eco-District in Malmö . Between the 1980s and 1990s,city was facing the challenges like social and economic decline and was mostly flooded by an overflowing drainage system. The initiative was launched in the late 1990s, transforming an existing district into a model of ecological urban renewal. On the official sources this initiative is quote as ''Augustenborg - Turning a Troubled District into an Attractive, Resilient Eco-City'' which exactly transform the history of this project and completed from 1998 to 2002. Before this project, Augustenborg experienced multiple chronic flooding, particularly during intense rainfall events, which most of time resulted in waterlogged basements and overwhelmed combined sewer systems. flooding water and improve the image of overall area. Here are some pleasing gallery pictures uploaded by the authorities:

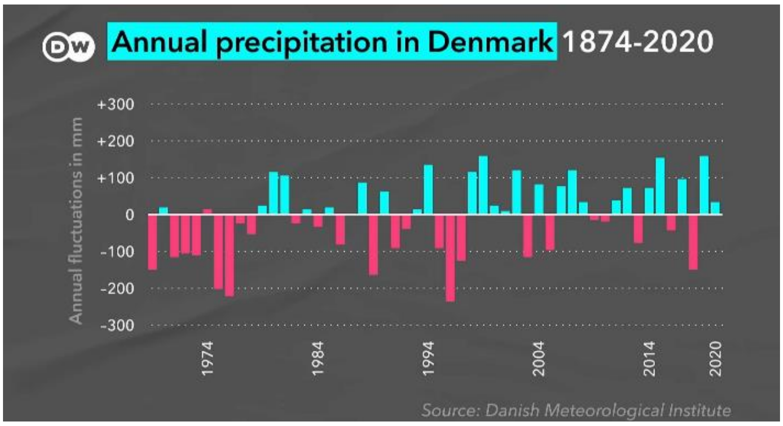




This project start giving encouraging results right after its completion and well recorded in city history and here are some events where this initiative played its role. In the summer of 2007, a 50-year rainfall event caused severe problems in most of Malmö by flooding access roads, but Augustenborg was unaffected thanks to the LID and GI. Again, it was tested by the nature in 2014 severe flood-damages and repair cost were avoided in Augustenborg during a heavy rainfall event with over 100 mm of rain in 6 hours. Beyond these event, many smaller heavy precipitation events have been handled well by the open stormwater system because it is performing better than a conventional system and that Augustenborg is well prepared for more intense rainfall events also in the future. The estimation figures are sound very encouraging as the that 90% of the stormwater from the rooftops and other impervious surfaces is led into the open stormwater system and annual runoff problem is also decreased with 20% reduction compared to the conventional system due to evapotranspiration from open channels and retention ponds between the rain events and as a result peak flow are less extreme and delayed.

5.2) Copenhagen Cloudburst Management Plan (Denmark)

The city of Copenhagen has experienced of the extreme climate change and results in urban flooding which caused the city financially, economically and more in vital life loss and put the city in future risk of unexpected and more intense events. An event of 2011 cloudburst damaged the city in all possible worse condition which produce the over 6 inches (150 mm) of rainfall across the city in two hours and caused almost $1 billion USD in damage. Local climate change projections indicate that intensity of downpour in future will be increased by the by 20-50% and give rise to greenhouse gas emissions. The prediction of such events will overwhelm the city existing sewer system and related cost will make it difficult to meet its level of service objectives. In these circumstances city decided and consider it an opportunity to start planning city Cloudburst Management Plan. The term is cloudburst is defined as "a large amount of precipitation in a very short period of time, sometimes accompanied by hail and thunder."



Source: Danish Meteorological Institute

This figure shows the unpredicted tend of annually rainfall with the variability across the timeline

Copenhagen city use it an opportunity to develop adaptive city-wide plan for the manging the storm water and reduce the risk of flooding. It includes the combination of large-scale, Bluegreen infrastructure projects which align perfectly with city climate adaptation plan, and it create value, and innovation. According to the sources "the current cost risk of doing nothing to address cloudburst impacts in Copenhagen is estimated to be ~$60 million USD annually and will rise to ~$160 million by 2100."

Copenhagen thinks that protection against the 100-year events is a great the largest socio-economic gain. The plan used the trend of global rainfall intensity and suggested that acceptable flooding level average was 3.9 inches (10cm) of floodwaters above ground level during a 100-year event. The Danish Meteorological Institute (DMI) used the global climate

model output from intergovernmental panel of climate change and project that incoming time the intensity of rainfall will rise by 20-50% by 2100. With the use of results, a 6-step process known as the ‘Copenhagen Formula came in front which include the data acquisition and assessment, modelling and mapping, cost of doing nothing analyses, design and visualization, stakeholder engagement, design iteration, and economic assessment. In the figure below an asseed map for flood prone area zoning is given:

The ideology of Copenhagen city flood management plan is inspired by the term of **Sponge city** Which is inspired by the JAN JOE(China) city ,“it is an urban planning model by the Kongjian Yu, that emphasizes the implementation of hydro-ecological infrastructure.”

It is well documented that with the inclusion of such structures 121% green spaces increased as we know these spaces filter the dangerous gasses and improve environmental health, approximately 400kg co2 get absorbed each year, significantly decrease in urban heat island effect and increase 332% public activities which increase interactions humans and compelling them to physical activities which improve overall health and decrease the burden on health control authorities. Here are few examples indicating such initiatives:

Usage of public green spaces to detain water:

Figure below shows how smartly combination green blue strutures are being used:

A glimpse of Biovegated retention cell:

5.3) Constructed Wetland Systems for Stormwater Management in Marsala, Sicily, Italy

Southern Europe has increasingly focus on urban and peri urban areas for the flood water management which consists of controlling flood, pollutant removal and ecological enhancement. Constructed wetlands can be an effective green infrastructure solution in this context. Mediterranean climates encourage such approaches due to periodic heavy rainfall events and facing at same time water scarcity. Marsala is one of the locations located in western Sicily, Italy and practicing vertical subsurface flow constructed wetland (VSSFW) system to treat stormwater and evaluate its efficacy in nutrient retention and pollutant removal. There is a high risk of coastal flooding throughout the entire region, including the Trapani area where Marsala is situated. Urban and flash floods are common in Sicilian cities like Palermo and Catania due to heavy, intense rainfall events, which are made worse by climate change and occur particularly in late summer and fall.

The entire region, including the Trapani area where Marsala is located, is zone as having a high coastal flood hazard. Heavy, intense rainfall events (especially in late summer/fall, exacerbated by climate change) frequently cause urban and flash floods in Sicilian cities like Palermo and Catania. Definition of vertical subsurface flow (VSSFW) is explained as "**A vertical subsurface flow (VSSF) system is a type of constructed wetland or biofilter where wastewater is intermittently dosed onto a planted bed of gravel and sand and flows vertically downwards through the media, percolating through layers that contain a**

microbial biofilm supported by the plants' roots and the filter media. This aerobic process breaks down organic pollutants, and the treated water is collected from the bottom of the bed.''

The system consists of according to the research data as:

' '**Inlet and pre-treatment basin**: which Captures coarse debris and sediments from stormwater.

Vegetated filter beds: Planted with emergent species adapted to Mediterranean climates (e.g., Phragmites australis), promoting nutrient uptake and microbial degradation.

Gravel and sand media: This layer provide with filtration, adsorption of pollutants, and support microbial biofilm formation.

Outlet system: Facilitates controlled discharge of treated water to ornamental irrigation and potential groundwater recharge zones.

The system is designed efficiency for a hydraulic loading rate of approximately 5–10 cm/day, which allows sufficient residence time for physical, chemical, and biological treatment processes.''

The average removal efficiencies over the monitoring period (October 2018 to July 2019) were:

Parameter	Average Removal Efficiency (%)	Parameter	Average Removal Efficiency (%)
Total Suspended Solids	51–68%	Ammonia Nitrate (-N	66–72%
Total Phosphorus	21–33%	Copper ()	**25–66%**
Nitrate Nitrogen (-N)	**Negative** (increase)		
Lead	13–46%		
Zinc	25–66%		

These wetlands are design to priorities the water quality control, with stormwater storage and flood control as secondary outcomes. It has ability to store and recycle treated stormwater for irrigation purposes. The effluent has been successfully reused for irrigating ornamental plants (rosemary) and agricultural crops (pepper).

Here are some photos available from this site:

Marsala built wetlands mainly constructed for the purpose of stormwater quality treatment system, with the secondary purposes of reusing water, reducing flow, and retaining water locally. In an area with limited water resources, it is essential for lowering pollution loads,

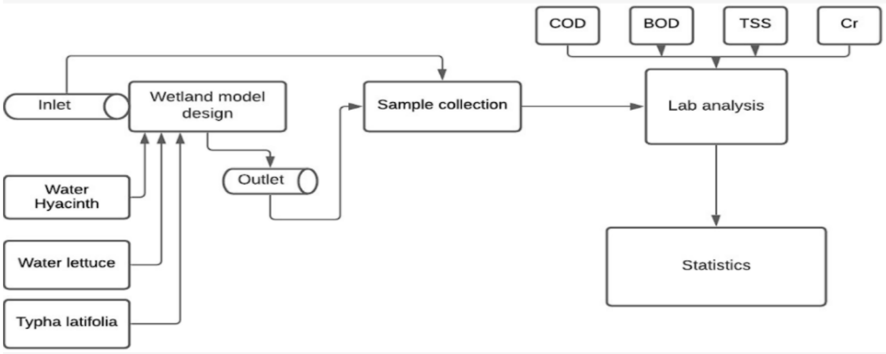
buffering stormwater peaks, and supplying irrigation-quality water, but it cannot be categorized as a large-scale flood control or storage facility. The system shows how artificial wetlands can help control pollution and hold onto some stormwater in Mediterranean industrial areas. This makes it a good model for other coastal cities that are at risk of flash flooding and the effects of climate change. It is important for reducing pollution loads, reducing stormwater peaks, and providing irrigation-quality water in a region with limited water resources.

5.4) Treatment of Industrial Wastewater in a Floating Treatment Wetland: A Case Study of Sialkot Tannery

Sialkot a city situated in province of Punjab and famous throughout the world for its industrial goods and mostly population of the area is mostly associated with medium to large scale industries, among these is a leather industry which produce millions of products each day and shipped throughout the world. This industry discharges millions of gallons of untreated effluent each day into the drains. Installing a conventional waste treatment is quite expensive and need proper bodies to operate regularly. So in case study of Sialkot Tannery came with a natural based solution which is cheap, easy to use and have promising results. A floating treatment wetland (FTW) was introduced to treat the excessive effluent using the local plant species through phytoremediation. FTW was tested with three different plant species each grown separately over the time observation period of the three months in FTK tank. Species like water hyacinth and water lettuce were floating and third specie was installed on the floating Styrofoam while the roots extended out of the mat and suspended down to the contaminated water. Wastewater was pumped into FTW tank with flow rate of 0.5L per minute and given time of 6 days for retention. Samples from influent and effluent were periodically tested from the FTW tank to determine the removal contaminants the total suspended solids, biochemical oxygen demand, chemical oxygen demand, and chromium. Over the 2 months' time lap, very encoring results were found from each different specie and quoted as "chromium was removed by up to 95 percent by the water hyacinth and water lettuce and 33 percent by the Typha latifolia". This pilot scale program was an effective system to treat industrial wastewater into cost effective way on the contrary conventional ways associated with high operational budget. To ensure the circular economy it is important the substances used in wetland foundations are recyclable and available in plenty at local level.

Figure below shows the working diagram

Figure 1. Methodology flow diagram.



The whole measurement system was designed according to the AWWA/APHA Standard Methods for the Examination of Water and Wastewater to measure The total suspended solids (TSS), biological oxygen demand (BOD), and chemical oxygen demand (COD).

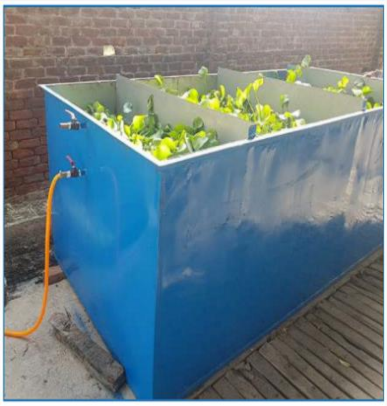
metal chromium (Cr) was qualified from samples using atomic absorption method. The pilot scale FTW system was established in Sialkot and consists of 3 chambers designed at the flow rate of 0.72 m^3/day (0.5 L per minute, as described above) and designed after carefully studies of already done locally and internationally.

Design aspects of the floating treatment wetland used to treatment tannery wastewater.

Design	Measurement	Unit
Design flow	0.72	m^3/day
Detention time	6	days
Width	1.37	M
Length	3.6	m
Depth	0.84	m
Area	5.01	m^2
Volume	4.31	m^3

Plantation selection was based on locally availability. Three vascular plant species (water hyacinth, water lettuce, and *Typha latifolia*) was used and planted by the hands.

The plants were sited at equal water level as the water level inflow. After selection of plantation the water was pumped into FTW. Plants were grown on different time period to check contamination and treatment of wastewater.



Fig(1) Water hyacinth floating

Fig(2) Water Lettuce

Fig(3) *Typha latifolia*

Water hyacinth (*Eichhornia Crassipes*) grows massively in tropical and subtropical areas of the world. It is a floating water plant which named among world's 100 most invasive global plants. In recent years it gain an importance due to its capabilities of pollutants removal when it gets installed in biotreatment plants. It grows thick and reduce the sunlight to reach water and its long roots float inside the water bodies which become a source of aerobic microbes into treatment system and these microbes eat organic material and nutrients in wastewater and convert them into organic compounds ,those get absorbs by the plants. Treated water had low amounts of COD, BOD, TSS, and chromium (Cr) during the period of 2-month observation.

Obtained results are clearly mentioned into the research done and quotes as ''The influent value of COD was more than 1500 mg/L, which decreased to less than 10 mg/L after treatment. The BOD influent value was found to be 1000 mg/L, which was reduced to 10 mg/L after treatment. The TSS values were noted to be above 150 mg/L, which reduced to under 50 mg/L after the treatment. The chromium inflow values were noted as above 14 mg/L, whereas the effluent values were reduced to below 2 mg/L. Additional processes such as the gravitational settling of solids and coprecipitation with insoluble compounds may have contributed to the high chromium removal in the wetlands .Overall, the average reduction in the pollution in tannery wastewater by the water hyacinth was more than 90 percent for COD, BOD, and Cr, and 85% for TSS). The results for Cr were similar to those reported in a previous study, which found that the water hyacinth removed 87.52% of Cr from the contaminated water source''. Results are in figure below:

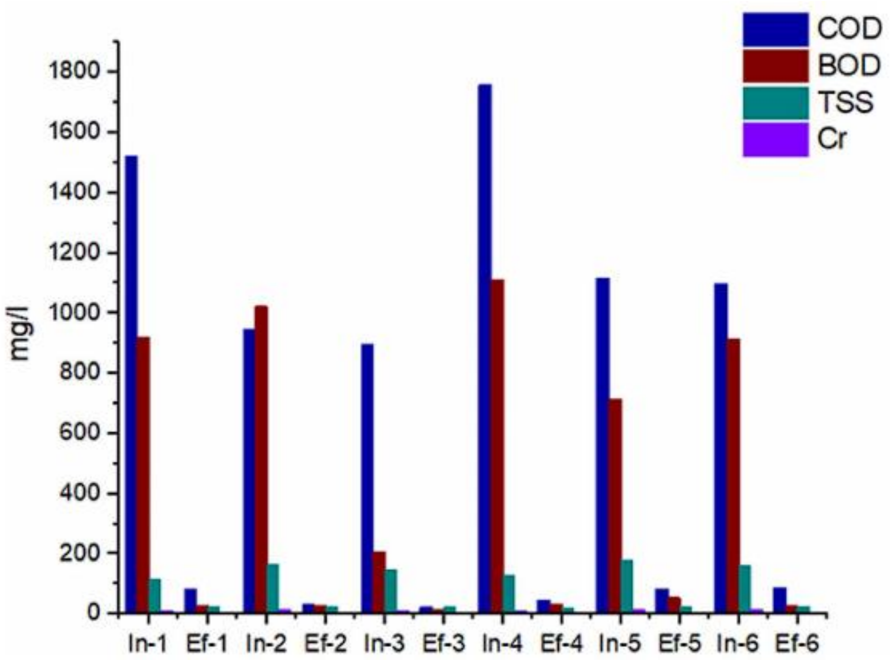
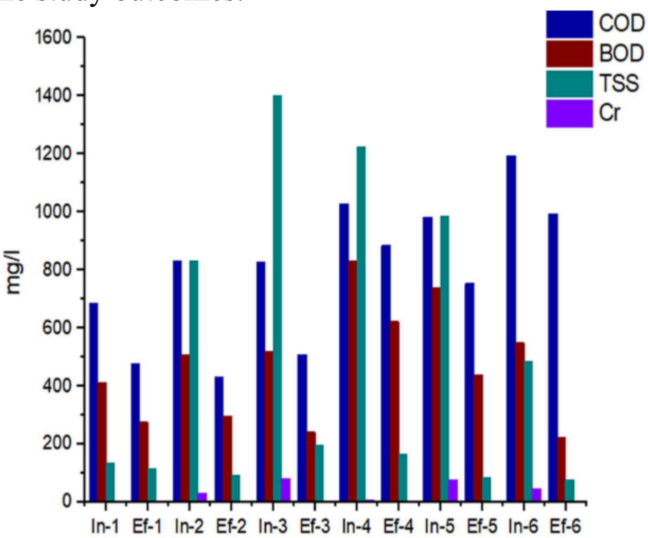


Figure 5. Pollutant concentrations in the FTW inflow (In) and effluent (Ef) over six biweekly sampling periods (1 through 6) using water hyacinth.

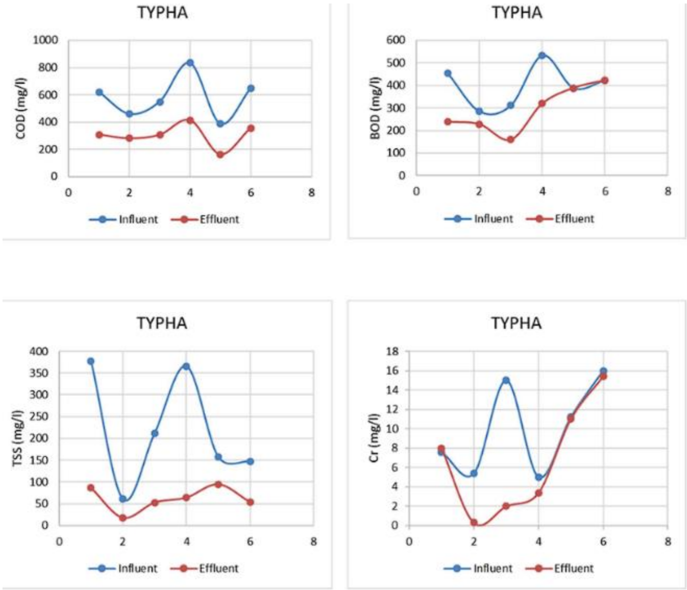
Water lettuce, (*Pistia stratiotes*) belongs to the Araneae family and it also float on the water surface and roots remain suspended into the water. According to the information available it shows that this plant has high capacity of absorption of pollutant degradation including dangerous metals and absorbs pollutants inside its components. During the observation of 2mont observation period into FTW tank, and values shows it wasn't that effective into the removal of , BOD and COD in the tannery effluent those ranged from 400 to 1200 mg/L; and after treatment the average removal of COD was only 27% and BOD by 41%.But The removal of TSS (80%) and Cr (more than 90%) was similar to water hyacinth. Other studies at different locations denoted that higher removal percentage of BOD (82%), along with efficient removal of phosphate (95.4%) and chloride (51%). The fecal coliform removed by water lettuce (over 98%) and showed the ability of the plant to uptake nutrients and release toxins for pathogen disinfection. From such experimental data it is clearly revelled vertical design could be a better option for wetlands using the species of water lettuce.

Graph below shows the study outcomes:



Typha latifolia is an hyperaccumulator plant and have shown abilities of collection of metals like ‘’copper, mercury, chrome, copper, and lead up to 0.1 percent of the plant dry weight and iron and zinc up to 1%’’. In the experimental site the removal efficiencies were reduction in COD of 278 mg/L with 48% removal efficiency, BOD 123 mg/L with 31% efficiency, and chromium of 3.36 mg/L with 33% efficiency and TSS reduction was 72%. This study shows that BOD and COD results are less encouraging than TSS obtained results between inflow and effluent. So its clearly visible that *Typha* species are more resistant to metal toxicity in comparison to the other in practice species.

Here variations in COD, BOD, TSS and Cr concentration into and out of the *T. latifolia* FTW at each of the six biweekly sampling periods:



Floating treatment wetland(FTW) is a sustainable practice and capable of treating wastewater from domestic, industrial and bioremediation. This comparatively simple and low cost make it upfront as an alternative for the treatments ponds and conventionally created wetlands. The sustainability of the tannery sector is important for the GDP of Pakistan and this sector use large amount of water and give useless wastewater. To deceive the expensive treatments plants this practice must be installed treat effluent using local plant species.

5.5) Study of rainwater harvesting potential in an industrial area using stormwater management model(SWMM V 5.0), Quaid-E-Azam Apparel Park, Sheikhupura, Punjab, Pakistan

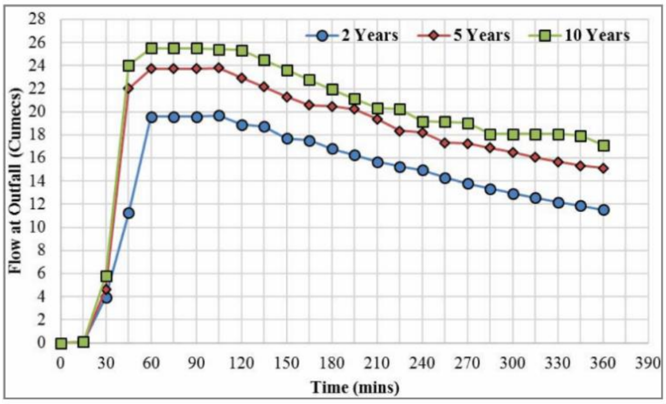
The threat of water scarcity is an issue that constitutes one of the biggest challenges to Pakistan. Therefore, alternate water sources including rainwater harvesting (RWH) is dire need of the time and its one of the water conservation approaches which stores rainwater and utilize it later for processes like cleaning, Rainwater harvesting is one of the water conservation techniques cars washing, horticulture, agriculture etc. After careful treatment it can be used for drinking. Industrial areas have a great potential for RWH because they have large roof areas therefore rainwater on the roofs can be collected and stored for various uses. A pilot rainwater-harvesting (RWH) system was assessed at the Quaid-e-Azam Apparel Park (QAAP), Sheikhupura, to evaluate the feasibility of managing stormwater runoff and recovering water for non-potable reuse. Area is spread over 622 hectares (1,536 acres) and the whole project is based on the decentralized rain-barrel installations at individual industrial plots. The roof space of each unit used as a primary collection point which directing rainfall through downpipes those installed with first-flush diverters to stop debris and early contamination. Small rooftop or ground-level tanks are made of fiberglass or reinforced concrete and used to store the collect rainwater. These tanks temporary detain water to reduce runoff peaks, and the provide stored water for on-site uses like cleaning, irrigation, and certain industrial processes following proper treatment.

The EPA Storm Water Management Model (SWMM) version 5.0, a popular dynamic rainfall-runoff simulation program, was utilized to model and optimize the system.

Figure below shows Typical rain barrel installation:

The model was used by researchers Aneeque Ahmed and Amir Farooq (2018) of the University of Engineering and Technology, Lahore, to model storm events with return periods of two, five, and ten years. Two main situations were compared in the simulations:
1. Baseline state (no RWH)—only a traditional drainage system; and
2. RWH scenario (complete plot coverage): rain barrels are dispersed throughout every industrial plot.
This method made it possible to assess the system's economic feasibility as well as hydraulic performance. The model outputs show that the distributed RWH system has a lot of hydraulic advantages.

Maximum flow obtained for rainfall of two, five and ten-year return period W/O RWH



IDF curves for QAAP

Return Period	Peak Flow without RWH (m^3/s)	Peak Flow with RWH (m^3/s)	Reduction (%)
2 years	19.7 (≈ 693 cusec	14.98 (≈ 529 cusec)	24 %
5 years	23.81	19.94	16 %
10 years	25.42	22.77	10 %

These findings demonstrate that the RWH system significantly lowers peak discharge, especially during storm events those occur more frequently. The system efficiently delays and flattens the hydrograph by reducing the outfall discharge by about a fifth during the two-year storm, which is representative of the usual seasonal rainfall intensity in central Punjab.

Additionally, the frequency of manhole flooding dropped by about 9%, with the help of RWH and number of manholes that had surface ponding under baseline conditions were not affected by flooding, shorter ponding times at crucial nodes also showed increased drainage effectiveness and less hydraulic strain on the conveyance system.These hydrological improvements improve the risk of less flooding and prove itself as environmental co benefit by enhancing groundwater recharge potential when the harvested water is infiltrated or reused.The study's economic analysis shows that there is a compelling economical case for using the rain-barrel system. The primary cost metrics that were taken from and analysed by Ahmed & Farooq (2018) are shown in Table : Estimated payback period ≈ 3 years

Parameter	**Without RWH**	**With RWH**	**Change / Saving**
Annual O&M cost of pumping (PKR million / yr	445	330	↓ 115 (-26 %)
Capital cost of installing rain barrels (100 % coverage			347 million PKR

The results indicate that the RWH system can save about PKR 114.5 million annually in operating and maintenance costs by reducing pumping needs and energy consumption. The system achieves a simple payback period of around three years, which is economically attractive for an industrial-scale infrastructure project while considering the moderate capital cost of PKR 347 million. Furthermore, the estate's sustainability profile is improved by the decreased pumping loads and energy demands which translate into an estimated 26% reduction in greenhouse gas emissions linked to electricity use. The Quaid-e-Azam Apparel Park experimental RWH system shows great promise as a low-impact development (LID) approach for industrial estates in semi-arid areas from both hydraulic and economic standpoints. The decentralized rain-barrel structure works especially well since it controls runoff at the source level and conserves water locally for the frequent, moderate rainfall events. According to the studies by the Ahmed & Farooq (2018) they stress that rain barrels are not enough to manage runoff from storm events that are larger than five and ten years. Therefore, the RWH plan should be combined with complementary stormwater management techniques as detention basins, infiltration trenches, or permeable pavements in order to provide complete flood prevention.

5.6) CDA Rainwater-Harvesting Ponds and Recharge-Wells in Islamabad

Growing urbanization, increased demand for water for homes and businesses, and extensive groundwater mining have all put further strain on Islamabad's aquifers. According to many estimates, groundwater levels are steadily declining in several sectors. As a result, national and municipal authorities are experimenting with distributed rainwater harvesting and managed aquifer recharge (MAR) to lessen urban flooding and increase aquifer storage (PCRWR, 2023). To collect stormwater and direct it into underlying aquifers, the Capital Development Authority (CDA), in partnership with PCRWR, IWMI, and development partners, has advanced a program of pilot recharge wells and retention/ponding cells across specific sectors (such as the Kachnar Park sector and other public green spaces).Capital Development Authority (CDA) is up to construct 100 recharge wells and 10 underground storage tanks across Islamabad as part of a larger water-security program and also has integrated the pilot into building bylaws and municipal planning discussions and with the great support by the Pakistan Council of Research in Water Resources (PCRWR) which providing technical hydrogeological assessment, well design guidance and monitoring support. CDA approach includes surface ponding which means temporary retention basins or shallow collection ponds in parks/green belts with vertical recharge wells (injection or infiltration wells) that transfer filtered ponded water into suitable aquifer strata.

The design contains as Catchment and conveyance which collect runoff from roof tops and paved surfaces and with the help of gutters/drains direct it towards shallow collection ponds or lined infiltration areas. Then to remove large debris, a Pre-treatment (coarse screening / sediment forebays) is used to reduce sediment loading to the recharge structure. Recharge well

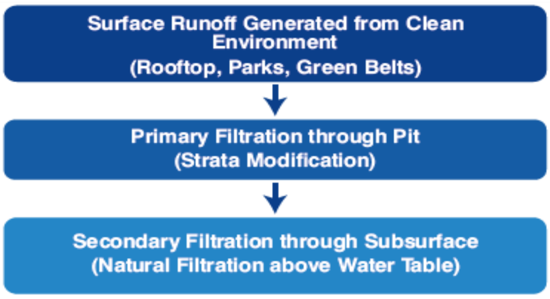


Figure 1: Filtration mechanism

construction is based on building :a sink or pond adjacent to a drilled or dug well and installed with gravel and sand layers those act as a source of natural filtration media and a well shaft that extends to an aquifer-near zone but above the water table to allow seasonal infiltration.

Results from Kachar park as follows and

This pilot program is very recent (pilots 2021–2024 expanding to a broader roll-out) so the most on surface results are evidence is in the form of monitoring briefs and press reports rather than long-term peer-reviewed articles but still some important evidence received which show the effectiveness of this pilot, for example: local monitoring reports indicate that pilot recharge sites reduced surface ponding during intense monsoon events. IWMI and pilot team members reported that the area around the Kachnar Park recharge site remained dry during an intense rain event in which neighbouring areas experienced surface flooding and mitigate flood risks.

PCRWR technical material and government briefings report that where recharge wells were installed and it seen short-term increases or stabilizations of groundwater level. For example, an IWMI-cited summary mentions "an observed improvement in water table near Kachnar Park (reported as a measurable change in the monitoring dataset). The Standing Committee and CDA briefings note that the first tranche of wells produced localized improvements and that 80 pilot bore-logs and monitoring installations have been prepared under the program for data analysis."

And reported in one report as follows "The flow meter recorded a rainwater flow of about 1,134,000 litters, which has been recharged at Kachnar site through this single event. Ultimately, an instantaneous rise of about 10 m shown in figure below was recorded through CTD divers installed in the nearby observation well. Accordingly, water table was raised from 38 to 28 m due to the groundwater recharge of 1,134,000liters Moreover, groundwater quality was also improved as EC of groundwater was decreased from 0.39 to 0.23 dS/m through rainwater recharge.

Table 2: Impact on water table

Location	Depth to Water Table (m), 2022		Change in DTW (m)
	Pre-Monsoon	Post-Monsoon	
PCRWR Office, H-8/1	51	48	+3.0
Agha Shahi Road, H-8	41	39	+2.0
F-9 Park Near Gate	13	8	+5.0
Kachnar Park, I-8	37	30	+7.0
Average rise in DTW (m) at project sites in Islamabad			+3.4

Table 1: Groundwater recharge calculation

Description	Groundwater Recharge) (01 Jan 2022 - 15 Aug, 2023)	
	Million Gallons	Million Liters
Recharge from CDA RWH Sites (89 Nos)	51.52	234.0
Recharge from FGEHA RWH Sites (10 Nos)	17.46	79.26
Recharge at IWMI Site Developed at Kachnar Park, I-8	3.40	15.43
Total Groundwater Recharge in Islamabad	72.38	328.60

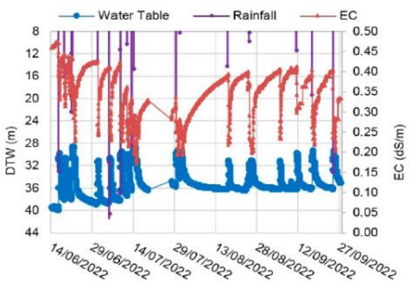


Figure 5: Groundwater recharge site at Kachnar Park, I-8, Islamabad

Despite of encouraging early results, there are several limitations remain that are important to state in analysis: Many pilot installations have only 1to3 years of monitoring and limit with short monitoring windows and longer datasets are needed to establish seasonal and interannual aquifer responses and to quantify net annual recharge versus losses. PCRWR and IWMI recommend multi-year monitoring for robust assessment is required. Recharge of urban runoff into shallow aquifers raises questions about contaminant transport (heavy metals, hydrocarbons, faecal coliforms) and raised water quality concerns. PCRWR guidance and pilot designs emphasize pre-treatment and first-flush diversion, but comprehensive published water-quality follow-up is limited ,so analysis reach up to the closing statement of careful design and monitoring are therefore critical to prevent aquifer contamination.

Beside of CDA targets 100 wells, it is still a small fraction of city area towards city wide groundwater recovery and will require larger networks of MAR sites and complementary demand management measures (borehole regulation, reduced abstraction). Several policy briefs call for integrated water resource management to couple MAR with supply side reforms.

Here are some gallery collections from sites:

recharge site at Park in front H-8 recharge site at Kachnar Park I-8, Islamabad

According to PCRWR's hydrological guidance, site selection and hydrogeological evaluation must come before the building of recharge wells.

When planning recharge wells, it's important to choose areas where the soil allows water to pass through easily and where the groundwater is not at risk of contamination, places with shallow polluted layers should be avoided. To keep the system working well, simple pretreatment steps like first-flush devices or sediment traps are needed to stop dirt and pollutants from entering and clogging the wells. At the same time, tools like water-level loggers, flow meters, and water quality tests as already used in PCRWR and IWMI pilots help track how much water is going in, whether it's improving the groundwater, and if there are any risks, so that problems can be caught early.

Chapter 6: Comparative and critical analysis: Effects of LID/GI projects in Europe (Sweden, Denmark, Italy) vs. Pakistan

This comparative analysis evaluates the implementation, performance, and outcomes of Low Impact Development (LID) and Green Infrastructure (GI) projects across European contexts (with emphasis on Sweden, Denmark, and Italy) and Pakistani urban settings. The analysis draws upon the case studies presented in previous chapters and examines them through multiple dimensions: technical performance, institutional frameworks, economic viability, and socio-environmental contexts.

6.1) Hydrological Performance Comparison

6.1.1 Runoff Reduction and Peak Flow Attenuation

European Projects:

• Augustenborg (Malmö): Achieved 20% annual runoff reduction through integrated open channel systems and retention ponds

• Copenhagen: Blue-green infrastructure reduced peak flows by managing 100-year storm events with acceptable flooding levels (10cm)

• Performance verified through 10-20 years of continuous monitoring Pakistani Projects:

• QAAP Sheikhupura: SWMM modeling showed 24% peak flow reduction for 2-year storms, decreasing to 10% for 10-year events

• CDA Islamabad: Recharge wells showed localized improvements with 10m water table rise after single events

• Limited to 1-3 years of monitoring data; reliance on modeling rather than empirical evidence

Critical Observations: The European projects demonstrate sustained, city-wide hydrological benefits across multiple storm magnitudes, while Pakistani initiatives show promising localized effects but lack long-term verification. The performance gap narrows for frequent, moderate storms but widens significantly for extreme events.

6.1.2 Climate Context Impact

Temperate Maritime (Northern Europe):

• Regular, moderate rainfall distribution (600-800mm annually)

• Systems designed for gradual infiltration and continuous evapotranspiration

• Winter challenges: freeze-thaw cycles, reduced biological activity Semi-arid/Monsoon (Pakistan):

• Concentrated monsoon rainfall (July-September): 60-70% of annual precipitation

• Extended dry periods requiring water storage rather than immediate infiltration

• High evaporation rates (1500-2000mm annually) affecting retention calculations

Design Implications: Pakistani systems require larger storage volumes relative to treatment capacity compared to European counterparts. The monsoon concentration means systems must handle intense, short-duration events followed by months of no recharge, fundamentally different from the European context where steady precipitation allows continuous system operation.

6.2) Water Quality Treatment Efficiency

6.2.1 Pollutant Removal Comparison

Total Suspended Solids (TSS):

• European systems: 70-95% removal (bioretention, wetlands)

• Pakistani systems: 51-85% removal (Marsala wetland: 51-68%; Sialkot FTW: 72-85%)

• Similar mechanisms but Pakistani systems show higher variability Heavy Metals:

• European bioretention: 40-90% removal efficiency

• Sialkot FTW: >90% Cr removal by water hyacinth and water lettuce

• Pakistani floating wetlands surprisingly effective, possibly due to higher initial concentrations promoting plant uptake Nutrients:

• European systems: Nitrogen 10-50%, Phosphorus 0-20% (often export during establishment)

• Sialkot FTW: Variable performance (BOD 31-90%, COD 27-90% depending on species)

• Marsala wetland: NH_4-N removal 66-72%, but NO_3-N showed negative removal

• Both regions struggle with nutrient management; neither has achieved consistent high performance

6.2.2 Water Quality Monitoring Gaps

European Advantage: • Standardized protocols following EU Water Framework Directive

• Continuous monitoring stations with telemetry

• Long-term datasets enabling seasonal and interannual analysis

• Published peer-reviewed studies with transparent methodologies Pakistani Challenges:

• Inconsistent sampling protocols across projects

• Limited monitoring budgets restricting sampling frequency

• Short monitoring periods (often <2 years) preventing seasonal analysis

• Reliance on one-time measurements or modeling estimates

• Few peer-reviewed publications; mostly government reports Impact on Knowledge: The data quality gap means that Pakistani project performance is less certain than European counterparts. While pilot results are encouraging, scaling up without robust monitoring risks implementing systems whose long-term effectiveness remains unverified.

6.3) Institutional and Policy Framework Analysis

6.3.1 Legislative Drivers

European Union Framework:

• Water Framework Directive (2000/60/EC): Legally binding "good ecological status" requirements

• Floods Directive (2007/60/EC): Mandatory flood risk management plans

• Urban Wastewater Treatment Directive (2024 recast): Explicit integration of stormwater and nature-based solutions

• EU Green Infrastructure Strategy: Policy framework promoting multi-benefit approaches

• Enforcement: Infringement procedures, financial penalties for non-compliance Pakistani Framework:

• National Green Building Code (2025): First federal policy mandating rainwater harvesting for buildings >4 floors

• Environmental Protection Act (1997): Requires EIA/IEE but lacks specific stormwater standards

• Provincial fragmentation: Punjab, Sindh, KP each with different local government acts

• Limited enforcement: Technical capacity gaps, weak inter-agency coordination

• Reactive rather than preventive: Regulations often follow disaster events Critical Assessment: Europe's integrated, legally binding framework creates strong implementation drivers, while Pakistan's fragmented, guidance-based approach results in inconsistent adoption. The 2025 Green Building Code represents progress but lacks the comprehensive scope and enforcement mechanisms of EU directives.

6.3.2 Integration into Urban Planning

European Integration:

• Augustenborg: LID/GI integrated into comprehensive eco-district regeneration (1998-2002)

• Copenhagen: Cloudburst Plan coordinates across 20-year timeline with prioritized implementation zones

• Spatial planning laws require stormwater management in development approvals

• Inter-departmental coordination: Water utilities, urban planning, environmental agencies work collaboratively Pakistani Fragmentation:

• Project-by-project basis: Each initiative (Sialkot, QAAP, CDA) operates independently

• Limited coordination: Industrial, municipal, and federal projects rarely share learnings

• Building codes focus on individual structures rather than catchment-scale planning

• Missing: Master plans integrating LID/GI with broader urban development strategies

Consequence: European cities achieve synergistic benefits through integrated planning, while Pakistani projects remain isolated pilots with limited systemic impact. Scaling requires moving from individual projects to city-wide stormwater master plans.

6.4) Economic Viability and Cost Effectiveness

6.4.1 Capital and Operational Costs

European Cost Context:

• Augustenborg: Significant upfront investment (exact figures not disclosed but estimated €5-10 million for full retrofit)

• Copenhagen: 20-year implementation budget addressing city-wide infrastructure

• Higher labor and material costs offset by long-term benefits and avoided flood damages

• Cost-benefit analysis: Doing nothing estimated at $60 million USD annually, rising to $160 million by 2100 Pakistani Cost Context:

• QAAP Sheikhupura: PKR 347 million capital cost for rain-barrel system

• Annual O&M savings: PKR 115 million (26% reduction in pumping costs)

• Payback period: ~3 years

• Sialkot FTW: Low-cost solution using local materials and plants

• CDA Islamabad: Pilot recharge wells relatively inexpensive but scale-up costs uncertain.

Cost-Effectiveness Comparison: Pakistani projects demonstrate shorter payback periods due to lower labor costs and use of local materials. However, European projects account for broader co-benefits (biodiversity, amenity value, carbon sequestration) that justify higher initial investments. Pakistani economic analyses tend to focus narrowly on direct water/flood savings, potentially undervaluing ecosystem services.

6.4.2 Funding Mechanisms and Financial Sustainability

European Funding:

• Municipal budgets with dedicated stormwater management line items

• EU funding programs (LIFE, Horizon Europe) supporting demonstration projects

• Public-private partnerships for large infrastructure

• Stormwater utility fees in some cities creating dedicated revenue streams

• Insurance industry involvement: Risk-based premiums incentivizing flood resilience Pakistani Funding:

• Ad-hoc project funding from federal/provincial budgets

• Development partner support (World Bank, IWMI) for pilots • Industrial projects self-funded (QAAP) with clear ROI

• Missing: Dedicated stormwater budgets, utility fee structures

• Maintenance funding uncertain after project completion

Sustainability Concern: European systems have established financial mechanisms ensuring long-term O&M, while Pakistani projects risk deterioration after initial implementation if ongoing funding is not secured. The 3-year payback at QAAP is promising but requires industry-wide adoption to generate sufficient O&M budgets.

6.5) Synthesis, Strengths, Limitations and Opportunities

6.5.1 European Strengths

• Integrated policy framework creating strong implementation drivers

• Decades of monitoring data enabling evidence-based design refinement

• Standardized design guidelines and professional training programs

• Comprehensive ecosystem service valuation justifying investment

• Established maintenance frameworks ensuring long-term performance

• Cross-sectoral collaboration embedded in planning processes

6.5.2 European Limitations for Pakistan Transfer

• High cost structures not replicable in resource-constrained contexts

• Design parameters calibrated for temperate climates

• Maintenance complexity requiring specialized skills and equipment

• Institutional structures (water utilities, enforcement mechanisms) not present in Pakistan

• Material specifications assuming availability not guaranteed in Pakistan

6.5.3 Pakistani Innovations and Adaptations

• Cost-effective floating wetlands (Sialkot) using local materials and plants

• Decentralized rain-barrel systems (QAAP) with strong economic returns

• Integration with water supply augmentation (not just flood control)

• Managed aquifer recharge (CDA) addressing groundwater depletion

• Industrial sector engagement demonstrating private sector viability

6.5.4 Pakistani Limitations Requiring Attention

• Fragmented policy framework limiting systemic implementation

• Monitoring gaps preventing performance verification and adaptive management

• Maintenance capacity constraints risking pilot project deterioration

• Limited ecosystem service valuation weakening economic justification

• Pilot-scale implementation without clear scaling pathways

• Water quality risks from recharging contaminated urban runoff

6.5.5 Opportunities for Hybrid Approaches

Pakistan should not simply replicate European models but develop hybrid approaches combining European technical rigor with Pakistani innovations:

• Adopt European monitoring protocols but use low-cost sensors and citizen science

• Implement European design standards but specify locally available materials

• Establish maintenance frameworks but train community-based organizations, not just municipal staff

• Integrate ecosystem service valuation but prioritize co-benefits most relevant to Pakistani context (water supply, groundwater recharge)

• Develop Pakistan-specific design manuals incorporating lessons from both European and local pilots. This hybrid approach can create context-appropriate solutions that are technically sound, economically viable, institutionally feasible, and culturally acceptable.

Chapter 7: Conclusion

This thesis has established that Low Impact Development (LID) and Green Infrastructure (GI) practices offer effective alternatives to traditional gray infrastructure for urban stormwater quantity and quality control. From comparative examination of European and Pakistani applications, the study offers considerable potential as well as major challenges for implementation of these nature-based solutions under different geographic and institutional contexts.

Performance and Effectiveness: The technologies reviewed here—bioretention systems, permeable pavements, grass swales, and green roofs—consistently demonstrate noteworthy hydrological and water quality benefits. Bioretention eliminates 70-95% TSS and decreases runoff by 40-60%; green roofs capture approximately 60% event-based; and properly designed swales convey and treat stormwater efficiently and reduce peak flows. European case studies verify long-term performance: Augustenborg's 20% annual runoff reduction resisted 50-year and 100mm/6-hour storm events (2007, 2014), and Copenhagen's blue-green infrastructure manages 100-year storms with $60 million USD cost savings estimates per year. Pakistani pilots, with short monitoring periods (1-3 years), have comparable technical potential with QAAP lowering peak flow by 24% and having 3-year economic payback, and Sialkot floating wetlands removing >90% chromium at low cost.

Critical Success Factors: European implementations succeed owing to policy integrated arrangements (Water Framework Directive, Floods Directive) providing legally enforceable standards, design guidance standardisation providing technical standardisation, intensive 10-20 year monitoring enabling adaptive management, and dedicated finance arrangements ensuring long-term operations. Pakistani initiatives are marred by fragmented provincial legislation, scattered enforcement, inadequate monitoring capacity, and inflexible post-project maintenance finance. Despite these institutional constraints, Pakistani projects have economic advantages in terms of reduced material/labor expenses, compact payback intervals, and efficient private sector participation (industrial self-financing).

Climate and Context Adaptation: Major climatic variations call for major design adjustments instead of European model copying. European temperate maritime climate (600-800mm evenly distributed rainfall) supports non-stop system operation with minimal storage needs, whereas Pakistani semi-arid/monsoon climate (60-70% rainfall for 3 months, 1500-2000mm evaporation) calls for large storage capacities, drought-hardy plants, and designs fulfilling dual functions of flood protection and water conservation. These variations directly undermine transferability assumptions.

Path Forward—Hybrid Solutions: Rather than copying European models, Pakistan does not have to but should develop hybrid solutions combining European technical rigor (monitoring practices, performance standards, valuation of ecosystem services) with Pakistani innovations (affordable floating wetlands, decentralized rain barrels, managed aquifer recharge) adapted to local contexts. Key recommendations are: (1) developing Pakistan-specific design manuals considering monsoon hydrology, local building materials, and native vegetation; (2) nationalizing monitoring requirements with at least a 3-5 year dataset using standardized procedures; (3) committing stormwater funding sources by utility or development fees that guarantee long-term upkeep; (4) integrating LID/GI requirements in municipal master plans rather than building-by-building regulations; and (5) developing institutional capacity through demonstration sites, professional training courses, and inter-agency coordination systems.

Conclusion Overview: LID and GI are more than technical solutions but paradigm shifts in urban water management—from rapid conveyance to source control, from single-function infrastructure to multifunctional landscapes, from gray to hybrid green-gray systems. Two decades of European practice validate technical feasibility and long-term sustainability under supporting institutional design. Pakistani pilots demonstrate that these measures can be effective in resource-scarce, climatically challenging environments if appropriately transferred. The future of sustainable urban stormwater management in Pakistan lies not in the blanket copycatting of European paradigms, but in judiciously blending international best practices with local innovations, indigenous knowledge, and context-specific solutions. With reinforced policy frameworks, committed monitoring commitments, invested funding mechanisms, and coordinated planning strategies, Pakistani cities can create stormwater infrastructure that is resilient and at the same time addresses flooding, water scarcity, pollution control, and ecosystem restoration—delivering multifunctional urban landscapes that support both environmental health and human well-being at the same time as it remains economically feasible within developing country limitations.

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