JOÃO VICTOR GALVANE

# THE IMPACT OF GREEN INFRASTRUCTURE (GI) ON THE URBAN WATER CYCLE

A MULTI-SCALAR APPROACH

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UNIVERSIDADE DO ALGARVE

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**Master in Urban Water Cycle**

**Supervised by:**

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**Declaração de Autoria de Trabalho**

Declaro ser o autor deste trabalho, que é original e inédito. Autores e trabalhos consultados estão devidamente citados no texto e constam da listagem de referências incluída.

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João Victor Galvane

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This master dissertation is the result of many hours of work, and it is important to express my sincere “thank you” to a few people who have helped me in one more stage of my life.

To my supervisors Dr. Jorge Manuel G. P. Isidoro and Dr. Daniel Green, for suggesting this theme and for the support and wisdom. Thank you for your patience, advice, and hard work.

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I would like to dedicate this dissertation to my late and beloved grandmother, Dilma Galvani, may we meet again.

**Abstract**

Building urban resilience has attracted significant attention in recent years. In response to climate change, innovative technologies are emerging to help manage and attenuate flood risk. One frequently used approach to help build resilience capacity is Green Infrastructure (GI), which is considered an important strategy of urban planning aimed at enhancing sustainable development. Studies revealed that the various types of GI practices offer multiple benefits in addition to stormwater benefits, in widely varying geographic and climatic regions.

This dissertation assesses the state-of-art on GI to discuss its effectiveness as a solution to tackling urban flood risk, as well as characterises a Spanish city (Vitoria-Gasteiz), as a city-scale case study. Vitoria-Gasteiz's GI managed to improve and correct historical issues with urban flooding water quality, preserving its environmental and landscapes.

Data from a monitored bioretention cell lysimeter, located at the National Green Infrastructure Facility (NGIF), Newcastle University, was analysed. The objective was to determine whether the bioretention cells offer an effective solution to urban flood management, by presenting its behavior in response to real rainfall events. Three rainfall events were chosen for analysis: the first one with a total rainfall of 26,2 mm, in which the lysimeter stored 80,7%; the second with 48,6 mm (of which 39,8 mm was only in 24,5 h), delaying the start of runoff by 12 hours and generating a lag time of 11 hours, storing 20%; and the third with 8 mm, where the lysimeter received 16 L and outflowed 100 mL.

The bioretention cell characteristics were modelled in the software Storm Water Management Model (SWMM), to assess its hydrologic potential to manage runoff during flood events, from hypothetical wider catchment drainage areas. The best simulated SWMM scenario ratios were the 12,5:1 that showed, respectfully, a runoff peak and volume reduction of 30% and 32%, while the 25:1 showed a reduction of 3,45% and 16,5%.

**Key words:**

Green Infrastructure, Vitoria-Gasteiz, Bioretention cell, Lysimeter, SWMM, Urban water management.

**Resumo**

Num contexto de mudanças ambientais globais e de rápida urbanização, a construção de resiliência urbana tem atraído uma atenção crescente tanto de profissionais como de investigadores em planeamento urbano. Uma cidade precisa de avaliar e construir capacidade de resiliência para absorver, mitigar, adaptar e proteger a sua população, propriedades e infraestruturas a muitos tipos de perturbações, incluindo águas superficiais, mantendo ao mesmo tempo a sua organização e funções sociais, ecológicas e económicas.

Estão a surgir tecnologias inovadoras para ajudar a gerir o risco de inundações, mas estas nem sempre são fáceis de implementar. Uma tecnologia frequentemente proposta para ajudar a construir capacidade de resistência é a utilização de técnicas de drenagem urbana sustentável, ou Infraestrutura Verde (GI, de *Green Infrastructure*, em inglês), como parte de um plano de gestão de águas pluviais. A utilização destas tecnologias é considerada uma importante estratégia de planeamento urbano, destinada a reforçar o desenvolvimento sustentável. De facto, os espaços verdes urbanos e a GI podem proporcionar múltiplos cobenefícios, para além dos benefícios das águas pluviais, e podem aumentar a resiliência urbana.

Pensando nisso, esta dissertação avalia o estado da arte existente sobre GI, de forma a discutir as suas eficácias como soluções para o risco de inundações urbanas, bem como caracteriza uma cidade espanhola (Vitoria-Gasteiz) como um estudo de caso à escala de cidade, e, finalmente, analisa dados de um lisímetro de célula de bioretenção, localizado no National Green Infrastructure Facility (NGIF), na Universidade de Newcastle (Reino Unido), para determinar se a sua célula de bioretenção poderia ser uma solução eficaz para eventos de gestão de inundações urbanas, apresentando o seu comportamento em eventos de chuva reais. Além disso, ao modelar as características da célula de bioretenção no software *EPA's Storm Water Management Model* (SWMM), esta dissertação simula o potencial hidrológico da célula de bioretenção para gerir o escoamento de áreas hipotéticas impermeáveis à superfície.

Através da revisão bibliográfica, verificou-se que muitos estudos revelaram que os vários tipos de práticas de GI oferecem múltiplos benefícios aos ecossistemas urbanos e ao escoamento urbano, em regiões geográficas e climáticas muito variadas. As instalações de bioretenção, por exemplo, podem reduzir 50% a 97% do volume total do escoamento, promovendo a infiltração para recarregar as águas subterrâneas com um efeito de

purificação eficaz, intercetando poluentes e, também, promovendo a evaporação. Os cintos verdes de baixa elevação podem recolher o escoamento pluvial, retardar as cheias urbanas, e complementar as águas subterrâneas. Os pavimentos permeáveis podem ser utilizados para substituir as superfícies tradicionais das estradas de alcatrão. No entanto, as GI não possuem sempre o mesmo desempenho, dependem do clima e do regime pluviométrico de onde é implementada, e os seus benefícios a longo prazo e manutenção são ainda muito limitados. A combinação de infraestruturas convencionais cinzentas e verdes é importante para conseguir uma gestão de águas pluviais que funcione bem por períodos mais longos.

Uma implementação bem-sucedida de GI, por exemplo, é a premiada cidade espanhola Vitoria-Gasteiz, onde o projeto e execução do “Cinturão Verde” desencadeou a Câmara Municipal a continuar a implementar outras GI. A cidade conseguiu melhorar e corrigir questões históricas da qualidade das águas urbanas e cheias, preservando o seu ambiente e paisagens e também melhorando a biodiversidade. Apesar da necessidade de trabalho árduo, é possível implementar Infraestruturas Verdes, procurando melhorar a vida dos seus cidadãos e das gerações futuras, uma vez que os inquéritos públicos indicam que 99% da população da cidade concorda que o “Cinturão Verde” e a suas GI melhoraram a sua qualidade de vida, uma vez que aumentou o número de espaços verdes, parques e jardins urbanos.

Em relação aos dados analisados do NGIF, estes compreenderam um período de 9 meses de dados, nos quais a célula de bioretenção recebeu um total de 1.211,2 L como entrada e reteve eficazmente 52,7% do mesmo. Foram escolhidos três eventos pluviométricos no período dos dados: Setembro de 2020, com uma precipitação total de 26,2 mm em 2 dias, em que a saída no lisímetro foi atrasada em 17 horas, conseguindo armazenar 80,7%; Outubro de 2020, com uma precipitação de 48,6 mm em 3 dias (sendo que 39,8 mm foram apenas em 24,5 horas), atrasando o início escoamento em 12 horas e gerando um tempo de retardo do pico de escoamento em 11 horas, gerindo 20% do total de fluxo; e Abril de 2021, com uma precipitação total de 8 mm em 14 horas (sem chuvas anteriores por 43 dias), onde o lisímetro recebeu 16 L de entrada e teve como saída apenas 100 mL, resultando numa eficiência de 99%. De maneira geral, concluiu-se que células de bioretenção podem armazenar totalmente o volume de pequenos eventos de precipitação. Ou seja, a intensidade da chuva é a principal propriedade pluviométrica que influencia na

eficiência da célula de bioretenção, com uma relação inversa (quanto maior a intensidade, menor a eficiência).

Além disso, foram simulados diferentes cenários no software SWMM para a célula de bioretenção existente no NGIF, de acordo com as suas propriedades de laboratório, para gerir o escoamento proveniente de diferentes superfícies impermeáveis, a fim de descobrir uma razão ótima de área impermeável-célula de bioretenção. A melhor relação foi a de 5:1, que não gerou pico de escoamento e transbordamento de superfície, e geriu eficazmente 62% do fluxo total de escoamento. O cenário 12,5:1 mostrou uma redução de 30% do pico de escoamento e uma redução de 32% do volume de escoamento e o cenário 25:1 apresentou uma redução de 3,45% do pico de escoamento e uma redução de 16,5% do volume de escoamento.

Os resultados, tanto reais como simulados, demonstraram que as células de bioretenção são infraestruturas verdes que, quando combinadas com sistemas de drenagem convencionais, podem ajudar as zonas urbanas a gerir os seus eventos de inundações e aumentar a sua resiliência, visto que os resultados demonstraram que essa GI pode atrasar o início do escoamento e os seus picos, além de diminuir os volumes totais. O lisímetro analisado é um de terra, portanto não possui nenhuma vegetação específica, por isso esta alternativa singular pode ser utilizada em todo o mundo, mostrando a sua implementação favorável e inclusiva.

**Palavras-chave:**

Drenagem Urbana Sustentável, Vitoria-Gasteiz, Célula de Bioretenção, Lisímetro, SWMM, Gestão de Águas Pluviais Urbanas

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# 1. Introduction

## 1.1. Scope

This dissertation assesses the benefits of green infrastructure in stormwater management of urban areas at a variety of scales to help and improve conventional drainage systems response to urban floods due to intense storm events, enhancing rainwater runoff quality and making cities more flood risk resilient, social receptive and aesthetics. Green Infrastructure (GI) practices involve source-level, localised infrastructure (combining 'green' (*i.e.*, biophysical, living vegetation and soil elements) that work with nature to reduce stormwater runoff and improve water quality from sources using landscape natural features, as opposed to conventional drainage, which focuses on reducing peak runoff discharge rates by removing water quickly from a site (Dhakal & Chevalier, 2017) through a series of pipes and conduits.

Current intense urbanisation in cities, as well as climate change, are challenges that GI techniques could help urban areas and urban population to cope with. Urbanisation disrupts natural biodiversity and hydrological processes by removing plants and topsoil and erecting impermeable structures. As a result, urban dwellers have lost touch with environment and are missing out on the ecological services and benefits that nature gives to humanity (Millennium Ecosystem Assessment, 2005). Urban landscapes convert most rainwater into stormwater runoff due to diminished vegetation, impervious surfaces, and broken drainage connections, resulting in major downstream detrimental consequences. The flow gathers up contaminants from urban environments, carries them to receiving waters and can result in poor water quality entering rivers and the seas. Furthermore, the faster conveyance of higher runoff increases the rate, peak, and frequency of flooding downstream, posing a greater risk to public safety, property, and socioeconomic activity (Dhakal & Chevalier, 2017).

A broad definition of Green Infrastructure for flood management includes straightforward "green" concepts meant to address various types of flooding, such as varied natural land cover that provides flood protection and water quality benefits (Chenoweth *et al.*, 2018). GI fits within the wider umbrella term of Nature-Based Solutions (NBS). In North America, this more holistic design and management approach is known as Low Impact Development (LID) or even GI, as well as Water Sensitive Urban Design (WSUD) in

Australia, as Sustainable Urban Drainage Systems (SUDS) in the UK (CIRIA, 2015), and as the "Sponge City" concept in China (Chan *et al.*, 2018; Kabisch *et al.*, 2016). All these terms are used interchangeably with GI, although there are subtle distinctions that are beyond the scope of this dissertation (see Fletcher *et al*., 2015; Koc, Osmond & Peters, 2017; Chan *et al.*, 2018; Chenoweth *et al.*, 2018; Green *et al.*, 2021). This dissertation will refer to this approach with its more holistic term from North America, Green Infrastructure (GI), and will consider these different terms as practically as the same, treated only with different nomenclatures.

Despite appearing natural, urban GI mimics natural processes and belongs somewhere between a grey-to-green continuum (Figure 1.1) to make sure they are optimised and regulated for their intended purpose. This enables GI to be adapted to a range of locales, conditions, and functional requirements, as well as the ability to adapt to changing conditions in the future, which may be more difficult in subsurface drainage systems (Zimmermann *et al.*, 2016).

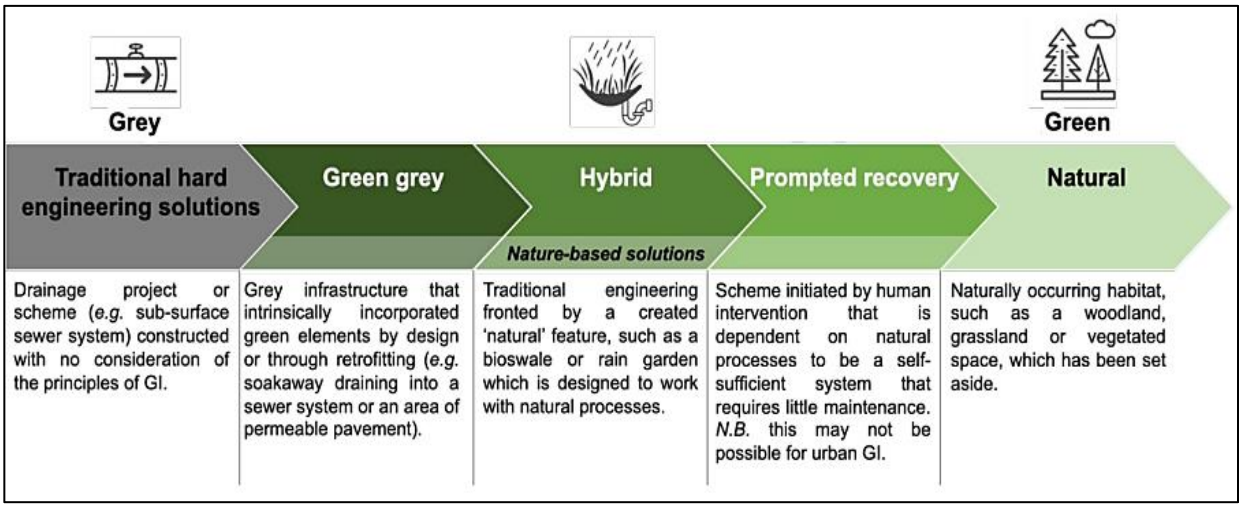


**Figure 1.1** Grey to green continuum of urban GI (Source: adapted from Roca *et al.*, 2017; Green *et al.*, 2021).

The assessment of positive influence of GI in urban areas will be possible by an extensive and critical bibliographic review of scientific articles published in journal and international congresses, guides to cities and countries that have successful examples and official documents from public authorities. A systematic literature review was conducted to find relevant, timely published sources to assess the effectiveness of GI. Also, by the report of a real successful GI implementation at a city-scale in a European city as a study case, the Green Belt and Green Infrastructure of Vitoria-Gasteiz, Spain, where it presents the main problems with stormwater, climate change and biodiversity scarcity, presenting social, and, of course, flood resilience benefits. This dissertation will also present results analysis of open-source, publicly available data from a controlled field-experiment to determine its potential hydrologic performance and efficiency to treat a runoff from a hypothetical pavement traditional parking lot, by simulations with a modelling rainfall/runoff software.

### 1.2. Research Objectives

This dissertation aims to critically assess whether GI systems offer an effective and holistic solution to tackle urban flooding when compared to traditional stormwater management approaches. To achieve this overarching aim, the following main objectives (Research Objectives - *ROs*) must be successfully considered:

- To assess the state-of-art on Green Infrastructure to determine its effectiveness and suitability at providing a holistic and complementary solution to managing urban flood risk (*RO 1*).
- To characterise the Spanish city of Vitoria-Gasteiz as a city-scale case study, assessing the effectiveness of current GI interventions at stormwater resilience matter, social impacts generated, and future GI projects intended by the city (*RO 2*).
- To analyse field data from a small-scale bioretention cell lysimeter located at the National Green Infrastructure Facility (NGIF), Newcastle University, UK, in terms of Volumetric Water Content (VWC), to determine whether the infiltration of this GI approach can provide an effective and complementary solution to urban flood management. Also, it is intended to assess the potential hydrologic performance of the same bioretention cell if it treated a hypothetical impervious surface, assessing different area ratios making use of SWMM as an enabler (*RO 3*).

### 1.3. Dissertation Structure

This dissertation structure is as followed in Figure 1.2.

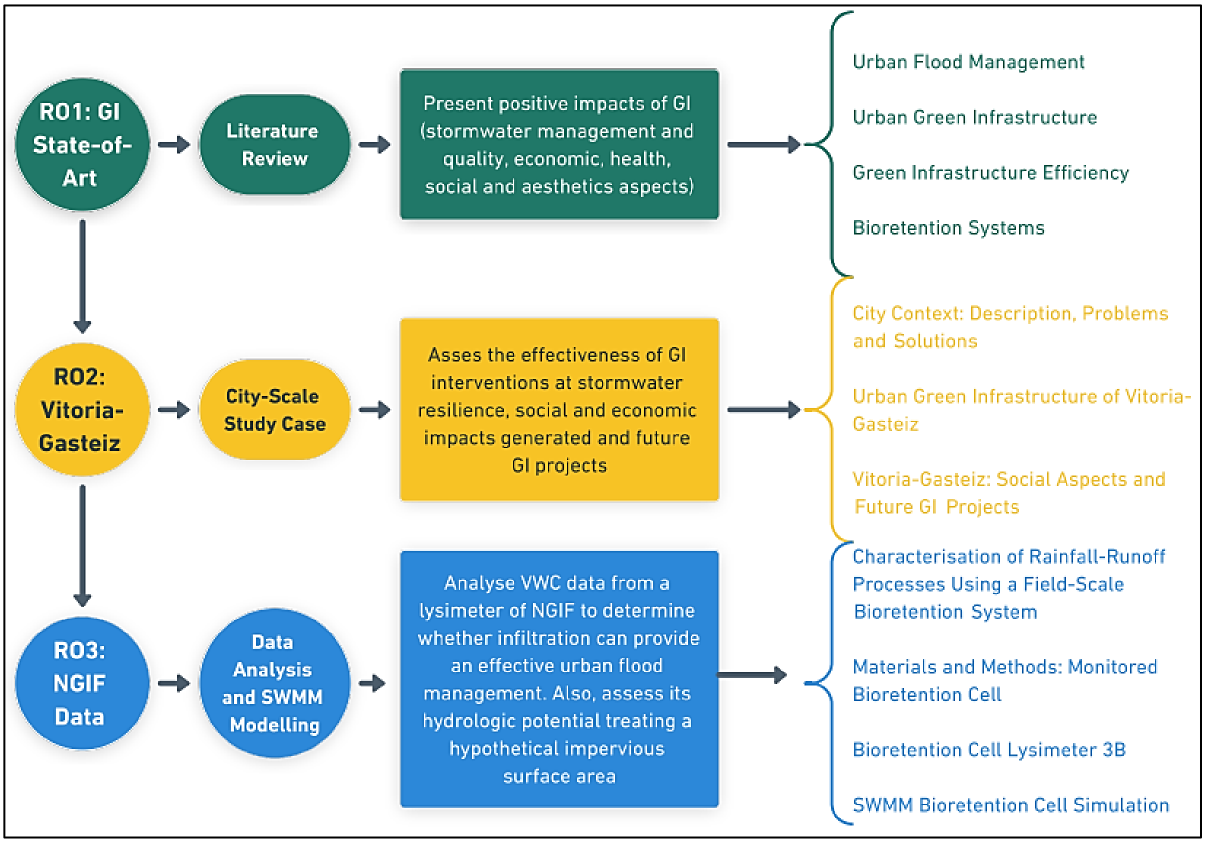


**Figure 1.2** Dissertation structure flow chart.

*RO1* will be achieved by conducting a systematic literature review (see Chapter 2). The subchapter "Urban Flood Management" evaluates the fundamental cause for why conventional urban drainage systems are no longer functioning adequately and why GI is the best possible approach to help urban areas in flooding caused by extreme storm events, improving their resilience against flood risk. The second subchapter, "Urban Green Infrastructure", introduces and describes some of the most familiar GI, followed by the explanation of the difference between constructed GI and possible social and political changes. This chapter also approaches the economical (investment difference between conventional grey drainage and green infrastructure), social and health benefits of GI. "Green Infrastructure Efficiency" it is the third subchapter of "Literature Review" and presents results from studies that analysed theoretical and real efficiency of GI managing stormwater runoff, and its implementation difficulties and maintenance. The final subchapter "Bioretention Systems" presents its definitions, possible designs and shows stormwater management studies results and a brief of life cycle and economical discussion.

*RO2* will be achieved by means of the chapter "Study Case: Vitoria-Gasteiz, Spain". The subchapter "City Context: Description, Problem and Solutions", presents a description of the city of Vitoria-Gasteiz, addressing its social and economic aspects, historical problems with flood stormwater, runoff water quality, lack of environmental biodiversity and future problems with climate change. This case-study provides a real-world example for how GI has been implemented across a city to help tackle urban flooding, whilst also providing multiple co-benefits to the urban population of Vitoria-Gasteiz Also, it presents how the city managed to overcome these obstacles. The second subchapter "Urban Green Infrastructure of Vitoria-Gasteiz" approaches the GI projects in specific, describing what was the exact problem and what was the built infrastructure that attenuated/solved the problem. The third and last subchapter "Vitoria-Gasteiz: Social Aspects and Future Green Infrastructure Projects" is based on two satisfaction surveys in relation to GI, bringing mainly social and health aspects. It also presents a status of the GI already implemented in the city, and comments on future in the stormwater management sector.

*RO3* is related to and will be achieved with the "National Green Infrastructure Facility (NGIF)" and the "Results" chapters. The NGIF chapter explains what the National Green Infrastructure Facility is, where it is located and what are their main GI experiments. It has three subchapters. The first one, "Materials and Methods: NGIF Bioretention Cell Lysimeter" presents the bioretention cell that will be analysed in this dissertation, describing its design, substrate composition and sensors. The subchapter "Bioretention Cell Lysimeter 3 Cell B" presents real rainfall events that will be used to analyse VWC data. The last subchapter "SWMM Bioretention Cell Simulation" simulates hydrologic potential of the NGIF bioretention cell managing runoff from hypotheticals impervious surface areas.

The "Results" chapter is the one where all results found for the real VWC data will be presented, as well as the SWMM simulation results and discussions.

## 2. Literature Review

The purpose of this chapter is to critically assess the state-of-art of green infrastructure in urban areas by taking a critical look at conventional drainage systems and showing the positive impacts of sustainable urban drainage. Focus will be in stormwater management, but also, bringing water quality, economic, social and aesthetics aspects of green infrastructure (*RO 1*).

### 2.1. Urban Flood Management

Since the first urban conurbations, people have congregated preferentially next to watercourses due to numerous benefits including the availability of drinking water, transport and waste removal. Rapid population increases in the 19th century within urban areas resulted in a rapid construction of infrastructures. Urban floods appeared, since buildings became more frequently closer to streams and rivers. Consequently, major epidemics of cholera and typhoid have struck Europe (Baptista, de Nascimento & Barraud, 2011). As a result of these problems, hygienist concepts emerged, and the relationship between rainfall and runoff were established for the design of sewage works (Braga, Tucci & Tozzi, 1998).

Therefore, urban drainage was, and still is in some places, the engineering practice of draining rainwater to nearby streams, rivers, or the sea as quickly as possible, replacing the natural drainage of a catchment by using channels and pipes to efficiently transport rainwater runoff away from the urban areas and therefore prevent flooding of low-lying regions (Wu, Wu & Zhang, 2019). As such, conventional urban drainage tends to treat surface water as an "unruly substance" (Jones & Macdonald, 2007). Besides, another issue about urbanisation and population growth are the impacts that these two aspects cause to the urban water cycle, mainly due to changes in surface and runoff channeling, increased pollution due to contamination of air and urban surfaces, and solid material disposed of by the population (Tucci, 2003).

Nowadays, conventional stormwater management systems and practices are not delivering satisfactory as once was, as the demand level is currently higher. The percentage of global populations living in urban areas has increased from less than 30% in 1950, to about 56% in 2019, an indication of recent rapid global urbanisation (World Bank, 2019). Population increases are focused within urban areas and will continue to be in the next decades (Pour *et al.*, 2020). As such, intense urbanisation, population growth and climate changes are some reasons of the inadequacies of urban drainage systems (Miller & Hutchins, 2017). For example, an analysis by Huong & Pathirana (2011) showed that flood depths in Can Tho (Vietnam) could increase by 20% from urbanisation alone. Figure 2.1 shows the impacts of impervious areas and urbanisation on surface water flows.

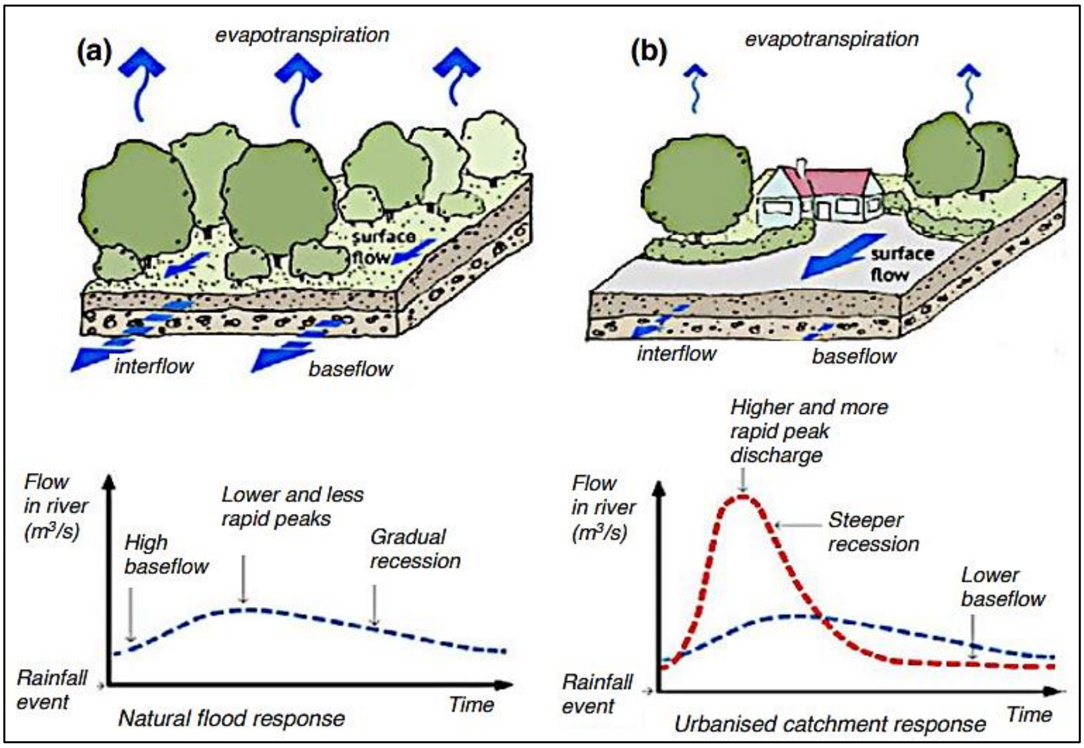


**Figure 2.1** Overview of surface water flows in: (a) a natural catchment, and (b) a more urbanised catchment, illustrating the impact of urbanisation on surface water flows. (Source: Scottish Government, 2013 *apud* Green, 2018).

Against the backdrop of global environmental change and rapid urbanisation, building urban resilience has attracted increased attention from both practitioners and researchers in urban planning (Calderon-Contreras & Quiroz-Rosas, 2017). Therefore, a city needs to assess and build capacity for resilience to absorb, mitigate, adapt, and to protect its people, properties, and infrastructure to many kinds of disturbances, including surface water, while maintaining its organization and social, ecological, and economic functions (Brudler, Arnbjerg-Nielsen & Hauschild, 2016; Fu, Hopton & Wang, 2020;). In fact, flood impacts not only cause damage to the physical systems of cities, but also to the social and economic systems. Thailand's summer and autumn 2011 flood events showed that these can lead to national or even global effects. Apart from the direct impact on the Thai society and economy, the floods had global effects on the production and supply of a wide range of goods and services, including cars and hard drives. About 25% of all hard drives in the world are manufactured in Thailand. As a result, the prices of hard drives in other parts of the world rose significantly (Munich RE, 2012).

Bosher (2008) has suggested that a resilient built environment should be designed, located, built, operated, and maintained in a way that maximises the ability of built assets, associated support systems (physical and institutional) and the people that reside or work within the built assets, to withstand, recover from, and mitigate for, the impacts of extreme natural and human-induced hazards. Moreover, Mens *et al.* (2011), like Arnbjerg-Nielsen & Hauschild (2016) and Fu, Hopton & Wang (2020) have defined that ecological resilience for flood risk systems is the ability to remain functioning under disturbances, where the magnitude of the disturbance is variable and uncertain. The analysis of this resilience requires insight into the response curve and recovery threshold (Figure 2.2). This response curve shows to what extent the socioeconomic system is impacted by flood events of varying magnitude. The recovery threshold indicates how likely the socio-economic system is to recover fully. Comparison of the response curve with the recovery threshold provides an indication of the robustness of the system. Thus, the more the system lengthens the response and recovery time, increasing the resilience time in relation to flood events, to keep the point of no recovery as far as possible, the more resilient the system will be.

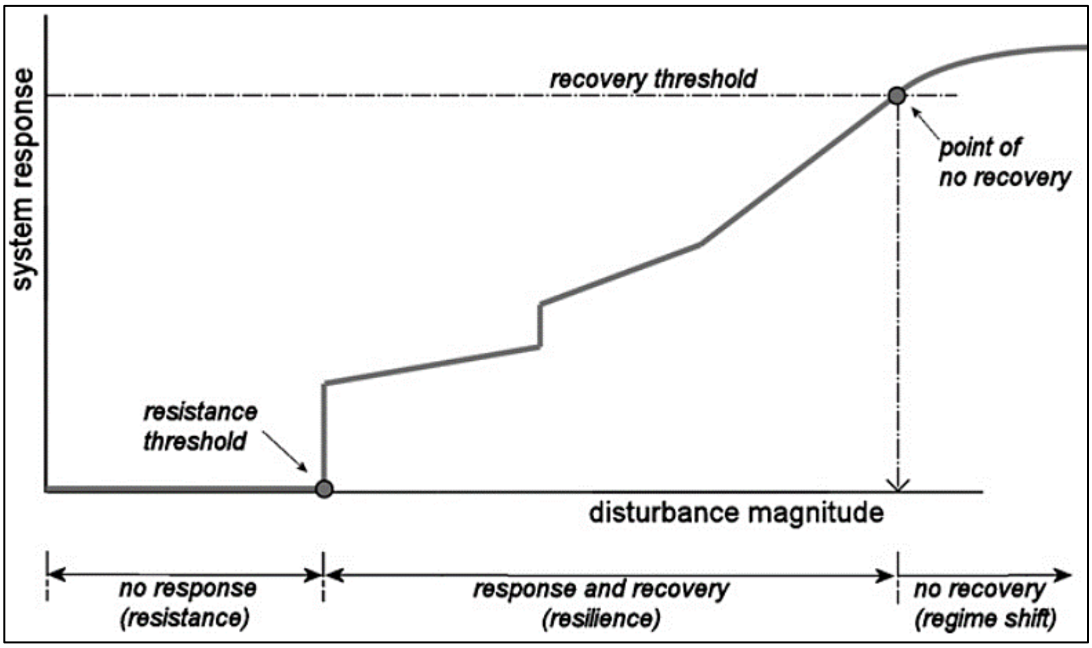


**Figure 2.2** Theoretic response curve, showing system response as a function of disturbance magnitude, indicating resistance, resilience, the point of regime shift, and the recovery threshold (Mens *et al.*, 2011).

More generally, the resilience of flood management interventions under conditions of uncertainty can be managed through building capacity by:

1. Continuous monitoring and analysis of the natural system, flood defences and protected assets to understand current flood risks and how they might change in the future (Jonkman & Dawson, 2012).
2. Managing vulnerability and exposure of the population and built environment, for example, through awareness raising and training (McEvoy *et al.*, 2010).
3. Reducing the cost of repair, recovery, and the time to respond in the event of a flood. Not just through improved emergency preparation and response but by exploring alternative models such as greater local access to financial resources and more flexible governance systems (Bauriedl, 2011).
4. Keeping options open by adopting flexible, multiple use solutions and enhancing variety (Allenby & Flink, 2005), which may involve development of adaptable engineering techniques in construction and refurbishment.

Current urban drainage systems designed to manage runoff to prevent floods, also tend to ignore the impact of ongoing land-use changes on runoff volume and peak (Pour *et al.*, 2020), impacts already showed in Figure 2.1 of surface water flow in natural versus urbanised catchments. Besides, the stormwater management systems are generally designed to handle runoff from a 10 to 20-year return period extreme rainfall event. It normally does not consider any changes to the land-use and associated land cover of the catchment area in which it is located (Hirsch & Ryberg, 2012). Also, lack of maintenance of piped sewer systems causes losses of performance.

For instance, floods in the UK in 2007 resulted in 350.000 people losing water supply for up to 17 days, 42.000 people losing electricity supply for over 24 hours and over 10.000 people being stuck on a Motorway or stranded on trains (Pitt, 2008). For example, in 2007, Hull City, in the United Kingdom, suffered a major urban flood due to inadequate maintenance within the city’s conventional urban drainage systems relating to blocked gullies resulting in sewer systems being unable to convey flood waters at their design capacities. As a result, direct and indirect damage to over 8.600 homes and 1.300 businesses were observed (Coulthard & Frostick, 2010).

Floods that occurred in early 2011 led to substantial damages in the Brisbane region in Australia and highlighted the challenge engineers must both balance water resource supply and flood management (Van den Honert & McAneney, 2012). Still about Thailand's 2011 floods that occurred in the Chao Praya River Basin, the damage was estimated to be more than US $45 billion (Impact Forecasting, 2012), making it one of the costliest disasters in history. Although, while often less visible than catastrophic flooding, chronic flooding can nevertheless have major consequences, especially for vulnerable populations, from affecting individuals' and households' finances, health, and water security, to damaging physical infrastructure of cities and incurring widespread disruption of transportation systems and other urban networks (Saulnier, Ribacke & von Schreeb, 2017). On a global scale the losses due to floods and other natural disasters are increasing (Munich RE, 2012) and one of the most important drivers of this trend is the increase of population and economic values in flood-prone areas in coastal, riverine and delta regions (Bouwer, 2011).

Innovative technologies are emerging to help manage flood risk, but these are not always straightforward to implement, and technology alone will not address all our challenges (Jonkman & Dawson, 2012). One frequently proposed technology to help build resilience capacity is GI as part of a stormwater management plan, which is considered an important strategy of urban planning aimed at enhancing sustainable development. In fact, urban green space and GI can provide multiple co-benefits in addition to stormwater benefits and may increase urban resilience (Meerow & Newell, 2017). Moreover, according to Wong & Brown (2009) the use of GI to manage runoff is increasing; focusing on local infiltration and the retention and discharge of water on the surface is imperative to ensure resilient urban communities. These approaches differ significantly from construction-based grey underground solutions that mainly employ dense networks of sewer pipes. Material demands and construction, operation and disposal processes vary between the two approaches, which leads to different environmental impacts throughout their life cycle. In addition, GI can improve the ability for communities to become more resilient to changes in climate (Roseen *et al.*, 2011). In some areas, the storm depth for today's 100-year storm may occur at a frequency of a 25-year storm in the future (Stack *et al.*, 2010). The hydrological consequences will be manifested by more frequent flooding and increased damage to private property and critical infrastructure such as bridges, roads, and utilities. GI provide distributed storage and infiltration throughout the watershed and has a positive cumulative effect on downstream areas by protecting those critical resources. (Roseen *et al.*, 2011).

The Netherlands, often seen as an example of "the best protected delta in the world", with high safety standards and an advanced organizational and funding structure for flood management. It is therefore striking that in the most recent safety assessment it became apparent that about one third of the primary defence mechanisms in the Netherlands are not up to standards (Inspectie Verkeer en Waterstaat, 2011 *apud* Jonkman & Dawson, 2012).

Stormwater management must meet multiple targets regarding environmental quality, flood safety and liveability (Brudler, Arnbjerg-Nielsen & Hauschild, 2016). Maintenance checks on buried systems are also complicated, so it is difficult to determine whether a buried drainage system is operating as expected (Coulthard & Frostick, 2010). For that reason, Green Infrastructure is widely and broadly understood as a set of strategies in built environments that serve a variety of ecosystem needs such as controlling temperature, improving air quality, increasing drought resilience, and managing floods (Block, Livesley & Williams, 2012). Moreover, with the ubiquitous natural and semi-natural landscape features, GI practices can substantially decrease the urban flooding risks through reducing stormwater runoff and delaying the lag time, thereby reducing the property losses caused by floods (Li *et al.*, 2018).

### 2.2. Urban Green Infrastructure

Since the 1970s many stormwater managements measures have been proposed to control the negative influence of urbanisation on hydrology and improve the ecological environment around the city (Yuan, Liang & Li, 2018). One sustainable solution to manage this problem is implementing Green Infrastructure in urban areas. The concept of green infrastructure originated from the Best Management Practices (BMPs) proposed by the United States in the mid-80's, to accomplish more holistic stormwater management goals for runoff volume reduction, erosion prevention, and groundwater recharge (Schueler, 1987 *apud* Li *et al.*, 2018), and the term formally emerged in the 90's (Li *et al.*, 2018).

Green infrastructure has been defined by multiple studies and reports, so no single, universally accepted definition of GI exists. With reference to the available literature, GI is broadly defined as the interconnected network of natural and semi-natural elements that provide multiple functions and EcoSystem Services (ESS), including positive ecological, economic, and social benefits for humans and other species (Koc, Osmond & Peters, 2017; Li *et al.*, 2018). Although it is possible to consider some various synonyms for GI, such as natural or nature-based infrastructure, Low Impact Development (LID), Sustainable Drainage Systems (SuDS), Water Sensitive Urban Design (WSUD), Blue-Green Infrastructure (BGI), and Best Management Practices (BMPs) for stormwater runoff (Fletcher *et al.*, 2015).

GI can take many forms, both above and below ground. Generally, GI is designed to manage and use rainwater close to where it falls on the surface by incorporating vegetation to provide the greatest benefits. The GI approach involves slowing down and reducing the volume of surface water runoff from a developed area to manage downstream flood risk and reducing the risk of that runoff causing pollution. This is achieved by harvesting, infiltrating, slowing, storing, conveying, and treating runoff on site on the surface, if possible, always trying to mimic and replicate natural hydrological processes (CIRIA, 2015).

These approaches are alternatives to conventional ones, because they consider the impacts of urbanisation globally, seeking to offset the effects of urbanisation by controlling impervious surfaces and avoiding the transfer of problems downstream, and aims to work with surface water by "making room for water" within urban areas (Jones & Macdonald, 2007; Baptista, de Nascimento & Barraud, 2011). The application of these alternative actions involves technical (*e.g.*, infrastructure) and social changes (*e.g.*, changing practices, regulations, policies, and networks; Dobre *et al.*, 2018).

Figure 2.3 shows a conceptual illustration of rainfall-runoff responses between highly urbanised and more “natural” and attenuated scenarios.

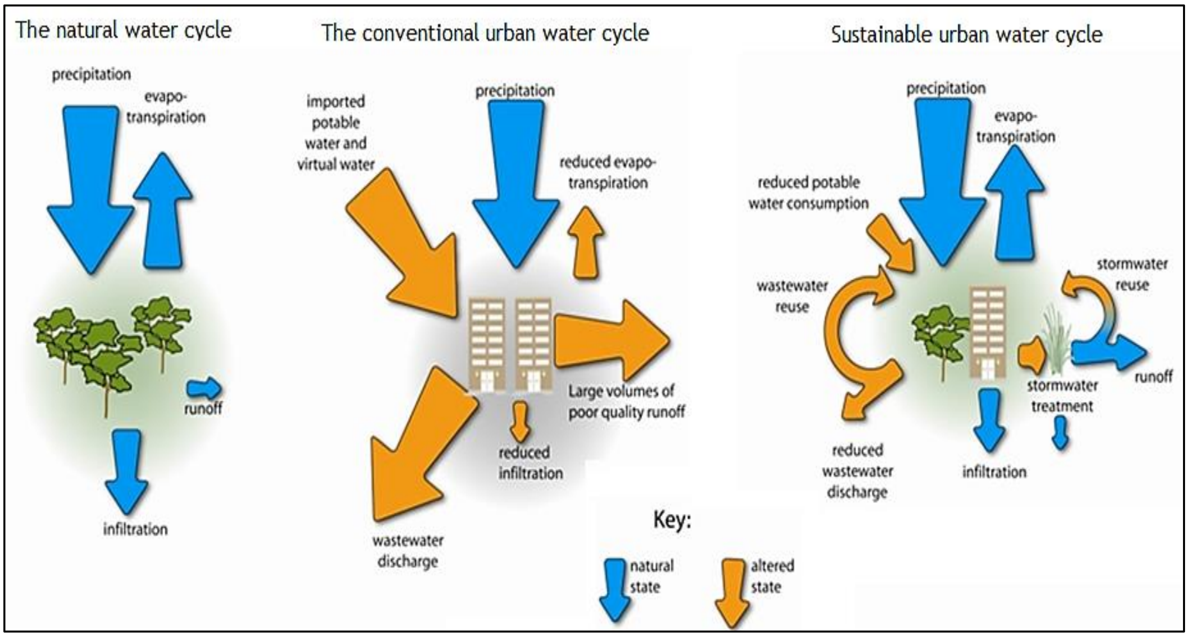


**Figure 2.3** The effects of urbanisation in urban water cycle (Source: Mostafazadeh, 2015).

According with the UK CIRIA SuDS Manual (2015), SuDS/GI are designed to maximise the opportunities and benefits we can secure from surface water management. Accordingly, there are four main pillars of benefits that can be achieved GI design. These include:

1. **Water quantity:** to control the quantity of runoff to support the management of flood risk and maintain and protect the natural water cycle.
2. **Water quality:** to manage the water quality of the runoff to prevent pollution.
3. **Amenity:** to create and sustain better places for people.
4. **Biodiversity:** to create and sustain better places for nature.

Green infrastructures also help to counteract some impacts on our water cycle caused by increased urbanisation, such as reduced infiltration which in turn can result in diminished groundwater supply. This dissertation will focus predominantly on the water quantity and stormwater management functionality of GI systems. To differentiate actions in terms of technical attributes, we may distinguish them between soft, green, and grey actions (EEA, 2013). In the stormwater management domain, green actions are on-ground, small-scale devices for harvesting, treating, infiltrating, and reusing stormwater (*e.g.*, swales, wetlands, rainwater gardens, bioretention cells, detention basins, greenspaces, green roofs, permeable pavements, *etc.*) to complement underground drainage pipes (grey actions; Howe *et al.*, 2011; Fletcher *et al.*, 2015; Li *et al.*, 2018). Rain garden and bioretention cell are similar, but the bioretention cells have an underdrain below its media, while rain gardens do not have such feature (USEPA, 2015). Soft actions include guidelines, legislation, and manuals sustaining the application and integration of these devices in the current institutional and physical context, and often involve changes in water governance (EEA, 2013). Figure 2.4 presents examples of some GI.

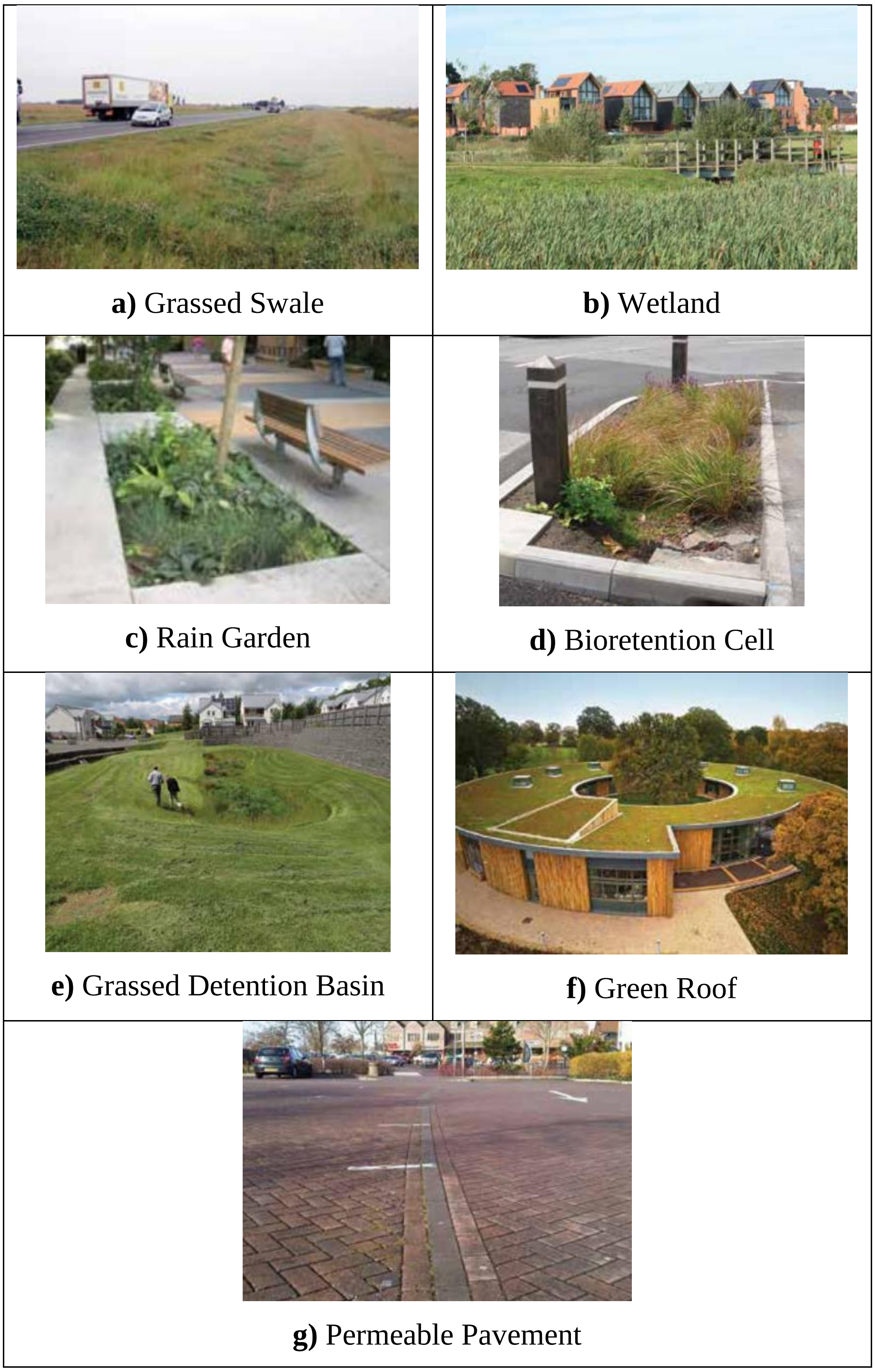


**Figure 2.4** GI applied to reduce urban floods (Source: CIRIA, 2015).

As for social changes, or soft actions, according to the UK CIRIA SuDS Manual (2015), GI can improve the quality of life in urban spaces by making them more vibrant, visually attractive, sustainable, and more resilient to change, by improving urban air quality, regulating building temperatures, reducing noise, and delivering recreation and education opportunities. Other positive aspects of SuDS are the designs that are integrated into the overall design of the development and that it can attract tourism and investment, thus driving economic growth for the local area. These solutions can be used anywhere, green infrastructure can be used for new developments and redevelopments and can be retrofitted into existing developments. However, in a democratic society, social acceptance plays a central role in mainstreaming a technology. The increased social acceptance of GI can foster a market, leading to an enhanced GI contributing to establish these technologies (Dhakal & Chevalier, 2017).

On the other hand, engineers, urban planners, ecologists, and economists have explored GI for stormwater and flood management extensively, but there has been relatively little integration between fields of expertise, or attention to the ramifications beyond physical infrastructure or environmental impacts. There is substantial evidence that GI can catch stormwater and minimise runoff, improve water quality, and provide environmental advantages (Eckart, McPhee & Bolisetti, 2017). These range of benefits also includes savings associated with increased flood resiliency, reduction of flood damage to drainage infrastructure, and reduction in energy demands for heating and cooling (Roseen *et al.*, 2011). ECONorthwest (2007) for example, reported that a natural vegetation and reduced pavement development in Davis, California using GI helped to lower energy expenses by 33% to 50% compared to surrounding neighborhoods.

GI can help minimise combined sewer overflow events and the volume of contaminated flows by keeping runoff out of combined sewers (ECONorthwest, 2007). Although communities rarely attempt to quantify and monetise the avoided treatment costs from the use of green infrastructure, the benefits of these practices to decrease the need for combined sewer overflow storage and conveyance systems can be factored into any economic analyses (EPA, 2007). Green infrastructure is frequently misunderstood as simply adding cost to a project. However, this viewpoint ignores the broader capital benefits that can be seen in terms of overall project costs for new construction, as well as higher life cycle benefits in some cases. The additional cost of GI can be mitigated by reductions in other traditional practices that rely significantly on below-ground drainage infrastructure by combining both grey and green techniques (Roseen *et al.*, 2011).

Figure 2.5 shows an illustrative list of hypothesised causal pathways between GI projects and their initial, intermediate, and long-term outcomes for economics, human health, social well-being, and flood resilience improvements perspectives.

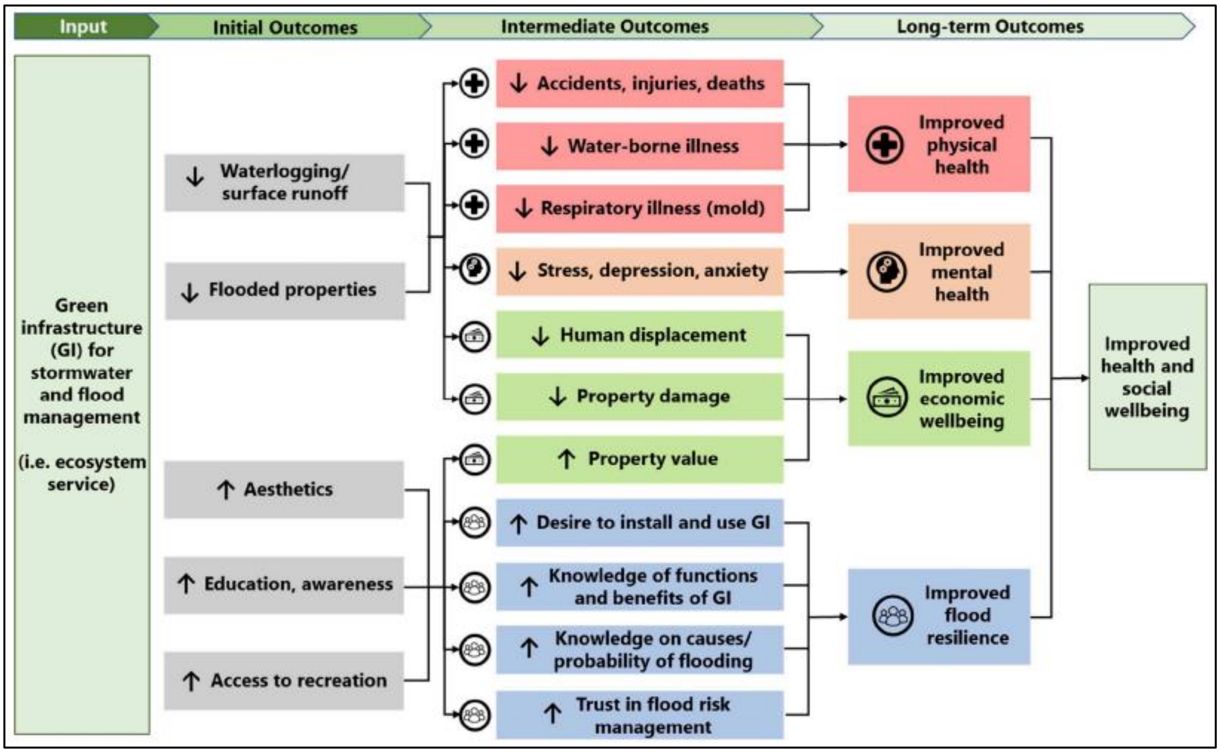


**Figure 2.5** Hypothesised causal pathways of GI (Source: Venkataramanan *et al.*, 2019).

Venkataramanan *et al.* (2019), studied and evaluated 18 studies that reported at least one health, social well-being, or economic improvements to corroborate with Figure 2.5. The authors did not identify studies that directly measured physical health or mental health outcomes relating to GI designed for stormwater and flood management, with most findings focusing on economic improvement surrounding the implemented green infrastructure device. However, Adkins *et al.* (2012), analysed the association between green streets and its walkability (the wanting to walk by these streets), creating an “attractiveness for walking” score of 0–1 through a survey-based mapping exercise and physical inventories of green streets. They reported that green street facilities, which had easily visible and attractive greenery were one of the strongest predictors for perceived walkability, increasing attractiveness scores of a street segment by 0,34, suggesting that greener streets have a greater appeal. This study can be related to physical and mental health, since people will walk more, and a green street brings a calmer aesthetic to urban areas.

Tupper (2012) reported that, although green infrastructure costs were on average 34% higher than traditional grey developments, houses in the former were able to retain sale price value better than traditional developments in the aftermath of the 2007 USA recession (13,9% decrease in GI areas vs. 18,3%–48% in grey areas). Still on economical assessment of GI, MacMullan (2010) reported that the City of Portland, Oregon has a Green Roof bonus that provides an additional 0,3 $m^2$ of floor area for every 0,1 $m^2$ of green roof, if the green roof covers at least 60% of the building roof area. King County, Washington pays 50% of the costs, up to $20.000, to builders who install green infrastructure. Similarly, Austin, Chicago, provide discounts for homes that employ GI. Also, in New York City, a project can earn a one-year tax credit up to $100.000 for inclusion of a green roof on 50% of the structure. A green roof is a rooftop cover with a drainage function, made up of vegetation, substrate, filter layer, and drainage material, this layer aims to drain the excess of water from the substrate, and it can be made up of granular material (*e.g.*, expanded clay, crushed bricks, *etc.*) or modular panels produced with plastic materials (polyethylene or polystyrene; Cascone, 2019).

Roseen *et al.* (2011), analysed the price difference between two different drainage systems projects, one conventional grey and one with a mixed grey-GI drainage system, of a 0,06 $km^2$ condominium with 24 households in Pelham, New Hampshire, USA. The initial grey design had substantial wetland impacts, asphalt paving, and typical drainage (curbing, catch-basins, stormwater ponds, outlet structures). A second design, with GI, was proposed that used widespread infiltration and filtration on the site's extensive upland sandy soils, and included rooftop infiltration trenches, porous asphalt driveways, sidewalks, and New Hampshire's first porous asphalt road. Table 2.1 presents the cost difference between these projects.

**Table 2.1** Comparison of material unit costs from a grey and GI drainage system projects (Source: adapted from Roseen *et al.*, 2011).

| **Item** | **Grey** | **GI** | **Difference** |
|---|---|---|---|
| Site preparation | US$ 23.200 | US$ 18.000 | -US$ 5.200 |
| Temp. erosion control | US$ 5.800 | US$ 3.800 | -US$ 2.035 |
| Drainage | US$ 92.400 | US$ 20.100 | -US$ 72.273 |
| Roadways | US$ 82.000 | US$ 128.000 | US$ 45.918 |
| Driveways | US$ 19.700 | US$ 30.100 | US$ 10.386 |
| Curbing | US$ 6.500 | US$ 0 | -US$ 6.464 |
| Perm. erosion control | US$ 70.000 | US$ 50.600 | -US$ 19.460 |
| Additional items | US$ 489.700 | US$ 489.700 | US$ 0 |
| Buildings | US$ 3.600.000 | US$ 3.600.000 | US$ 0 |
| **Project total** | US$ 4.398.000 | US$ 4.340.300 | **-US$ 49.000** |

It is possible to see that despite the money expend in roadways and driveways, due to permeable features, the savings made in all other aspects have left the GI system project $49.000 cheaper than the conventional one.

The substantial use and widespread adoption of GI practices can reduce the need for expensive grey stormwater drainage systems, as well as the burden of stormwater runoff on urban infrastructure, which can change stormwater management toward a more distributed and at-source approach (Fletcher *et al.*, 2015). Yet, to achieve an intensive and substantial implementation of GI, it's necessary to establish education and outreach programs to raise public awareness on benefits of GI, disadvantages of traditional grey drainage systems, and about how GI works, to have programs in place to train existing staff responsible for stormwater management and other related functions, encourage universities to offer research opportunities and courses on GI to graduate and undergraduate civil engineering students, include courses on GI and ecosystem services from kindergarten until 12th grade curriculums and, to establish award and recognition programs to encourage individual and social capital (Dhakal & Chevalier, 2017; Green *et al.*, 2013).

As decentralised and autonomous infrastructures to supplement current grey infrastructures in urban systems, GI is widely recognised as effective in reducing risk of flooding and harvesting water for potential future use as part of stormwater management

(Fletcher *et al.*, 2015). As already mentioned, this commonly includes engineering measures that includes bioretention facilities, green roofs, low elevation greenbelts, or permeable pavements (Yuan, Liang & Li, 2018).

## 2.3. Green Infrastructure Efficiency

Urban hydrological systems have been affected by increasing imperviousness, as evidenced by increased surface runoff and peak flow, decreased rainwater infiltration and groundwater recharge, and deterioration of water quality (Bell *et al.*, 2016). The risk of urban flooding may be amplified due to the increasing occurrence of heavy rainfall events and the insufficient capacity of drainage systems (Tao *et al.*, 2014).

Numerous studies have reported the effectiveness of GI to mitigate urban floods (*e.g.*, Jackisch & Weiler, 2017; Tredway & Havlick, 2017). These studies revealed that the various types of practices offer multiple benefits to urban ecosystems and urban runoff in widely varying geographic and climatic regions (Tredway & Havlick, 2017). The need to protect or restore urban stream ecosystems has become a focus of recent evolution of stormwater management. Central to these approaches are restoration of the water balance at small-scales with GI, which intercept runoff from impervious areas and promote water loss, infiltration, and water quality treatment (Bonneau *et al.*, 2020). Vegetation-based stormwater control measures are commonly used because of their ability to attenuate stormwater volumes and peaks (Winston, Dorsey & Hunt, 2016).

Brown & Hunt (2008) found that bioretention devices can reduce 50% to 97% of the runoff volume, promoting infiltration to recharge groundwater with an effective purification effect, intercepting pollutants and, also, promote evaporation. Bioretention systems are built mainly in parking lots, along roads, or in residential areas (*i.e.*, where runoff and stormwater management is most needed).

Bonneau *et al.* (2020) monitored the hydrology and water quality of a 1.800 $m^2$ bioretention basin system densely vegetated at the surface during a three-year period. The bioretention drained a 33 ha peri-urban catchment in Melbourne, Australia, with an impervious area of approximately 5 ha (house roofs, driveways, and roads), equivalent to 15% of the total catchment area. The average annual rainfall of the catchment is 730 mm. The authors found that GI are highly effective at flood flow reduction and water quality treatment. The average peak flow reduction was 81% and the infiltration increased to 31%

of monthly catchment runoff. Regarding to water quality, it was observed that 95% of the catchment surface runoff entered the bioretention basin and was subject to at least some treatment, resulting in a reduction of TSS (Total Suspended Sediments), TP (Total Phosphorous) and TN (Total Nitrogen).

Given that buildings can occupy 50% or more of a city's surface area (Dunnett and Kingsbury, 2008 *apud* Zheng *et al.*, 2021), green roofs have a high exploitative potential (Kelly, Sen & Tatari, 2020) to tackle the multiple threats imposed by urbanisation and climate change (Akther *et al.*, 2018). Moreover, water leaving the green roof systems through evapotranspiration contributes to a cooling effect and can help to mitigate the urban heat island effect (Sanchez & Reames, 2019), as well to adjust the indoor thermal environment (Coma *et al.*, 2016). Conversely, Berndtsson (2010), states that green roofs can delay runoff peak for approximately 2 hours, and, also, can reduce runoff. As such, green roofs are considered a multipurpose GI that alleviates multiple urban problems and strengthens urban resilience, especially in the face of climate change (Loiola, Mary & da Silva, 2019).

Zheng *et al.* (2021) critically analysed 75 articles about green roof runoff retention. The authors found that rainfall intensity is negatively correlated with the runoff retention of green roofs, by every 1% increase of rainfall intensity in a rainfall event, the runoff retention rate decreases by 0,14%. The negative correlation between runoff retention performance and rainfall intensity is explainable. Generally, runoff will only occur when rainfall exceeds the maximum runoff retention capacity of a green roof (She & Pang, 2010). When rainfall intensity is small, rainfall water will be largely absorbed by the green roof. But, when rainfall exceeds the green roof maximum runoff retention capacity, subsequent runoff occurs. In more intense storms, there is less time for substrate and plants to absorb moisture, resulting in decreased retention capacity and increased elasticity to rainfall intensity (Zheng *et al.*, 2021).

Among all the studies analysed by Zheng *et al.* (2021), 77% were in temperate climates. Observations for the other three types of climates, such as continental, dry, and tropical, only accounted for 12%, 8%, and 3%, respectively. The authors' statistical analysis revealed green roof in tropical climates, characterised by hot temperature and abundant rainfall distributed throughout the year or seasonally, outperform the others located in dry, temperate, or continental climates in matter of runoff retention. However, increased water stress (too much and too little water), as well as high temperatures in tropical locations, provide significant issues for green roof design, including plant selection and upkeep (Simmons, 2015). The seasonal variations of green roof runoff retention performance were statistically significant. The runoff retention rates increase by 13% in summer compared to winter, and by 6% in spring compared to winter (Zheng *et al.*, 2021). This is supported by higher evapotranspiration in spring and summer months, which facilitates recovery of green roof retention capacity (Mentens, Raes & Hermy, 2006).

Mentens, Raes & Hermy (2006), found that for a region of Brussels, Belgium, the application of extensive roof greening on just 10% of the buildings would already result in a runoff reduction of 2,7% for the entire capital region and of 54% for the individual buildings. Figure 2.6 illustrates the reduction in peak runoff from a green roof, as observed in Belgium during a rainstorm.

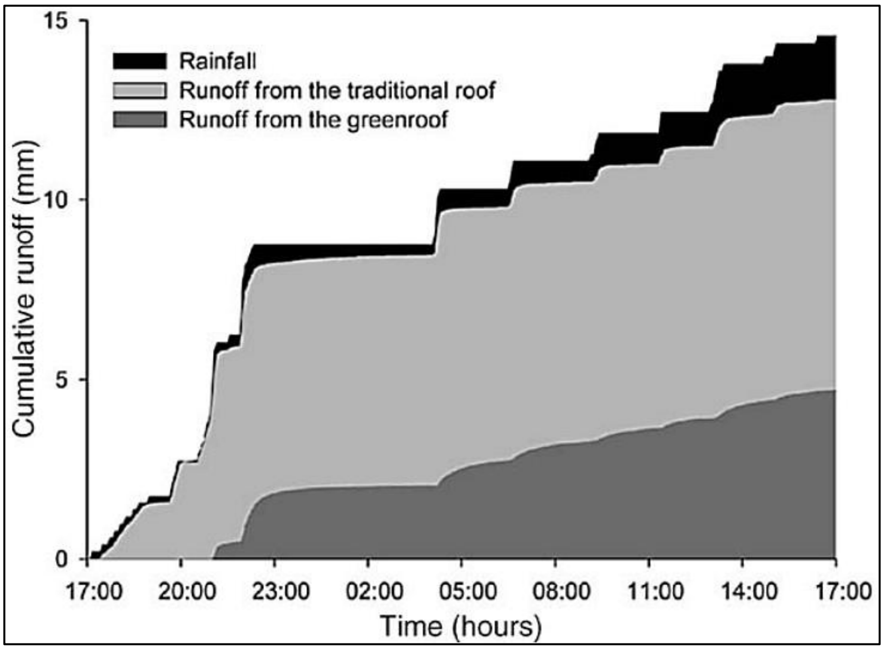


**Figure 2.6** Typical cumulative runoff from a non-greened roof and an extensive green roof as observed in Leuven (Belgium) during the 24 h period of a 14.6 mm rain shower (April 2003, 5 p.m.–5 p.m. on the next day). Both roofs had a slope of 20° (Source: Mentens, Raes & Hermy, 2006).

Low elevation greenbelts refer to a green space that is below the surrounding hardened ground surface by 5 – 25 cm. These green spaces can collect rainfall runoff, slow urban flooding, and supplement the groundwater because the overflow spillway is higher than the green land and is below the ground level. Conversely, these green spaces can improve runoff quality (Bonneau *et al.*, 2020; Cheng *et al.*, 2009 *apud* Yuan, Liang & Li, 2018).

Permeable pavements can be used to replace the traditional hardened road surfaces. These are comprised of a network of impermeable bricks combined with pervious asphalt, pervious cement, vegetation, or by filling the pores with sand. Permeable pavements are mostly used on roads with poor drainage or small traffic flow, to temporarily store runoff, alleviate road-area water and accelerate the infiltration of rainwater into the soil (Rushton, 2001). Permeable pavements have been established as a method for pollution control affecting surface runoff from places used as roadways or parking spaces, where contaminated water may permeate into the underlying soil, common applications of this green infrastructure are residential driveways, golf courses (cart paths and parking), parking lots, pedestrian access, bicycle trails (Scholz & Grabowiecki, 2007). Figure 2.7 presents two typical schematic layouts of a permeable pavement.

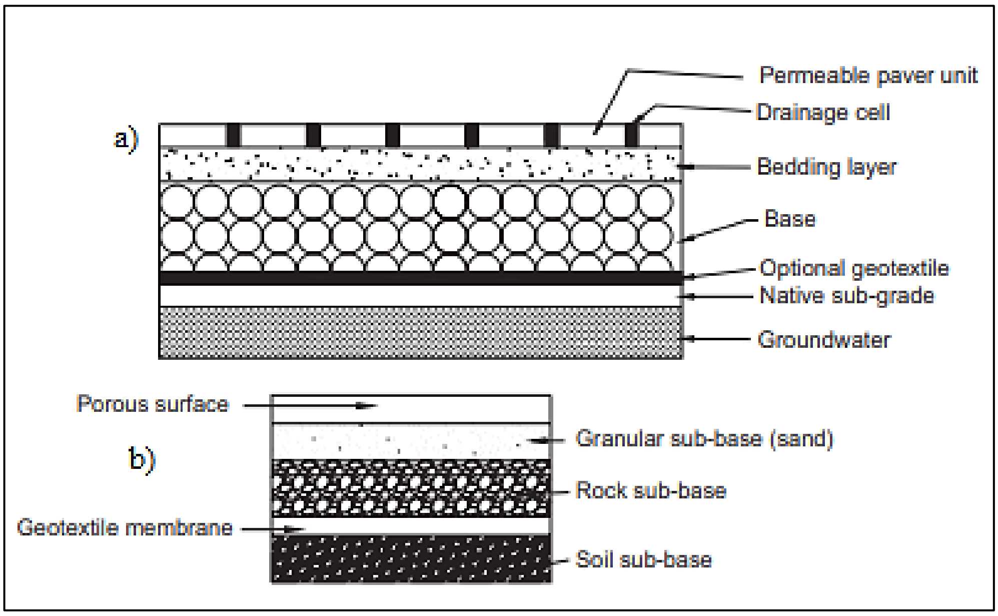


**Figure 2.7** Typical schematic layout of a permeable pavement system (Source: Scholz & Grabowiecki, 2007).

Jato-Espino *et al.* (2016) found that, for a Northern Spanish city with 1500 mm/year rainfall, permeable pavements can reduce the surface runoff of a 31,4 ha catchment by 67,6%. Table 2.2 summarises six different studies about the efficiency and use of GI applied to reduce the impact of impermeabilization and urban floods in different parts of the world.

**Table 2.2** Studies on the efficiency and use of GI applied to reduce urban floods.

| Reference/Location | GI | Brief description | Results |
|---|---|---|---|
| **Jackisch & Weiler, 2017 (Freiburg, Germany)**[2] | GR; PR; PP; G; H and BC | Residential site, with 15,34 ha and 145 inh./ha. Runoff coefficient of 0,47 and imperviousness of 25,4%. Mean annual rainfall of 955 mm. | Rainfall precipitation, discharge, and streamflow monitorization for 30 months. 73% event capture, 66 to 87% volume reduction, 39 L/ha/s peak discharge, 4,5% streamflow amplification. |
| **Tredway & Havlick, 2017 (Colorado Springs, USA)**[1] | PP; RG; SN; Also, the GI combi-nation | Templeton Gap watershed SWMM Modelling for 2, 5, 10, 15, 25, 50, 100 and 500-year storms. | Reduction of runoff by 18,8% using the Pervious Pavement, 4,7% using Rain Gardens, 12,3% using Stream Naturalization and 32,7% using a GI combination. |
| **Zhang *et al.*, 2016 (Naijing, China)**[2] | RH | Implementation of GI at a dense urban area with limited space. | Reduced flood volume by 0,6 to 36,8%. |
| **Ahiablame & Shakya, 2016 (McLean County, Illinois, USA)**[1] | PP; RB and RG | PCSWMM Modelling for an 87,6 km² drainage area with 30 years rain historical data. | For separate GI: 3 to 40% annual flood volume reduction. For combined GI: 16 to 47% flood volume reduction. |
| **Galvane, 2018 (Florianópolis, Brazil)**[1] | PP; GR and RG | SWMM modelling for the Santa Catarina Federal University campus watershed with 4 km² for a real flood event of 143 mm in 4 hours and 30 minutes. | For all GI combined, the results were the reduce of runoff peak by 64% and volume by 17%. |
| **Walega, Cebulska & Gadek, 2018 (Krakow, Poland)**[1] | BC | SWMM modelling of a 0,784-ha area site with 96,3% impervious surface with a real rainfall event from 2015 of 50,7 mm in 80 min. | Culmination of flooding reduced by 55,3 %, volume wave reduced by 56% and discharge volume reduced by 28%. |

***GI types**: GR: Green Roof; PR: Pebble Roof; PP: Pervious Pavement; G: Grass; H: Horticultural; BC: Bioretention Cells; RG: Rain Garden; SN: Stream Naturalization; RH: Rainwater Harvesting; RB: Rain Barrel.*

***Method of assessment**: 1 = Numerical model based, 2 = Field-based*

Green Infrastructure does not perform equally and depends on the climate and rainfall regime where it is implemented, and its long-term benefits and maintenance are still very limited. Its efficiency also reduces with time, even with regular maintenance GI may not prove to be effective in the longer-term due to changes in variables such as rainfall intensity. Also, another challenge is that most areas of the world lack the technical and human capability to implement GI (Pour *et al.*, 2020). Therefore, as discussed by Brudler, Arnbjerg-Nielsen & Hauschild (2016), the combination of conventional grey and green infrastructure is important to achieve a well-functioning stormwater management for longer periods.

As an example, at permeable pavement infrastructure has a much shorter lifespan when compared to traditional impermeable pavement due to deterioration by runoff, air infiltration, and subsequent stripping and oxidation (Scholz & Grabowiecki, 2007), and this deterioration may not even be noticed for many years. However, in comparison to conventional asphalts, permeable pavements provide more effective peak flow reductions (up to 42%) and longer discharging times. There is also a significant reduction of evaporation and surface water splashing (Pagotto, Legret & Le Cloirec, 2000 *apud* Scholz & Grabowiecki, 2007). Booth & Leavitt (1999) evaluated four commercially available permeable pavements after six years of daily parking usage for structural durability, ability to infiltrate rainfall, and impacts on infiltrate water quality. All pavement systems showed no major signs of wear. It was necessary to reference such dated work due to the lack of long-term studies on the performance of permeable pavements. In contrast, there are results that show that the infiltration rates generally reduced following the second year after installation, the need for maintenance is evident at several sites, therefore, in intense rainfall regions, some researchers recommend maintenance to be conducted two to four times per year. It is also evident that for sites with no maintenance, after 4 years the surface infiltration rates have generally reduced to below 1000 mm/hr. although in some countries such as Australia, this is still an acceptable rate for pavement infiltration. In addition, there is a positive correlation between surface infiltration rates and an average annual rainfall precipitation. Rainfall and its characteristics are important in the design and clogging potential of permeable pavement surfaces (Razzaghmanesh & Beecham, 2018). Conversely, studies have reported that the clogging depth only extends into the upper surface of the permeable pavement system and therefore simple cleaning of a permeable pavement upper surface can potentially return the surface infiltration capability to an acceptable level (Baladès, Legret & Madiec, 1995; Haselbach, 2010).

Another issue is the lack of universal GI design available, and construction and operation are usually based on the specifications developed and used in developed countries (Pour *et al.*, 2020). Galvane (2018) reports a difficult to find studies and real implementations of GI in Brazil and South America, being necessary to rely on papers and research from developed regions with varying climates such as North America, Europe, and Oceania.

Li *et al.* (2018) studied and analysed a total of 2.763 original and peer-reviewed articles obtained between 2008 and 2017 related to green infrastructure (study cases, modelling, implementations, *etc.*). Of these 2.763 articles, none were from subdeveloped regions (Africa and South America), although it was seen an increase of GI studies along the years, with more than 400 published studies per year since 2015. The domination of studies was from North America (USA and Canada), followed by Western Europe (mainly UK, Germany, and France), Eastern Asia (China and South Korea) and Oceania (Australia and New Zealand). And, the most popular studies are with green roofs, followed by bioretention cells, permeable pavement, rainwater harvesting system and bioswale.

The fact that compensatory techniques are generally modeled and applied, as well as necessary for already developed urban areas, *i.e.*, areas where land use and occupation have been altered by society, with a high rate of impermeabilisation and limited physical space for the application of various green infrastructure systems, reduces the number of realistic practices that need more available area, for example, the use of vegetative infiltration trenches, wetlands, revitalisation of waterways, or vegetative detention basins (Galvane, 2018). Moreover, in the case of vegetated filter strips, it may just be suitable for a small parking space but not for a large drainage zone (Pour *et al.*, 2020).

The social acceptability of green infrastructures is another issue to overcome in regards of its successful implementation. Developing countries are less prone to accept such technologies, even in regions where urban floods are a frequent occurrence. There is also a lack of government interest and associated policy focus (Pour *et al.*, 2020).

As already mentioned on *RO3*, one of the objectives of this dissertation is to assess the infiltration efficiency of a small-scale bioretention cell experiment. To do it, it is important to present what really a bioretention cell is, to assess its stormwater runoff treatment benefits, and to address some other aspects, such as water quality and economics benefits. The next paragraph, therefore, will be about these GI systems only.

## 2.4. Bioretention Systems

Bioretention (also referred as bioretention, biofilter, bioinfiltration, bioswale, bioretention cell and rain garden; Spraakman *et al.*, 2020) is a type of green infrastructure that is often used in urban watersheds (Davis *et al.*, 2009). Its purpose is to regulate stormwater runoff as near to its source as feasible to emulate predevelopment circumstances by lowering peak runoff flow and volume while also enhancing water quality. This technique decentralises stormwater management, demonstrating that small-scale efforts can produce long-term results. Bioretention systems are typically constructed in depressions on developed sites to catch runoff from parking lots, rooftops, streets, and driveways (Roy-Poirier, Champagne & Filion, 2010). The hydraulic, chemical, physical, and biological processes that occur in the integrated plants, soil, and microorganism components are essential for bioretention. Vegetation, a surface mulch layer, biofiltration medium, and underdrains make up a traditional bioretention system. The volume of water and level of contamination that exists in the bioretention system, the groundwater demand, and native soil permeability all influence the necessity for underdrains (Kratky *et al.*, 2017).

Since 2000, academic research on bioretention has significantly increased. The first known guidance document that described a bioretention system was the Prince George's County Maryland Low-Impact Design Manual (Prince George's County, 1999). And, in 1999, during the American Society of Civil Engineers' Annual Water Resources Planning and Management Conference, the first known academic research on bioretention was presented (Yu *et al.*, 1999 *apud* Spraakman *et al.*, 2020). Prior to 2010, less than 20 papers per year were published. Since 2011, the number of annual publications of bioretention research has grown, and, because of its ability to store, treat, and permeate rainwater, bioretention research and application is gaining appeal around the world, including in the United States, Canada, Norway, Australia, New Zealand, the United Kingdom, China, and Singapore (Jia, Yao & Yu, 2013). Li *et al.* (2018) found that bioretention studies are the second most popular publications of GI scientific articles. Figure 2.8 shows a typical bioretention cell, according to literature.

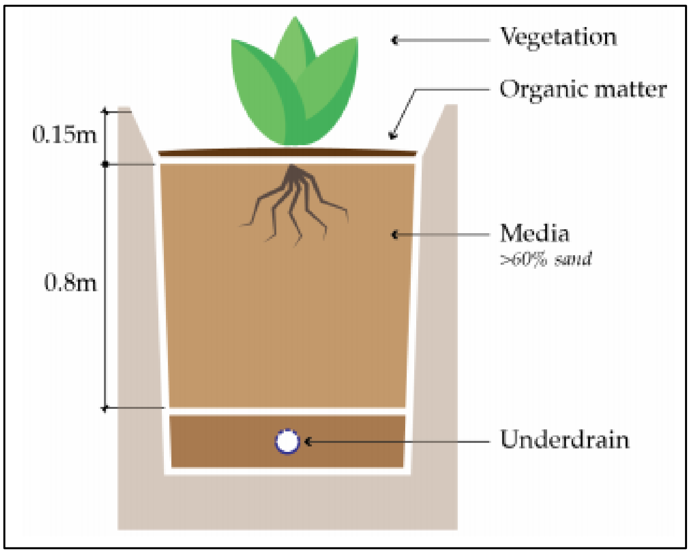


**Figure 2.8** Typical bioretention cell. Media depth, ponding depth, and media percentage represents the average values reported in the literature (Source: adapted from Spraakman *et al.*, 2020).

Bioretention systems smooth stormwater runoff hydrographs by reducing peak flow, which reduces erosion, scour, and sediment transport to the receiving stream (Davis, 2008). The stormwater volume reduction, as bioretention systems are as a landscaped depression, is a result of media storage capacity, evapotranspiration, infiltration, exfiltration, and ponding water depth (He & Davis, 2011; Tang *et al.*, 2016). Media porosity has water storage capacity and when the soil is saturated, this capacity is referred to as maximum retentive capacity, which may be reached during a large rainfall event. When the inflow rate exceeds the infiltration rate of the soil column, water starts ponding on the ground surface. When the surface depression depth is exceeded, the excess water becomes overflow and flows out (Zhang, Hamlett & Saravanapavan, 2010).

Bioretention cells, as previously stated, are biologically-based media filters that are used to temporarily store and treat a specified volume of water from very impermeable catchments (ODNR, 2006). Bioretention cells typically pond 15–30 cm of stormwater in their surface storage (*i.e.*, bowl, ponding area), with 60–120 cm of bioretention media, usually a mixture of sand, finer particles (silt and clay), and organic matter, with a design infiltration rate of 50–1000 mm/h (Hunt, Davis & Traver, 2012; Spraakman *et al.*, 2020). The presence of organic matter in the media has been shown to be favorable to physical qualities and the slowing of media compression, resulting in an improved hydraulic performance (Kratky *et al.*, 2017). Bioretention cells also have an underdrain bordered by a gravel layer to enable for inter-event drainage when the underlying soils are poorly drained (Davis, 2008; Davis *et al.*, 2009).

The media encourages the growth of plants such as trees, shrubs, forbs, and/or grass that have been chosen for their ability to resist a variety of situations, including drought and flooding (Page, Winston & Hunt, 2015). Root macropores appear to offset the detrimental effects of media compaction and sediment deposition by promoting evapotranspiration (ET) and maintaining the soil infiltration rate throughout time (Jenkins *et al.*, 2010).

Exfiltration to the underlying soil, ET, drainage through the underdrain, and overflow/bypass are the four options for bioretention cell outflow (Winston, Dorsey & Hunt, 2016). The texture and moisture of the native soil that surrounds bioretention cells have an impact on exfiltration. Low outflow in the underdrains will be encouraged by bioretention systems surrounded by high conductivity soil (*e.g.*, sandy clay loam; He & Davis, 2011). The porosity of the fill material provides storage capacity for stormwater, allowing it to be returned to the atmosphere via ET. The only way to lower outflow quantities in a lined bioretention system (where exfiltration is not allowed) is to use ET. The fill media is the only hydraulic control on outflow rates in a system with an unrestricted outlet (De-Ville *et al.*, 2021).

The efficiency of bioretention in terms of volume reduction is determined not only by the system's design, which influences the above mechanisms, but also by the magnitude of rainfall events. For example, bioretention facilities can readily capture the entire inflow volume during small events (Ahiablame, Engel & Chaubey, 2013). Single GI facilities, on the other hand, are thought to have limited reduction capability, especially during larger storm occurrences. Integrating GI facilities, on the other hand, can improve the effectiveness of storm reduction. As a result, the best possible combination of integrated green infrastructures is required to reduce storm runoff impacts, and community implementation might make a significant contribution to urban flood control (Liu, Chen & Peng, 2014). Figure 2.9 presents a schematic of a bioretention cell with all the possible stormwater runoff treatment.

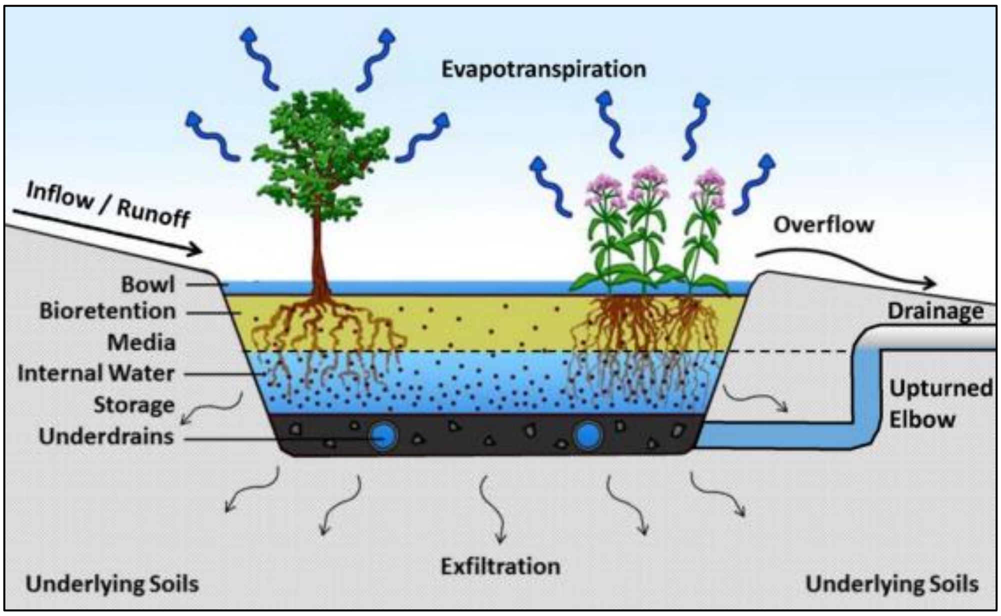


**Figure 2.9** Schematic of a bioretention cell with internal water storage zone (Source: Winston, Dorsey & Hunt, 2016).

Several indicators can be used to assess bioretention's hydraulic efficacy, including peak flow reduction, lag time, flow rate time delay, and stormwater volume reduction, all of which are highly variable depending on bioretention design and rainfall event (Kratky *et al.*, 2017). Lag time, expressed in minutes, is the time from the beginning of inflow into the bioretention cell to when outflow reaches the underdrain and has been observed to range from approximately 60 to 600 min (Khan *et al.*, 2012). Reduced hydraulic conductivity in the media due to compression and clogging is the key worry for long-term peak flow reduction and hydraulic performance in bioretention (Khan *et al.*, 2012; Le Coustumer *et al.*, 2012). However, vegetation growth could help to maintain the soil structure and enhance infiltration without requiring much maintenance of the system (Stephens *et al.*, 2012). To maximise peak flow mitigation, proportionally large bioretention surface area, deeper surface storage depths, and deeper media depth are desired (Li *et al.*, 2009).

In recent years, a lot of effort has gone into monitoring the hydrological performance of implanted bioretention devices in the field. The information gained from this research is useful in predicting hydrological performance; however, it is frequently constrained by *a)* being regionally particular in terms of system components as well as climate, and *b)* monitoring intervals that are frequently insufficient to offer convincing proof of performance in high-return-period situations, such as those associated with urban flooding (De-Ville *et al.*, 2021).

Luell (2011), for example, studied two bioretention cells built in compacted sandy clay loam soils, one sized to treat a 25-mm event and one to treat a 12.5-mm event. The cells reduced runoff volume by 30% and 20%, respectively. Two in-lined bioretention cells in Maryland with impermeable membranes to prevent exfiltration presented no outflow in 18% of rainfall events monitored (Davis, 2008).

Winston, Dorsey & Hunt (2016) determined the water balance of three bioretention cells located in northeast Ohio, USA, two bioretention cell constructed at Holdem Arboretum (HA) and the other one constructed at Ursuline College (UC). The UC bioretention cell was created on the college campus to treat a 0,36 ha parking lot (responsible for 77% of the impervious area), the bioretention cell media was 87% sand, 4% silt and 9% clay, organic matter was 4,3% of the media. The media was 60 cm and was underlain with gravel, also, a single 15 cm diameter underdrain the cell. The bioretention cell surface area was 182 $m^2$.

The two HA south and north bioretention cell had catchment areas of 0,19 and 0,27 ha, respectively, but, unlike the UC bioretention cell, 42% of each catchment was pervious and well vegetated. Their surface areas were 57 $m^2$ (HA south bioretention cell) with 84 cm media depth and 79 $m^2$ (HA north bioretention cell) with 90 cm media depth, built with 40 cm ponding depths. The south bioretention cell was designed for a 45,2 mm storm event, while the north bioretention cell was designed for a 44,7 mm event. Both cells had as media composition 88% sand, 2% silt, and 10% clay, the media was also underlain with gravel. Underdrains were 10 cm in diameter and were tied into existing catch basins located within each cell. Over the monitoring period at UC (May to November 2014), fifty storm events were observed. The monitoring period at HA was from October 2013 through November 2014, during which 90 separate storms were reliably monitored. Total rainfall depths during the monitoring periods at UC and HA were 742 and 1175 mm, respectively, with maximum event depth was 89 mm at UC and 71 mm at HA. Over the monitoring periods, the three monitored bioretention cells reduced runoff volume (*i.e.*, the sum of exfiltration and ET) by 59% (UC), 42% (HA South), and 36% (HA North). During events exceeding the 1-year, 5-minute rainfall intensity, the UC and HA cells provided 53–88% and 24–96% peak flow mitigation, respectively.

To simulate the rainfall/runoff behaviour of these devices, particularly their performance in response to extreme events, stormwater engineers require fit-for-purpose hydrological/hydraulic modeling tools. The most well-known of the open-source modeling tools is the Stormwater Management Model (SWMM; Rossman, 2015). As previously stated, the fill media is the largest single component of any bioretention system in terms of volume, and it plays a crucial role in retaining stormwater and detaining runoff. Thus, rainfall/runoff models like SWMM lay a strong focus on the fill media's function in determining hydrological performance. Each component of the bioretention system must be thoroughly characterised to provide reliable hydrological performance forecasts. These physical qualities are used as input parameters in models that are physically based, such as SWMM (De-Ville *et al.*, 2021).

De-Ville *et al.*, (2021) physically characterised the fill media of a real bioretention cell located at the National Green Infrastructure Facility (NGIF) in Newcastle, UK. The bioretention cell is a bare earth bioretention cell lysimeter. A lysimeter is a device for measuring the percolation of water through soils and for determining the soluble constituents removed in drainage. Lysimeters can be used in a laboratory, greenhouse, environment chamber, or situated in the natural outdoor environment (Howell, 2005). As such, a lysimeter provides a controlled, closed environment to thoroughly understand the behaviour of a bioretention cell and other GI systems, like green roofs and rain gardens, to manage flood waters. This NGIF outdoor experimental lysimeters, in-ground bioretention cells, are linked by an environmental sensing network (Yildiz & Stirling, 2021).

Therefore, with SWMM the authors evaluate the potential hydrological performance of the lysimeter fill media when treating a hypothetical pavement area. De-Ville *et al.* (2021) compared the simulated hydrological results with a simulated bioretention system with fill media recommended and characterised by the UK CIRIA SuDS Manual (2015). The fill media for the bioretention studied and modeled is 100% recycled waste components. The waste components were (by weight): 50% Quarry Waste Material (5–20 mm), 25% Crushed Recycled Glass, 15% Green Waste Compost, and 10% Sugar-beet Washings (topsoil) to a depth of 700 mm. This fill media is used extensively throughout Sheffield in the City Council's Grey-to-Green retrofit bioretention systems (Susdrain, 2016). A laboratory characterization led to a 101 mm/h media conductivity. While CIRIA (2015) recommends the following composition, fines (slay and silt) >5%, sand 85-100%, gravel >10%, the recommended saturated hydraulic conductivity is between 100-300 mm/hr and media depth is 400-1000 mm.

The bioretention systems were modelled to treat runoff from this hypothetical pavement area using a 1-min time-step, three simulated 1-hour design storms for Newcastle, UK, with return periods of 10, 30 and 100 years. Newcastle was chosen for design rainfall as the modelled system represented the pilot-scale bioretention currently being monitored at the NGIF. The final potential simulated results of De-Ville *et al.* (2021) led to minimal differences in performance compared to UK CIRIA (2015). So, it is possible to be even more sustainable implementing green infrastructure, since sustainable and recycling substrate can be used in GI design and potentially deliver same results as traditional media/soil substrate.

Besides stormwater runoff management, bioretention systems can also provide water quality. For example, according to Brown & Hunt (2011), bioretention is the most effective GI for Total Suspended Solids (TSS) removal via filtration and sedimentation at generally over 80% total removal efficiency, a 60 cm bioretention media depth monitored achieved a 60% TSS concentration reduction. Heavy metals are also a concern in stormwater events. These are typically cadmium, copper, zinc, and lead, in particulate and dissolved phase, and potentially bound with organic compounds or carbonates. Generally, total metals removal efficiency in bioretention is at least 80%–90% (Li & Davis, 2008). According to Hunt *et al.* (2006), usually, ammonium is the only nitrogen form effectively removed by bioretention (approximately 80%) via adsorption and nitrification. However, conventional bioretention systems in warm climates have achieved 64% to 9% of nitrate removal (Hunt *et al.*, 2006).

As explained in the chapters above, in general, GI has good economic advantages for implementation over traditional grey drainage systems. Bioretention systems, encompassed in existing techniques, also has economic advantages. Roseen *et al.* (2011) present a bioretention retrofit at the University of New Hampshire campus in USA. The installation of a bioretention system within a parking lot's vegetated median and subsequent direct connection of the system to surrounding drainage infrastructure was the focus of this retrofit. For adapting existing infrastructure, facilities operations may usually provide both personnel and equipment. Retrofit expenditures were limited to merely design and materials costs in this case, while installation costs for labor, equipment, and certain infrastructure were avoided. Total project cost per 0,4 ha of impervious cover was $14.000. With labor and install provided, costs were limited to materials and plantings at $5.500 per 0,4 ha of impervious cover area.

Another important aspect is the expected life cycle of a bioretention cell, the operational life of bioretention cells has been estimated to be anywhere between 35 and 50 years (Bhatt, Bradford & Abassi, 2019; Vineyard *et al.*, 2015), but there is still a need for a more critical examination of the performance of mature systems (>10 years).

As green infrastructure and bioretention cells are relatively new techniques, when compared to traditional ones, it is important a deeper knowledge behaviour. Therefore, this work will quantify mitigation benefits, as mentioned in *RO3*. But first, as an example of a successful project, this dissertation will present a study case of how green infrastructures can be implemented, showing its positive impacts regarding stormwater management, environmental and biodiversity, and social to the Spanish city of Vitoria-Gasteiz.

## 3. City-Scale Study Case: Vitoria-Gasteiz, Spain

This chapter focuses on the characterisation the Spanish city of Vitoria-Gasteiz as a city-scale case study and describes all the GI solutions implemented, explaining why this particular city was chosen to study (*RO2*). Further, this chapter presents social aspects and addresses the viability and potential of future planned green infrastructure projects proposed by the City Council.

### 3.1. City Context: Description, Problems and Solutions

Vitoria-Gasteiz, capital of the Basque Country, in northern Spain, is one of Europe's cities with the largest proportion of green areas per inhabitant, approximately 45 m² per person (all residents have access to public open and green space within 300 m; European Commission, 2012). In 2020, the city had an approximate population of 248.087 inhabitants (a medium-sized city) with a density of 898 inh/m², with a non urbanisable area in 2020 of 73,6% and a GDP per capita of € 35.225 in 2018 (Eustat, 2021).

The city has developed in an environment surrounded by a large area of agricultural land and natural vegetation, enclosed by forests, the Zadorra river to the North and the Vitoria Mountains to the South, exposing Vitoria-Gasteiz at risk of flooding (CEPS, 2015). The city occupies a central place on a plain offering large fertile areas for agricultural uses. The industrial sector has a very significant weight as well due to the industrial processes that took off in the 1960s. The whole area takes in a variety of activities, with a mix of residential-urban, industrial-urban, and agricultural uses that are distributed concentrically, with the forestry areas lying furthest from the centre (Aguado-Moralejo, Barrutia & Echebarria, 2013).

In the 60s, the city went through a heavy industrialisation process with a great impact on these peri-urban areas, reducing their ecological value and increasing the size of marginal spaces due to the expected changes in land uses, from agricultural to industrial uses (Orive & Lema, 2012 *apud* CEPS, 2015). Between 1960 and 1970 in just a single decade the population almost doubled, and in 30 years, from 1950 to 1980, it practically quadrupled (CEA, 2020). In 2018, the primary sector represented only 0,2% of the economic activity of Vitoria-Gasteiz, while the industry and energy sector represented 49,5% (Eustat, 2021). The peripheral areas were under heavy pressure from urban developers, uncontrolled landfills were coexisting with industry areas and new infrastructures, brownfield sites, villages, vacant and residual spaces, high-quality landscapes, *etc.* (Orive & Lema, 2012 *apud* CEPS, 2015).

The idea of creating a green belt around the city of Vitoria-Gasteiz was conceived in the 80s, when after years of improper practices, the degradation of the area became alarming (Aguado-Moralejo, Barrutia & Echebarria, 2013).

The city of Vitoria-Gasteiz was chosen as a study case for this dissertation, because, like many other densely populated European cities, that has suffered consequences of intense urbanisation, such as, flooding caused by extreme events and urban expansion. These are a common problem mostly in the north and south of the city due to Zadorra River and the small rivers which cross the city. Also, research studies from previous years showed that the city would also suffer real consequences of climate change with the increase of 18% of heatwaves and the increase of 10% in the daily extreme rainfall at the end of this century (2070 – 2100; Olazabal *et al.*, 2012). The GI project of Vitoria-Gasteiz does not identify a specific final date, otherwise, new projects and interventions will be designed and implemented if the City Council allocates budget to accomplish them, so it is a (still) on-going project (Climate Adapt, 2018).

In 2000, the United Nations chose the Green Belt, a project of Vitoria-Gasteiz, as one of the 100 best projects worldwide at its Third International Competition of Best Practices for Improving the Environment. By 2012, Vitoria-Gasteiz was awarded the title of "Green Capital of Europe" by the European Commission (Aguado-Moralejo, Barrutia & Echebarria, 2013). The Green Belt is a semi-natural green space partially recovered from degraded areas, such as gravel pits, burnt ground and drained wetland, which restoration started in the mid-1990s (CEA, 2014).

Figure 3.1 shows the location of Vitoria-Gasteiz in the Iberian Peninsula and details the central region of the city where it is possible to observe numerous green areas within the urban areas.

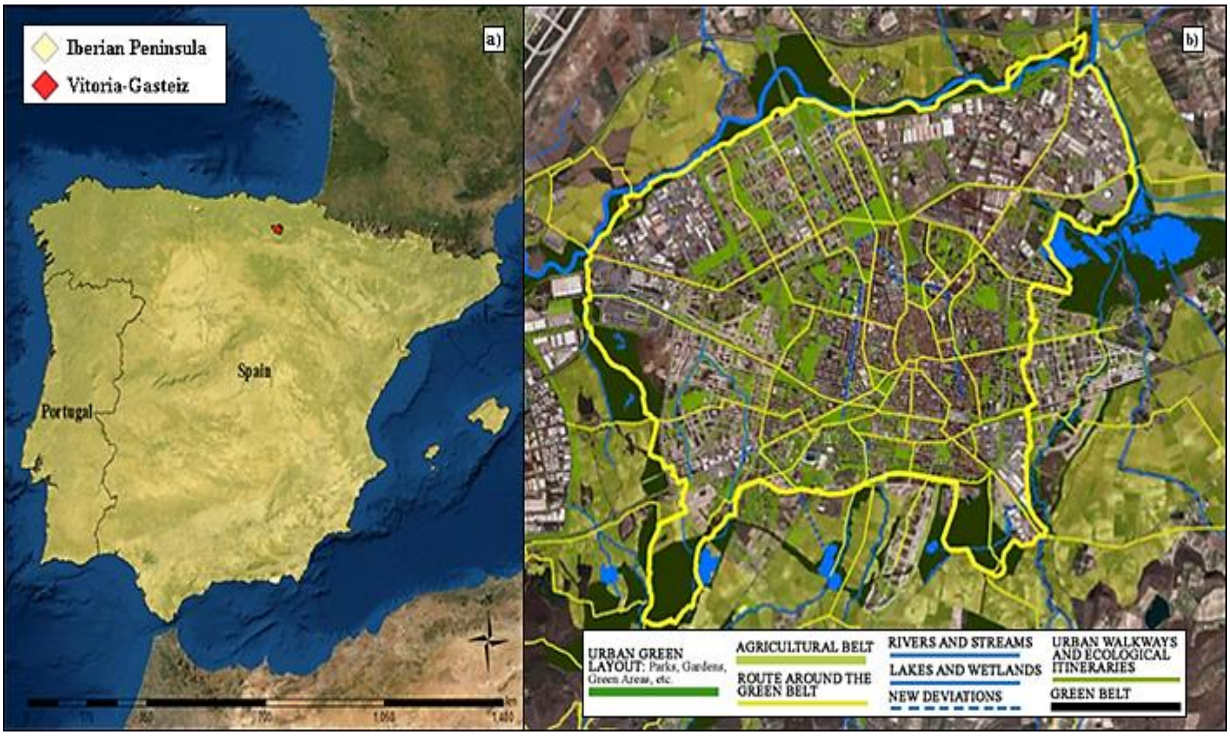


**Figure 3.1 a)** Location of the city of Vitoria-Gasteiz (Spain). **b)** Satellite view of the central region of the city with GI highlighted (Source: adapted from CEA, 2014).

The local governments have for a long time made significant efforts to improve habitability and, therefore, the quality of life of all citizens. The city was, in fact, the first city in Spain to develop Local Agenda 21. Another noteworthy feature is to be seen in efforts to provide all neighbourhoods with green areas and public services such as civic centres, sports, and educational facilities. The Vitoria-Gasteiz Green Belt was created in 1993 with the objective of an environmental and social restoration and conservation of the peri-urban areas of the city (Vitoria-Gasteiz City Council, 2021), with the creation of a natural continuum around the city, integrating the peri-urban parks with the urban outline and connecting them with the natural environment (Aguado-Moralejo, Barrutia & Echebarria, 2013).

To make this huge and audacious project possible, the involvement of several partners was necessary, including the Environmental Studies Centre of Vitoria-Gasteiz City Council (CEA), the City Council, the National Employment Institute (INEM), the Basque Government, the European Association of Periurban Parks (FEDENATUR), the EU, the Ministry of Agriculture, Foods and Environment and the Savings Banks of Vitoria and Álava (Vitoria-Gasteiz City Council, 2021; Aranzana, undated *apud* CEPS, 2015). The general total investment is currently approximately 34 million euros (43% from EU structural funds; Aranzana, undated *apud* CEPS, 2015).

The implementation of the Green Belt project was implemented through several phases, such as, regulating the hydrological system, creating hydrological connections, improving accessibility, integrating public use in natural surroundings, promoting pedestrian and bicycle mobility, reassessing agricultural activities, preserving rural landscapes, increasing biodiversity and biocapacity, and conditioning urban planning and design (Aguado-Moralejo, Barrutia & Echebarria, 2013). Currently, this project has an area of 727 ha, with a 993 ha total planned, 79 km of foot and bike paths and six funded parks: Armentia, Olarizu, Salburua, Zabalgana, Zadorra and Errekaleor (Vitoria-Gasteiz City Council, 2021).

Some general benefits of the Green Belt include protection and improvement of biodiversity and landscapes, less pollution, regulation of floods and fewer flooding episodes, conservation and rational use of natural resources, improved environmental awareness and respect, greater public participation, responsibility, and well-being, employment opportunities; tourism and high-quality urban development (European Commission, 2012).

The surface water system is made up of a dense network of rivers and streams that flow into the river Zadorra, the main river of the Llanada Alavesa plain, which crosses the city from east to west, forming its northern border (European Commission, 2012). The main problem was that the status of many of these rivers and streams was precarious due to the degradation of their banks and adjacent areas, because of agricultural practices and urban occupations of all kinds, especially the rivers in the South. Until just a few decades ago, these rivers, which connected the Montes de Vitoria (Vitoria Mountains) to the river Zadorra, were channelised at the entrance into the city and became the collectors in the city’s sewer network. In addition to the total loss of ecological and social functionality, their transformation into collectors generated problems, especially in times of heavy rainfall, as flooding in urban areas and overflows both in the network and in the water treatment plant (CEA, 2014). The Green Belt project came to minimise and correct these issues, and after Vitoria-Gasteiz won the title of Green Capital of Europe in 2012, the Green Urban Infrastructure Strategy was launched.

The Green Urban Infrastructure Strategy for Vitoria-Gasteiz main objectives are the regeneration of degraded areas through eco-design techniques, the enhancement of urban biodiversity, the improvement of connectivity and functionality of different urban and peri-urban green areas, the promotion of public use of green space, and the improvement of adaptation capacity to climate change (Climate Adapt, 2018). Figure 3.2 shows the main objectives for Vitoria-Gasteiz's GI strategy.

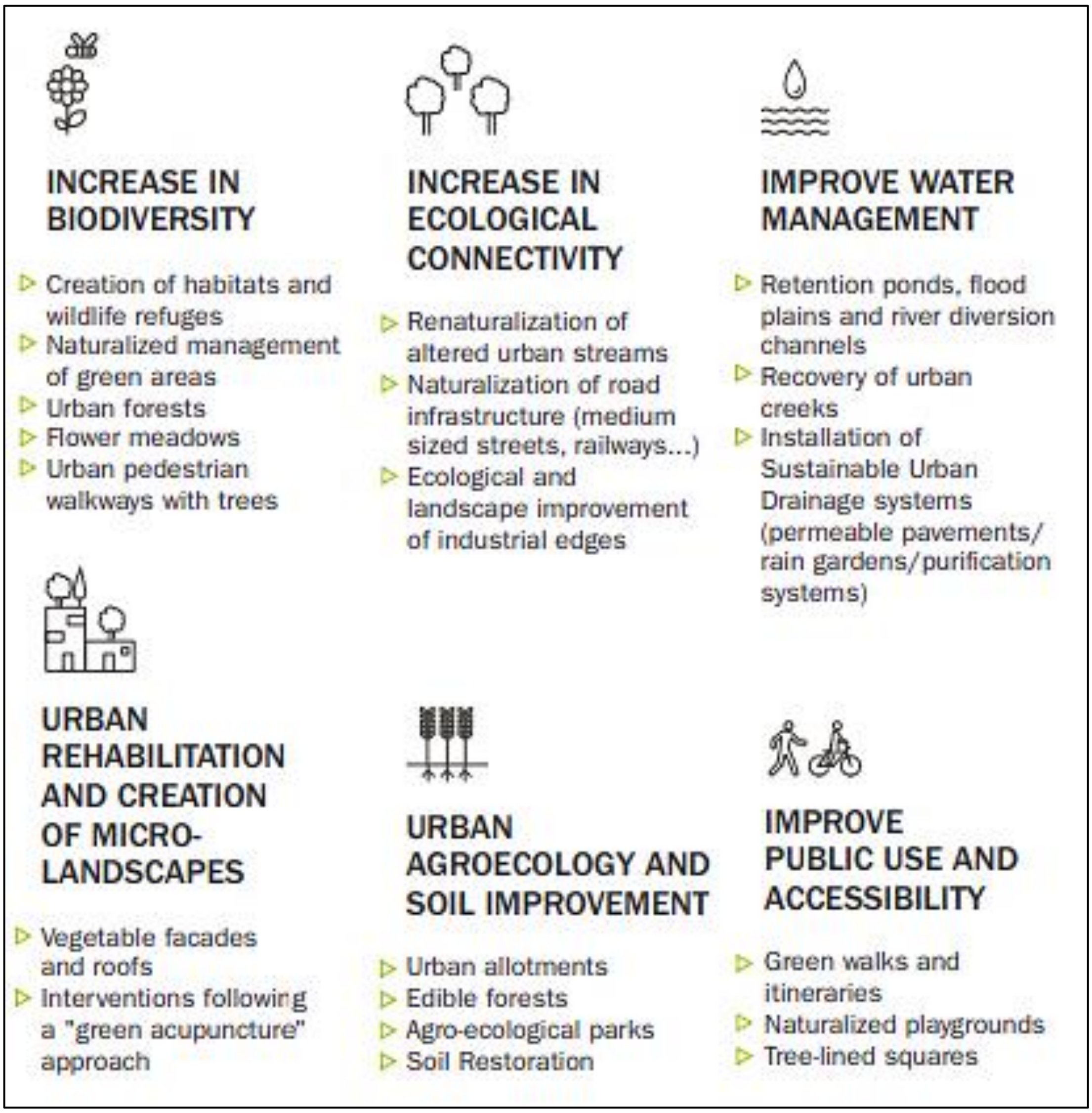


**Figure 3.2** The Green Urban Infrastructure Strategy measures (Source: adapted from CEA, 2020).

Some of the most emblematic interventions that have been already carried out in the city include the urban renovation of the Gasteiz Avenue with eco-design techniques, the creation of a green facade in the Congress Palace Europa, the installation of environmental facilities such as The Salburua Ataria Wetlands Visitor Centre, and the creation of a lamination pond and rain gardens (CEA, 2020). Even though all actions are relevant to GI flood risk reduction, the next items will explore some of the actions relating directly to urban drainage structures.

### 3.2. Urban Green Infrastructure of Vitoria-Gasteiz

This next chapter, including the figures, was based with the Environmental Studies Centre of the Vitoria-Gasteiz City Council (CEA) Vitoria-Gasteiz Green Capital: a human-scale city – Sustainable Mobility and Urban Green Infrastructure from June 2020. The CEA is an autonomous municipal body that ensures the sustainability of the city, promoting sustainable developments and its integrity and understanding. Also, it is the most updated document that describes all the GI implementations in the urban perimeter of the Spanish city. The Green Belt project was set out with five important objectives:

1. To provide a comprehensive solution to the periphery spaces, which were affected by the typical problems of the urban-industrial areas.
2. To promote the conservation of existing areas of natural interest and biodiversity in the peripheral areas.
3. To meet public demand for outdoor leisure spaces, thereby reducing pressure on other natural spaces.
4. To take advantage of the potential of nearby natural areas as an educational and visitor resource and involve the general population in its conservation.
5. To contain the urban growth of the city within limits given, maintaining urban green space balance.

The initial stage of the project consisted of establishing the main spaces that would make up the green belt, with the objective to enhance the ecological connectivity of the peri-urban natural spaces in the first instance, followed by the remainder of the natural spaces of the local area and the city's green areas. In this way, two of the main natural areas of the municipality were connected: the Zadorra River and the Vitoria Mountains, both declared Special Areas of Conservation as part of the Natura 2000 European Network. Figure 3.3 show the Green Belt’s parks and water courses.


**Figure 3.3** The Vitoria Gasteiz's Green Belt parks and water courses.

Some of the green actions implemented in the green belt project were restoration of gravel pits, recovery of wetlands, restoration of rivers, redevelopment of green corridors, creation of organic orchards, creation of a botanical garden, redevelopment of roads and living areas and installation of environmental facilities.

**Restoration of gravel pits**

In 1993, work began to restore an abandoned gravel-pit to the west of the city. The gravel-pit and its surroundings, which included a natural luritanian oak wood, were in a severe state of degradation with a build-up of waste, waterlogging, *etc*. The ground was relandscaped and turned into soft hills covered with meadows, two small lagoons were prepared, scattered copses were planted, and the condition of the woodland area was improved. This land now makes up the Zabalgana peri-urban park.

**Recovery of wetlands**

In 1994, regeneration work began on the old wetlands of Salburua, which were drained for cultivation purposes during the 19th and 20th centuries. Its restoration has contributed to flood prevention in the eastern part of the city, by functioning as flood abatement ponds, as shown in Figure 3.4, and has also helped to improve the quality of groundwater. Salburua has also been designated a Ramsar Wetland of International Importance and a Natura 2000 Site for its valuable flora and wildlife.

**Figure 3.4** Salburua recovered wetland.

**Restoration of rivers**

In 2003 the environmental-hydraulic redevelopment of the Zadorra river began. The creation of alternative channels for the water to use in periods of heavy rainfall has reduced flooding from the industrial estates of the north-east; in the dry season these channels are used by walkers and cyclists. The river acts as a green corridor between the wetlands of Salburua and the Zabalgana Park and has been declared a Natura 2000 Site for its rich biodiversity. A part of the restored Zadorra river is presented in Figure 3.5 bellow.

**Figure 3.5** A restored part of Zadorra river.

**Redevelopment of green corridors**

During the years 2001 and 2002, a project was completed to restore the Alegría River, which at the time was a narrow channel with hardly any vegetation on its banks, surrounded by factories. The river (Figure 3.6) now acts as a green corridor between the Zadorra river and the wetlands of Salburua, facilitating the movement of endangered species, such as the European mink and the otter. The transformation of the river has improved the environmental and landscape quality of the industrial area of Betoño-Eskalmendi.

**Figure 3.6** Alegría river restoration.

The Green Belt has served as an experimental and demonstrative space for several measures and NBSs to solve a whole host of problems related to water management, biodiversity, saving natural resources, public use, *etc*. The following Table 3.1 presents a resumed history timeline of every Vitoria-Gasteiz problems and green implemented green infrastructure.

**Table 3.1** Timeline of Vitoria-Gasteiz and its problems and GI solutions.

| Time | Milestone | Description and purpose |
|---|---|---|
| 1960's | Heavy industrialisation. | Reduce of land ecological value, increase of impermeable areas, changes in land uses, problems with flooding, studies that pointed an increase of daily extreme rainfall and heatwaves. |
| 1950's to 1980's | Population quadruplication. | |
| 1993 | Beginning of creation/restoration of the Green Belt. | Cost of 34 million euros, currently with 727 ha, with 993 ha total planned. |
| 1993 | Beginning the restoration of gravel pits. | Nowadays makes up the Zalbalgana peri-urban park and helps to control urban flooding. |
| 1994 | Beginning the recoveries of wetlands. | Its restoration has contributed to flood prevention and has also been designated a Ramsar Wetland of International Importance and a Natura 2000 Site for its valuable flora and wildlife. |
| 2000 | Best 100 projects worldwide. | United Nations chose the Green Belt as one of the 100 best projects worldwide. |
| 2001 to 2002 | Restoration of Alegría River. | Nowadays acts as green corridor between the Zadorra river and Salburua wetlands. |
| 2003 | Redevelopment of Zadorra river. | The creation of alternative channels for the water to use in periods of heavy rainfall has reduced flooding from the industrial estates and has been declared a Natura 2000 Site for its rich biodiversity. |
| 2012 | Green Capital of Europe. | Vitoria-Gasteiz won this title from the Europe Commission. |
| 2014 | Urban Green Infrastructure Strategy of Vitoria-Gasteiz. | Initiative to promote and spread the benefits from the projects of the Green Belt to other areas of the city. |

With current and future climate change, creating green infrastructure has become a priority on urban agendas, especially within Vitoria-Gasteiz. The Green Belt is a large-scale, biodiverse green infrastructure approach for managing the city's problems and tackling climate change with high levels of biodiversity, to become the seed of the Urban Green Infrastructure of Vitoria-Gasteiz. The results of the interventions and forms of management applied in the Green Belt related to flood prevention, increased biodiversity, *etc.* offered the opportunity to replicate them within the city.

The Urban GI Strategy of Vitoria-Gasteiz was approved in 2014 aiming the naturalisation of green spaces to increase biodiversity in the city and to improve ecosystem's function and services. Since then, work has been done to increase both biodiversity in these main areas and their connectivity. A lot of projects were implemented in every main objective of Vitoria-Gasteiz's GI Strategy (Figure 3.2). Regarding stormwater management, the following projects were carried out: rain gardens (at Voluntaria Entrega street), Batán and Zapardiel river retention basins (Lasarte), restoration of the stream and incorporation of urban systems of sustainable drainage (Gasteiz Avenue), retention basin and stream diversion (Olarizu), retention basin (Elorriaga/Arcaute), flood diversion course (Phase 1 at Zadorra river), restauration to natural environmental hydraulic condition (Phases 2, 3 and 4 at Zadorra river), retention basin (Ali river, in Armentia) and Salburua retention basins (Salburua Wetlands, Green Belt). The next subchapters are the detailing of some of these implementations.

#### 3.2.1. Creation of Ponds and Detention Systems

One of the main problems of the hydrological system of Vitoria-Gasteiz derives from the fact that with the growth of the city, with many of the streams that come down from the mountains in the south to flow into the Zadorra river, the northern boundary of the city, being channelled and converted into underground culverts which feed into the sewer network. A common practice to solve this problem is the construction of ponds to laminate the water of these streams and create new artificial channels that mimics natural streams to divert it to other streams and prevent it from entering the city. A lamination pond from the Olarizu creek, in Olarizu Park, in the Green Belt, was created to prevent clean river water from entering the city's sanitation system, reducing the risk of flooding following heavy rainfall.

#### 3.2.2. Gasteiz Avenue: Drainage and Recovery of the Abendaño River

The renovation on Gasteiz Avenue was completed in 2015 (Figure 3.7). The works included interventions to reorganise mobility in favour of sustainable modes, increasing the number of trees and installing sustainable drainage systems to improve water management. The mobility improvements consisted of pedestrianising the side service lane, eliminating the lanes reserved for parking, and implementing a five-meter-wide urban path and a bicycle lane. This has multiple benefits as it improves the connectivity and functionality of urban areas, as well as contributes to mitigate runoff from rainstorms events and reduces the heat island effect.

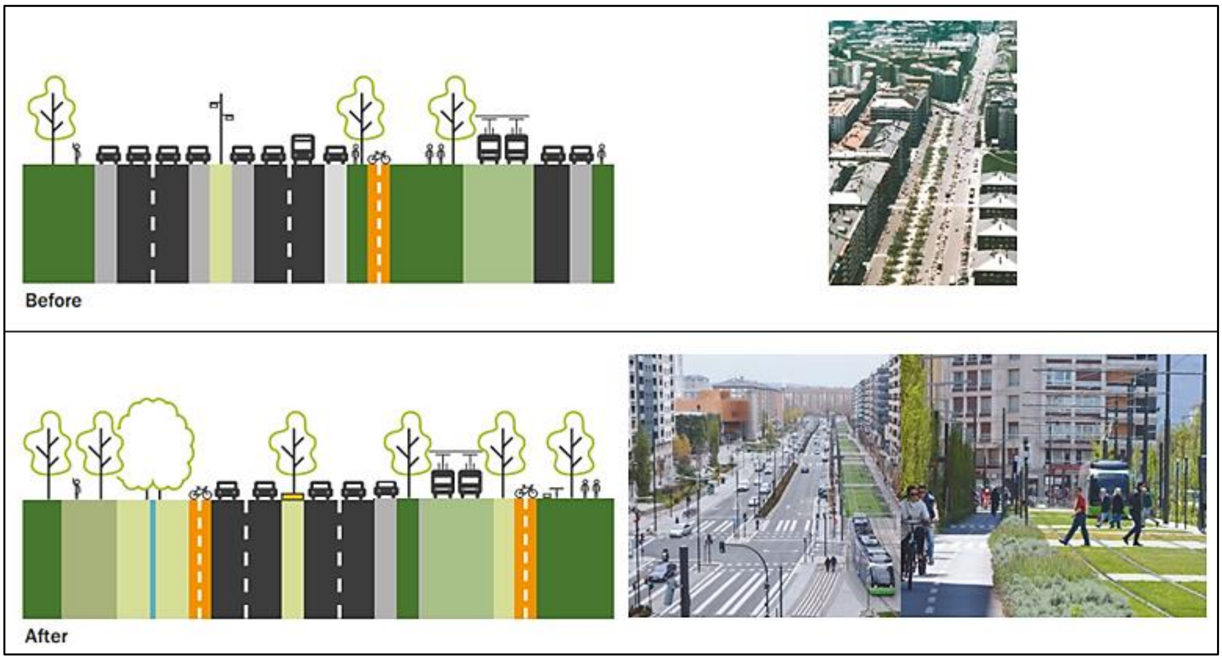


**Figure 3.7** Before and after of Gasteiz Avenue.

Before the renovation, a sewer network system ran under the avenue, carrying part of the water from the Abendaño and Zapardiel rivers, channelled at their entrance to the city. The action consisted of taking clean water at the point where it was flowing and introducing it into a conduit until it reached the open-air channel that runs along the avenue by gravity. This allowed clean water to emerge and made it possible to incorporate the river into the city as a cultural and identity element, providing freshness and recovering a lost ecosystem. Figure 3.8 shows the result to this renovation.

**Figure 3.8** Recovered channel on Gasteiz Avenue.

### 3.2.3. Recovery of Wetlands

Regeneration work on the old wetlands of Salburua began in 1994, which were drained for cultivation purposes during the 19th and 20th centuries. Its restoration has contributed to flood prevention in the eastern part of the city, by functioning as flood abatement ponds, and has also helped to improve the quality of groundwater. The wetlands recovered from Salburua act as flood abatement basins in times of heavy rain, preventing the frequent overflows in the industrial area in the northeast of the city (Figure 3.11).

The recovery of the Salburua wetlands has managed to recover more than 60 hectares of flooded land where more than 300 breeding pairs of aquatic birds, 2000 specimens of wintering species and some animal species of extraordinary interest such as the European mink, the bittern and the agile frog have been reintroduced. Deeres are the only species to have been artificially introduced to contribute to the area's conservation, as they prevent the fast growing of vegetation and avoid the introduction of heavy machinery for grass cutting and the associated processes of erosion and soil compaction such machinery causes (Aguado-Moralejo, Barrutia & Echebarria, 2013). Figure 3.9 shows the Salburua wetland before its recovery project and implementation, and Figure 3.10 and Figure 3.11 shows the Salburua wetland nowadays (27 years later after its recovery).

**Figure 3.9** Salburua wetland in 1991, 3 years before the recovery project (Source: retrieved from Google Earth Pro).

**Figure 3.10** Salburua wetland in 2021, 27 years after the recovery project (Source: Retrieved from Google Earth Pro).

**Figure 3.11** Recovered Salburua wetland.

### 3.2.4. Restoration of Rivers and Redevelopment of Green Corridors

In 2003 the environmental-hydraulic redevelopment of the Zadorra river began. The creation of alternative channels for the water in periods of heavy rainfall has reduced flooding from the industrial zone of the city's northeast; in the dry season these channels are used by pedestrians and cyclists. The river acts as a green corridor between the wetlands of Salburua and the Zabalgana Park.

A project to channel the river was drafted but rejected due to popular opposition, so, the government assumed that the treatment of this area should be more respectful with the environment and intervention be kept to a minimum, the key-objective not being only the prevention of floods but to act against the negative impacts of these overflows in residential and industrial areas. Several steps were taken. These involved the recovery of riverbank vegetation to curb the erosive process, optimisation of the hydraulic capacity of bridges and their surroundings, enhancement of the left bank of the river as a green area and its inclusion in the Green Belt, the installation of three footbridges to improve the connectivity of both banks, the creation of ecological routes, the building and signposting of urban pathways connecting the urban grid and the Green Belt, amongst other improvements (Aguado-Moralejo, Barrutia & Echebarria, 2013). Figure 3.12 presents the Zadorra river in 2004, one year after the beginning of the redevelopment project and Figure 3.13 shows the Zadorra river nowadays (18 years later).

**Figure 3.12** Zadorra river in 2004 (Source: retrieved from Google Earth Pro).

**Figure 3.13** Zadorra river in 2021 (Source: retrieved from Google Earth Pro).

Regarding the Alegría River, the project for its restauration started in 2001. At the time, the river was a narrow channel with hardly any vegetation on its banks, surrounded by factories, and now it acts as a green corridor between the Zadorra river and the wetlands of Salburua, facilitating the movement of endangered species. The transformation of the river has improved the environmental and landscape quality of the industrial area of Betoño-Eskalmendi.

### 3.2.5. Green Facade and Roof at the Europa Congress and Exhibition Centre

The green facade and roof increased the ecosystem services by housing a great variety of plants, favouring the thermal and acoustic insulation of the building, improving its energy efficiency, filtering, and retaining rainwater, reducing atmospheric pollution, and generating visual attraction (Figure 3.14).

**Figure 3.14** Green roof and facade of Europa Congress and Exhibition Centre.

### 3.2.6. Rain gardens on Voluntaria Entrega Street

The action consisted of the removal of waterproof tiles, the supply of topsoil and the planting of wetland species. Instead of a paved surface there is now a strip of vegetation, which increases the permeability of the soil and the infiltration of rainwater into the subsoil, preventing runoff and reducing the entry of rainwater into the sewer system. Figure 3.15 shows the result of these small-scale, localised interventions.

**Figure 3.15** Voluntaria Entrega Street's rain garden.

Another outstanding aspect is that the parks have been designed with eco-efficiency and ease of maintenance in mind, promoting infrastructures and facilities that are easy to maintain and offer not only economic savings but also clear environmental benefits. For example, the parks do not require artificial lighting, the materials used for equipment and furniture (essentially steel, stone, and wood) are low maintenance, the vegetation planted consists of native species and requires little maintenance, and the waste collection and information points, parking areas and fountains are located exclusively near the entrances (Aguado-Moralejo, Barrutia & Echebarria, 2013).

Projects have also been undertaken to increase biodiversity (seasonal ponds to collect rainwater and provide habitat for amphibians, stone walls in linear parks to encourage small fauna - lizards and invertebrates, different mowing of meadows to reduce maintenance and naturalise areas, planting native flower species in parks and streets) to increase ecological connectivity naturalisation of Zarauna creek - as it runs through the new Zabalgana neighborhood, naturalisation of streets with small mounds, to create an undulating landscape - with trees, shrubs and flowers, to create agroecology and soil improvement (agroecological parks, organic allotments, edible fruit tree forests on vacant lots in the Lakua neighborhood), to improve public use and accessibility (ecological playgrounds, tree-lined squares), and urban rehabilitation projects and creation of micro-landscapes (greening of medieval pipelines, reforms and creation of gardens in touristic sites). To stimulate the tourist promotion of the Salburua Wetlands, the City Council has signed an agreement with Basquetour (the tourism agency created by the Basque Government) to include Salburua in the Birding Euskadi network. Several routes surrounding and connecting the main lakes are publicised, two bird observatories are open to visitors, and the Ataria Interpretation Centre plays an important role in welcoming visitors (Aguado-Moralejo, Barrutia & Echebarria, 2013).

The next chapter will approach some of the social aspects and public reception regarding the Green Belt and green infrastructure implementations in Vitoria-Gasteiz, also, it will present some future GI projects that the Council wants to execute.

### 3.3. Vitoria-Gasteiz: Social aspects and future GI projects

As important as the implementation itself of GI, the collection of data on the satisfaction of the surrounding population and the quantification of the improvement of the quality of

life and social functions of the created spaces are essential. This next chapter aims to comment the results of two surveys from 2010 Mariño (2010) and 2015 Torrene Consulting (2015) carried out with the population of Vitoria-Gasteiz, as well as a situation point released in 2021 from CEA (2021) on the actions already implemented and planned.
The first research, Mariño (2010) had as the target population the users and visitors of the parks of the Green Belt of Vitoria-Gasteiz, with a confidence level of 95,5% and a sampling error of 5% (400 surveys). More than 95% of the surveyed users said they knew what the Green Belt was, but when they were asked a control question in which they had to choose one of the three possible definitions of the term proposed to them, the percentage dropped to 78,13%.
The form of access to the parks chosen by most of those surveyed was walking (73%). The most interesting part was that 24% of those who come to the parks by car do not use the car parks because they prefer to park a little further away for walking. When the surveyed were asked if they visit the Green Belt parks by themselves or with company, 32% say that they went alone, 29% with their partner, 22% with friends and 17% with their families.
Of the activities common to all the parks in the Green Belt, walking and hiking was the most popular (99%), followed by cycling (29%), and over 50% of the users surveyed did not know that the Green Belt had a walking tour. Of those who mention activities other than those proposed, walking the dog was the one most frequently mentioned (96%), most of them doing this activity once or several times a week. Other activities mentioned are visiting the city (in this case for the first time), taking photos (at least once a month) and flying the kite (once a year).
Between 96 and 99% of the users surveyed were familiar with facilities such as the bicycle lane, information panels, rest areas and fountains. These are followed by the picnic tables and information leaflets, known by 87% and 76% of respondents respectively. Equestrian trails, on the other hand, were the least known (58%).
The users were also asked to rank several facilities, and those who rated any of the facilities with a score lower than five were asked to give a reason. For example, most of those who thought that services such as picnic tables, rest areas, fountains or information panels should be improved do so because they consider that there were too few in some areas of the parks. In the case of pedestrian routes, the main observation was the appearance of puddles due to potholes. Regard to the cycle paths, the main complaint was the lack of continuity.

The study also sought to find out the reasons why some of the services and facilities in the Green Belt parks were not used. For example, those who knew about the picnic tables but did not use them are mainly because they prefer to walk or cycle. In the case of fountains, most say that they did not need to drink, as the route they take was not too long. The ones who did not use the cycle path or the equestrian trails mainly refer to the fact that they do not like these activities.

In general, the users surveyed were fairly or very satisfied with the different aspects of the Green Belt they were asked about. Most of them agreed with the fact that getting to the parks was easy, that they were accessible for people with reduced mobility, that they were clean, that the signposting inside the parks was good and that they were a good place to spend free time, or that they could enjoy them without being disturbed. As for the users' opinion of the Green Belt project, 99% think it was positive, while only 1% was indifferent. They were also asked to indicate those services, facilities, or activities that they would include in the current offer of the Green Belt parks and of those who made contributions, 11% suggested public toilets, 7% signs at the crossroads inside the parks and 4% believed that there should be more lighting.

This study was very important so that the city could agree on some points to take actions, as: more publicity should be given to the activities on offer, as many citizens are not aware of them and it would be good to try to advertise more; the photos on the information panels could be updated; a method could also be found to fix the paths, either by compacting the soil harder, making more drainage channels or sloping the sides of the paths; it could be considered to put litter bins inside the parks; and signposting should be improved both to and within the parks. Regarding the activities offered by the CEA, it was good to the City Council knows if what is offered was appropriate to what users request. Since all the modifications and improvements made to the parks are for the enjoyment of all the citizens of Vitoria-Gasteiz and visitors, from time to time it is very interesting to know their opinion.

Another similar study was conducted in 2015 (Torrene Consulting, 2015) to deepen the knowledge and improving the social dimension of the green spaces in the city.

The study has been carried out in a pilot area of the city on 56 green spaces of different types and sizes (parks, green corridors, garden squares, *etc.*), and has allowed to collect information on the functional characteristics and the social use of the spaces, as well as the degree of satisfaction and demands of the people who use them (and based on this

knowledge, to put forward proposals for improvement). More than 600 users were interviewed.
As strengths, some major conclusions were: walking was the main activity, while cycling/walking was the second most important activity; playing and caring were essential activities; the green corridor was shown to be the typology with the greatest diversification of uses; frequency of use was high; there was a high degree of recurrence because 53% of the people surveyed regularly visit the same park (note that comparing to the 2010 study, there are more people using the spaces); the types of park with the highest number of recurrent users were the garden squares and the walking areas; there was a high level of identification and satisfaction with the green infrastructure system; there was widespread knowledge of the most relevant green infrastructure elements (also note the difference between 2010); the majority of the population had a favorable opinion on the importance of the environment and green spaces; the most valued functions of green spaces were: "improving health", "reducing stress" and "curbing climate change", all above 10%; green spaces were spontaneously identified as elements of personal well-being; 80% of the interviewed population attached a great deal or quite a lot of importance to the environment in their concerns; most of the households were less than 100 m away from a green space and most people used green areas within 300 m of their homes (also in 2010 most people that did not use the areas said they were too far away); equipped areas, with higher levels of accessibility and urban continuity, were the ones that attract the greatest number of uses, with the exception of walking; the equipment was a basic instrument of activity for different types of users and uses (especially play and leisure); 94% of the people surveyed consider that the green areas were fairly or very well maintained; access to green spaces was fair and equal (all dwellings in the sector analysed had green spaces less than three minutes away); and the vast majority of people considered that in the design of green spaces, equal importance should be given to the improvement of the natural environment and the well-being and enjoyment of people.
For weak points, they found that: dog walking was an emerging use (predominant in some areas) and it was a source of conflict in some areas; resting and socialising was a relatively scarce use, especially in cafes and terraces; conflicting uses had been detected in some areas; the least used green spaces were those areas that were isolated and had no social function as corridor boundaries, interstitial areas and green corridor tips; among the least recognised social functions are the capacity of green infrastructure to favor social contact

and relationships; the majority of the population (75%) did not spontaneously identify the environmental function of green spaces.

In other words, there was a big lack of visibility of the function of green spaces. The declared environmental concern did not coincide with the recognition of the environmental functions of green infrastructure. The actions that generated the greatest rejection were reduction of watering frequency, live flowerbeds, retention ponds and meadows with differentiated mowing.

They were also able to identify that one of the factors that have the greatest impact on lowering the use of green areas was the lack of urban connection or continuity. It was decided that the green corridor required continuity, landmarks, and urban elements to articulate, and there were non-river corridor sections that had urban and environmental potential. One of the proposals was to project the articulation of green urban corridors complementary to the river corridors and create these corridors with a connecting function. It would be characterised by continuity in the design with uniformity of light points, sitting areas, giving priority to the pedestrian in interstitial areas, introducing symbolic elements of pedestrian path, same styles of vegetation.

Besides that, some other actions were to: disseminate a standardising image of the uses of green areas through images or other content; define areas for the use of unleashed dogs where two types of differentiated zones could be considered; design play areas that give centrality to some areas, taking into account the diversity of ages; develop and disseminate an argument about the multi-functionality of green spaces; make an estimate of the area of land that these small spaces represent in the city as a whole, and explain their function and ecological and environmental importance; and design of actions for local participation in the knowledge of the urban ecosystem.

Finally, in 2021 the Victory-Gasteiz Center for Environmental Studies launched a document called "*Cataloging of the NBS implemented and planned in Vitoria-Gasteiz*" which compiles and describes a large part of the Nature-Based Solutions (NBS) carried out and planned in the city, making it possible to evaluate the effectiveness of the measures in solving different urban problems and improve the selection, design, and implementation of new measures in the future. Of the 106 actions included in the document, 79 have been executed successfully, 12 are in progress and 15 have not been carried out yet (CEA, 2021).

These 79 interventions that have been finished were carried out in urban and peri-urban parks, streets, squares, streams, and less conventional spaces such as buildings and vacant lots, on a total area of 4.388.469,78 m². Even though 62% of the NBS were aimed at increasing biodiversity and ecological connectivity and only a small part was aimed at optimising water management and other areas, it is important to say that NBS are multifunctional and respond to several objectives at the same time. As already known, the planting of trees in streets and squares, the application of sustainable gardening techniques, the creation of lamination ponds and avenue channels, the installation of urban allotments and orchards, the development of green itineraries, *etc.* are some of the most frequent actions that are solving problems and providing benefits.

In the already finished phases of the hydraulic conditioning of the Zadorra River, for example, in addition to many services and ecosystem benefits to the climate change (such as runoff regulation and flood prevention), biodiversity (as being an natural habitat to many species and wildlife), environmental quality (such as air improvement and landscape improvement), it also has services for all the society, such as improving leisure, sport and health, promoting environmental education and natural tourism, as well as being able to create a cultural, spiritual and identity value to a community. Figure 3.16 presents the areas where actions were made and its NBS types.

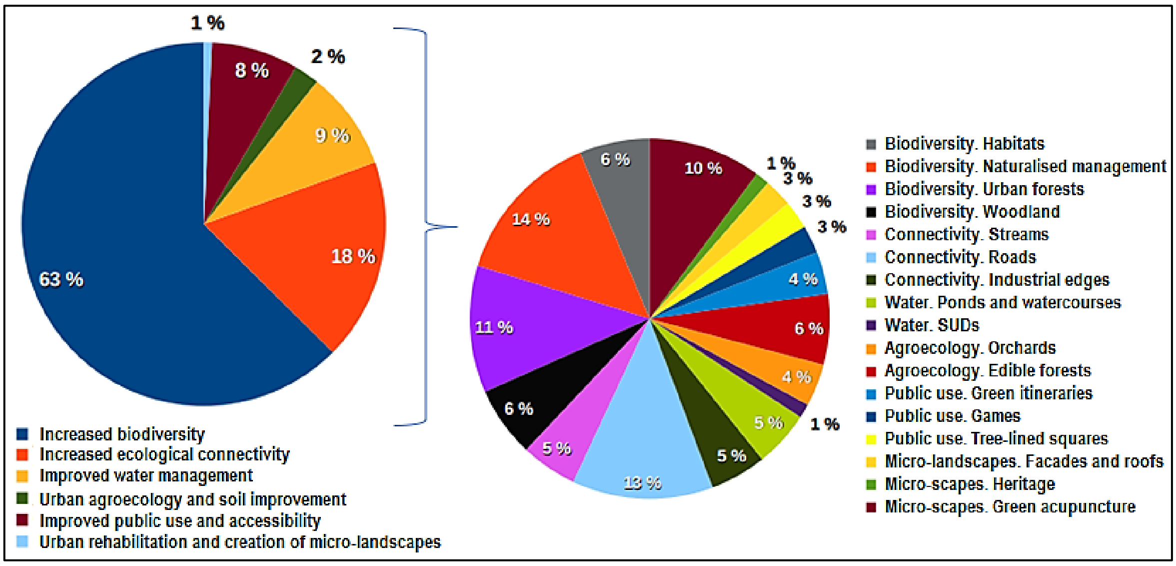


**Figure 3.16** Percentage of action area/typology of NBS and percentage of actions carried out/main type of NBS (Source: adapted from CEA, 2021).

It is worth highlighting the large number of actions (20%) carried out on residential, equipment and tertiary use plots, which were left vacant because of the urban expansion of the city in recent years. On these plots, urban forests, vegetable gardens, edible forests, naturalised play areas, *etc.* have been installed, which are giving a transitory use to these spaces that used to cause important social and urban development problems.

Eight green actions have also been carried out to improve the aesthetic and environmental quality of small urban spaces, such as, buildings and small squares, introducing and planting vegetation into these areas. The introduction of vegetation in these places helps to sponge the urban fabric, brings freshness and beauty and favours rest and social interaction.

Also noteworthy are the 10 interventions carried out on the streams that enter the city, to increase their role as ecological corridors and improve their hydrological function, preventing flooding and restoring their natural dynamics. The interventions carried out on the river Zadorra (as part of the Plan for the hydraulic adaptation and environmental restoration of the river), and the future Larragorri reservoirs that will laminate the water of the Batán and Zapardiel rivers and prevent flooding to the south of the city, are particularly noteworthy.

In the water management area, it is still pending to finish the 3rd phase on the river Zadorra, the lamination lagoons (river Ali, in Armentia) and lamination basins of the Batán and Zapardiel rivers (Lasarte).

The first one intends to create a new green area with lagooning systems that laminate the floods of the Ali stream in times of heavy rainfall and prevent overflowing downstream. In the Green Belt, there is an unused plot of land with signs of dirt and shantytowns, and the Ali stream runs through this plot, comes down from Montes de Vitoria, crosses the forest, the village and then runs on the surface until it reaches the river Zadorra. It is planned to annex this plot to the Green Belt by creating the lamination lagoons.

The lamination basins of the Batán and Zapardiel rivers intends to improve a degraded periurban agricultural area, affected by an old gravel pit and crossed by these rivers. Both rivers enter the city converted into sewage collectors, which causes flooding during heavy rainfall, overloading of the sewage network, direct dumping of untreated water, *etc.* It is proposed to use the hollow of the gravel pits as a re-submerged wetland and divert part of the flows to other watercourses. These ponds will form part of the future Larragorri park, which will complete the Green Belt to the south.

The engineering aspect of GI is important to improve flood management and resilience within urban areas. However, social acceptance plays a central and important role in mainstreaming the GI technologies, but social acceptability of GI needs to be overcome to have a full and successful implementation, even in regions with frequent urban floods. In developing countries, as stated by the literature review, people are less prone to accept the infrastructures. For that reason, the Vitoria-Gasteiz case could and should be a positive example of how it is possible to implement GI successfully, both socially and in terms of engineering, for the political and academic sector of today modern society. As the case presented showed that improving the life quality of urban area residents is not an easy task, but time-consuming, stressful, and labour intensive, the Green Belt and the GI started to be implemented in 1993, and it is not completely done yet. On the contrary, the GI is constantly evolving.

In this moment, the Green Belt project has 727 ha of forests, parks, wetlands, square and rain gardens, green roofs and facades, revitalised watercourses, and rivers, *etc*. This is the approximately amount of 727 football fields, or an even more shocking relation, Vitoria-Gasteiz has more than two Central Parks (one of the biggest urban parks in the world, located in New York, USA) of green infrastructure, managing to have 73,6% of the city area as non urbanisable areas. The City Council plans to have a total 993 ha of green spaces and infrastructure, as soon as public funds are available. The City Council also is always investing in public survey to check the social acceptance of implemented GI and plan actions to improve its population environmental education. The survey study from Torrene Consulting (2015) showed that every city resident had a public open and green space within 300 meters from its households, but this major green density would not be possible without the Mariño (2010) survey study. That is why the Vitoria-Gasteiz GI can be considered a constantly evolving project.

Although this case study can be used as example by other cities around the globe, it is important to state that every region will need different and particular GI, as it is not one-size-fits-all and every city has a different social, economic and background scenarios. As Vitoria-Gasteiz aimed and as one of important benefits of GI, these infrastructures must be used as a multi-purpose and multi-benefits actions. The city managed to improve its biodiversity, ecological connectivity, water management, urban rehabilitation and creation of micro-landscapes, urban agroecology and soil improvement and public use and accessibility. So, this city and its public document reports could be used, at least, as a GI implementation guideline for other urban areas, especially for GI social acceptability, since most of the city’s population are satisfied and feel that these green implementations bettered their quality of life, improving health, reducing stress while the city curbs climate change.

The next chapter will introduce the GI facility from the University of Newcastle where a bioretention cell facility is installed, and from data the VWC will be analysed, and a rainfall-runoff simulation will be carried out using Storm Water Management Model (SMWW).

# 4. Characterisation of Rainfall-Runoff Processes Using a Field-Scale Bioretention System

The National Green Infrastructure Facility (NGIF) based at Newcastle University, Newcastle, United Kingdom, is a "living laboratory", underpinning research into Sustainable Drainage Systems (SuDs), Green Infrastructure (GI) approaches, and making urban centres more resilient and sustainable for future generations (UKCRIC, 2021). The NGIF is a full-scale living laboratory for multidisciplinary testing and demonstration of fully functional green infrastructure, and features several heavily instrumented GI features (Stirling *et al.*, 2021), including a series of vegetated bioretention cells.

The NGIF has a series of GI pilot scale experiments installed allowing the investigation of key rainfall-runoff processes, such as, a sloped green roof on the top of the building, a grassed swale that discharges water into a vegetated wetland, a rainwater harvesting tank with ultrasonic pressure water level sensor, 6 rectangular rain gardens ensembles with different vegetations (amenity grass, mixed shrubs species, edible herbs) and 10 bioretention cells lysimeters with different sizes (surface area and volumetric capacity), surface layer, vegetation and media (Stirling *et al.*, 2021). These are all heavily instrumented with a series of environmental sensors to measure climatic, hydrological and hydraulic processes, allowing an assessment of SuDS performance.

## 4.1. Materials and Methods: Monitored Bioretention Cell

A series of monitored bioretention cell lysimeters systems are instrumented with a series of environmental, climatological, and soil-based sensors and exposed to natural events. The lysimeters´ monitoring provides publicly available data which can be used to determine the effectiveness of such systems at managing and attenuating flood waters through urban spaces. This dissertation will analyse data from one specific bioretention cell lysimeter (Lysimeter 3), which is the unvegetated control lysimeter for the EPSRC-funded Urban Green DaMS (Design and Modelling of SuDS) project. This wider project aims to investigate hydrological performance of GI, and began collecting data in August 2020. The lysimeter bioretention cell examined is split into two hydrologically isolated cells (two cells of 1m × 2m) which are identical except for having different outflow conditions. Cell A is fitted with a restricted outflow whilst Cell B has an unrestricted outflow and is free-draining into the gauged sewer system to determine whether the use of outflow restriction devices can be used to maximise soil storage and attenuate flows to the sewer systems following heavy rainfall events. For the purpose of this dissertation, data from Lysimeter 3B (unrestricted outflow) is examined. The data presented and analysed within this dissertation is publicly available (Stirling *et al.*, 2021). This lysimeter cell was chosen due to its unvegetated surface functioning as a control device in NGIF, allowing the institute to assess the influence of vegetation when comparing to it. Besides, vegetation it is not an impediment to this bioretention cell to be replicated in other regions. The unrestricted outflow is important to assess the influence of the soil in reducing peak flows, slowing the flow and mimicking natural areas.

The lysimeters currently only receive direct rainfall as an input, and are hydrologically isolated from the surrounding areas, so the localised rainfall measurement input (tipping bucket rain gauge with 0,2 mm/tip resolution) can be used to infer any inflow volumes of water. As such, any trends observed within the lysimeters (in relation to the soil-based sensors and outflow gauges) are a function of their inflow volumes. Figure 4.1 shows the Lysimeter 3 bare earth Green Urban DaMS that are installed and running at NGIF.

**a)** **b)**

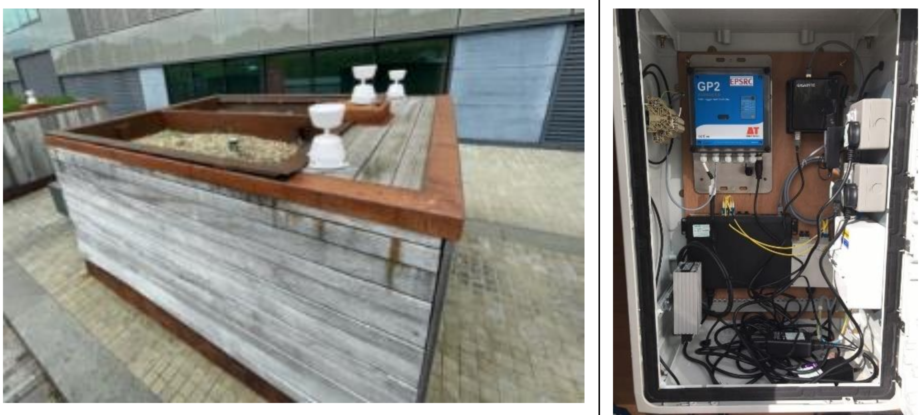

**Figure 4.1 a)** Lysimeter 3 with bare earth Urban Green DaMS (Source: Stirling *et al.*, 2021) **b)** Inside of the lysimeter data logger cabinets, showing the sensor wiring for measuring soil under controlled conditions, including soil moisture, percolation, rainfall, and drought (Source: NGIF, 2018).

According to Green & Stirling (2021), Lysimeter 3B is design is similar to international SuDS guidance and has the following media and layer composition, as outlined in Figure 4.2:

- Gravel (4-40 mm aggregate) drainage layer at the base with to a depth of 180 mm to allow free-drainage to the sewer system.

- A transition layer (2-6 mm aggregate) to prevent the migration of fine sediment through the soil profile, filled to a depth of 120 mm.
- Media with SuDS substrate made up of 50% quarry waste (5-20 mm), 25% crushed recycled glass, 15% green waste compost and 10% sugar beet washings. The media was filled to a depth of 700 mm, making a total 1 meter engineered soil profile.

The bioretention cell also has perforated underdrain piping (60 mm diameter) to direct water towards the gauged outflow, along with a dense network of sensors measuring key variables, including Volumetric Water Content (VWC; %). Figure 4.2 shows a schematic draw of the Lysimeter 3B.

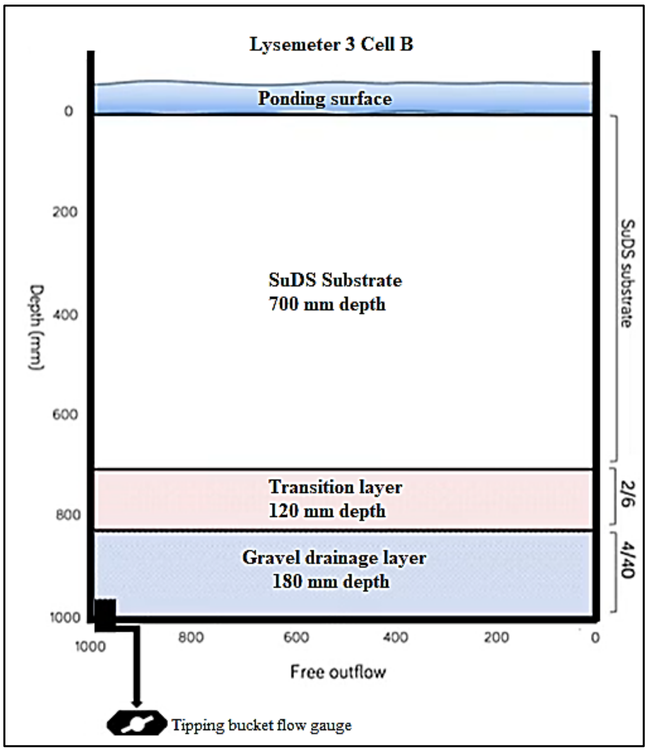


**Figure 4.2** Schematic draw of the Lysimeter 3B and its layers and media (Source: adapted from Green and Stirling, 2021).

A network of soil-specific sensors is located at varying depths throughout the engineered soil profile. Sensors measuring key soil parameters such as, VWC, Electric Conductivity (EC) and soil temperature are part of the internal soil structure of this green device. There is also a water level sensor, a tipping bucket rain gauge (0.2 mm) and a tensiometer. Below the media there is a 60 mm underdrain, and a tipping bucket outflow gauge measures the volume water collected by the drain. Figure 4.3 presents the Lysimeter 3B with the location of all the sensors installed.

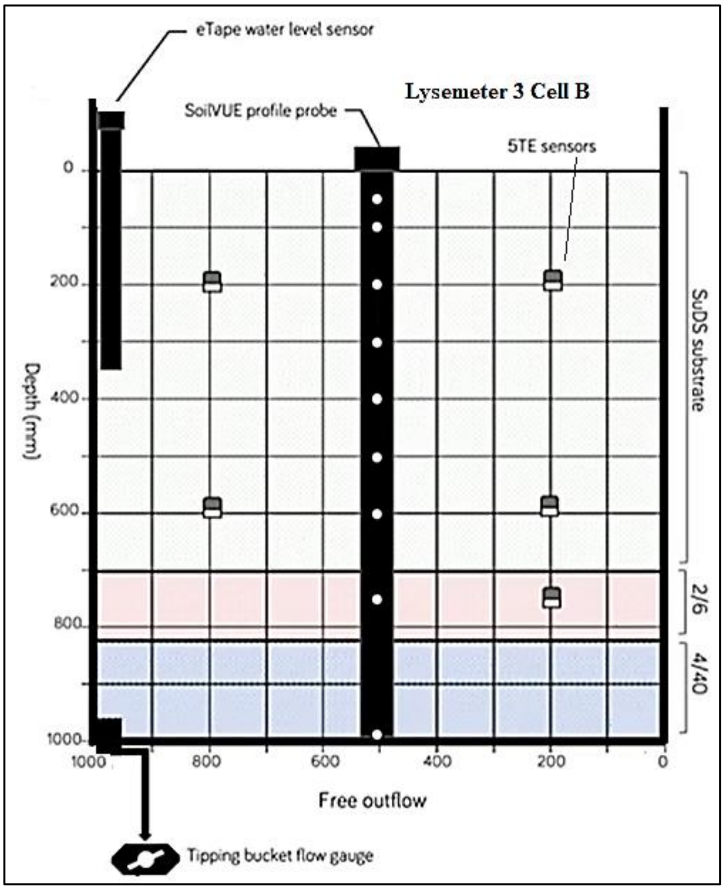


**Figure 4.3** Schematic draw of the Lysimeter 3B and its sensors (Source: adapted from Green and Stirling, 2021).

This dissertation analyses and discusses data from the parameters related to rainfall-runoff processes, namely rainfall precipitation from the rain gauge to infer volumes of inflow into the lysimeter system, VWC (%) to assess changes in soil water content associated with influxes of rainfall as it enters into the lysimeter, and the gauged outflow sensor, to determine the reduction in stormwater runoff. Data is analysed using an event-based approach to identify notable rainfall events in the instrumented period, and VWC net change in specifics events is assessed to evaluate the infiltration efficiency in rainfall events one after the other, *i.e.*, without sufficient time for the soil to dry out, and rainfall events after a long period of drought.

Following the VWC analysis, a second analysis is conducted, as if the bioretention cell received runoff inflow from an impervious surface area, to assess its runoff management. This hypothetical analysis is carried out with the aid of the Storm Water Management Model (SWMM) modelling software, so that the behaviour of the bioretention cell at different impervious area-bioretention cell ratios (scenarios) can be better understood.

#### 4.1.1. Bioretention Cell Lysimeter 3B

Since the data relates to a field-based bioretention cell experiments, it is important to introduce some important characteristics of the region and city where the NGIF is located. Newcastle upon Tyne is in northeastern England. It lies on the north bank of the River Tyne and it is 13 km from the North Sea (Britannica, 2021). According to Population UK (2021), Newcastle had a population around 317.000 people in 2020. The temperature in northeastern England is generally cool throughout the year, with mean annual temperatures over the region ranging from around 8,5 °C to 10 °C (Met Office, 2016).

In Newcastle upon Tyne there is a lot of rain, even in the driest month. The climate is Cfb according to the Köppen-Geiger classification, with annual rainfall precipitation of 718 mm. The driest month is March, with 49 mm, while the highest amount of rainfall occurs in August, with an average of 71 mm. The difference between the driest and the wettest month is only 22 mm. The month with the lowest number of rainy days is September (10, 40 days; Climate-Data, 2021).

Newcastle has around 2.165 hours of sunshine throughout the year, with an average of 71 hours per month (Climate-Data, 2021). In the region of northeastern England, the amount of "wet days" (days with 1 mm rainfall or more) are in winter (December to February) 50-30 days and in summer (June-August) 35-25 days (Met Office, 2016).

Approximately nine months of data from Lysimeter 3B is available, from September 2020 to June 2021. The total rainfall registered in the lysimeter rain gauge is of 605,6 mm. In these nine months the value for total rainfall was about 100 mm lower than the average annual Newcastle rainfall. The data to be analysed is the volumetric water content through the lysimeter soil. There is a total of nine VWC sensors installed inside the bioretention cell, and the sensors are distributed at different depths (Figure 4.3, represented by the SoilVUE profile probe). Sensors are located at depths of 5 cm, 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, 75 cm, and 100 cm, after the 100 cm. The flow gauge that measures the outflow volume is located below the 100 cm VWC sensor.

The rainfall inflow that entered the lysimeter is 1.211,2 L (since the total rainfall is 605,6 mm and the lysimeter has 2 $m^2$ as area). The total outflow is 573,2 L (registered by outflow gauge), which indicates an overall efficiency (managing runoff) of 52,68% (Figure 4.4). This runoff reduction, since the system is closed and the only way out is passing by the outflow gauge, is caused by water storage within the bioretention system, due to its permeability and evaporation (it is a bare earth bioretention cell).

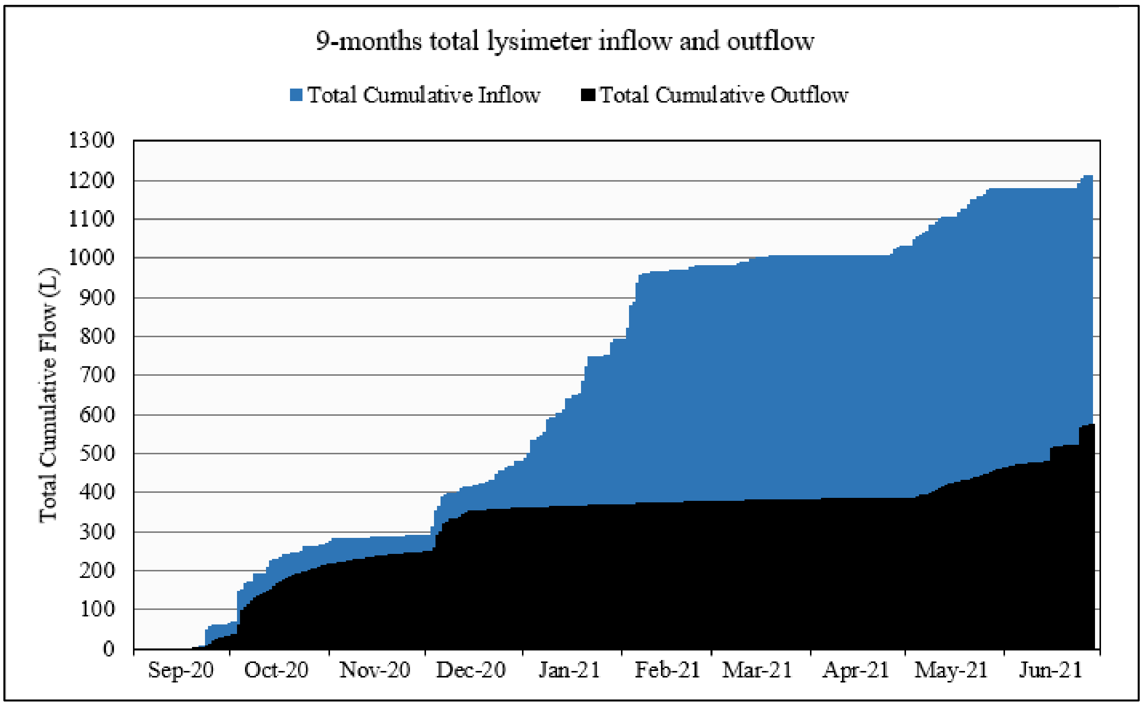


**Figure 4.4** Total Lysimeter 3B 9-month rainfall inflow and outflow.

The data that will be presented in the results chapter needed to be treated at first. The rainfall timestep was 5 min and in mm, so it was converted to L, correlating with lysimeter area. The VWC timestep was also in 5 min timesteps, but in percentage. VWC (%) is based on $m^3/m^3$, so to ensure that each depth is separated and represents its actual volume, it is necessary to multiply the VWC (%) values by coefficients. Otherwise, only one sensor would be used to represent the whole media depth. Table 4.1 presents the proper coefficient for each depth.

**Table 4.1** Lysimeter 3B VWC depths coefficients.

| **Depth** | **Coefficient** (percentage times coefficient) |
|---|---|
| 5 and 10 cm | 0,15 |
| 20, 30, 40 and 50 cm | 0,2 |
| 65 cm | 0,25 |
| 75 cm | 0,4 |
| 100 cm | 0,25 |

The three main rainfall events that were analysed to evaluate the potential of runoff management of this bioretention cell are presented in Figure 4.5 to close this chapter.

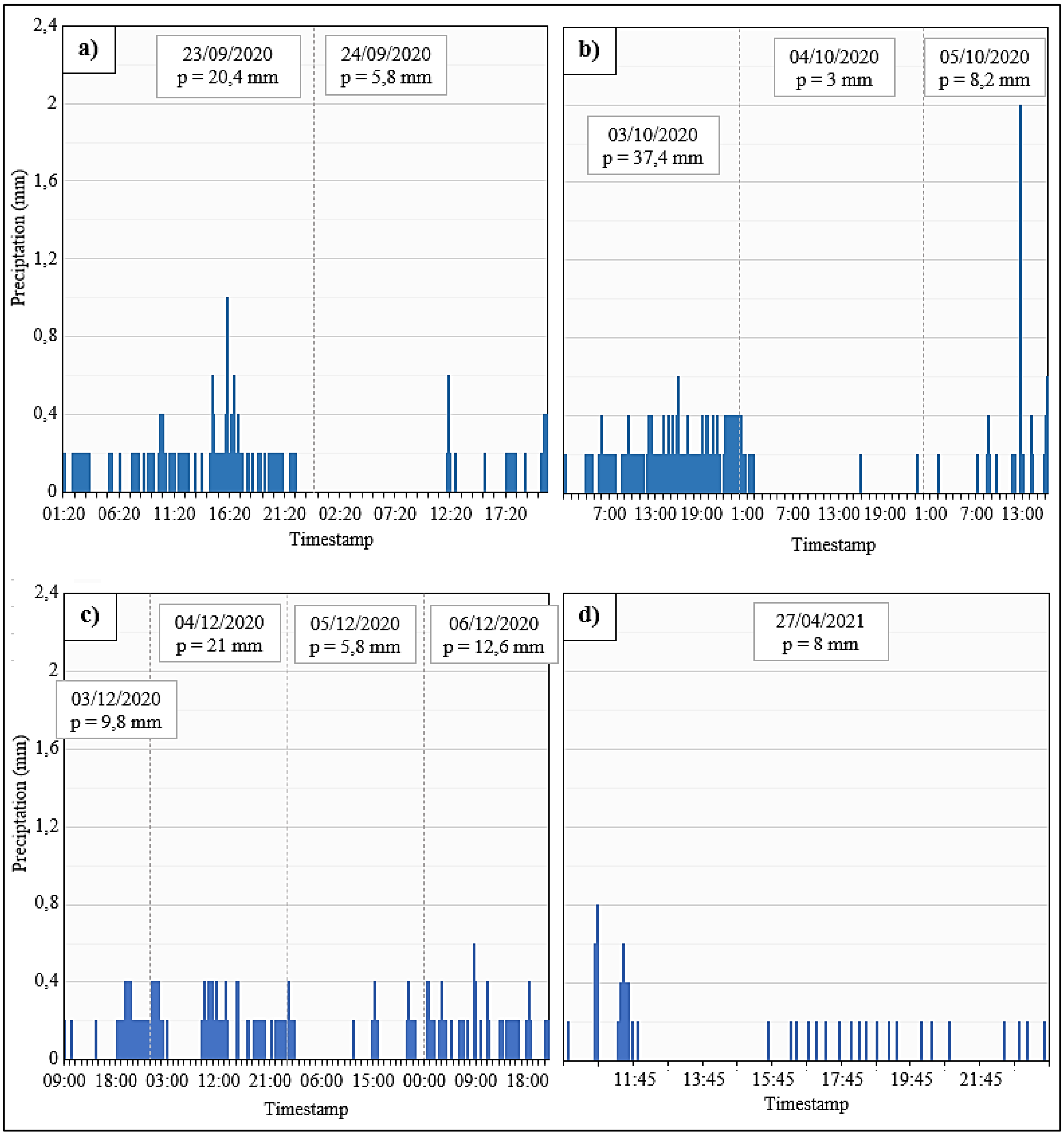


**Figure 4.5** **a)** 23 and 24 of September 2020 rainfall event (total p=26,2 mm). **b)** 03, 04 and 05 of October 2020 rainfall event (total p=48,6 mm). **c)** 03, 04, 05 and 06 of December 2020 rainfall event (total p=49,2 mm). **d)** 14-hr distributed 27/04/2021 rainfall event (total p=8 mm).

The first event (Figure 4.5 a), is also the first rainfall form that exists in available data. This event occurred from 19to 23/09. Then, in 23/09 there was a rainfall event of 20,4 mm in 21 hours, with a mean rainfall intensity of 0,97 mm/hr. In 24/09 a less significant rainfall (5,8 mm) event occurred. It is intended with this event to evaluate if the first event (20,4 mm) possibly influenced the efficiency of the lysimeter to deal with the 5,8 mm rainfall event.

The second event (Figure 4.5 b) is the rainfall event from 03, 04 and 05/10/2020. Since 24/09/2020, the end of the previous described event, there was no more rainfall. As so, the soil had just eight days, from 25/09to 02/10, to dry. The total rainfall depth of this event was 48,6 mm. The rainfall event from 03/10 to the beginning of 04/10 is the most intense rainfall event in all the nine months of available data. In this event, in 24 h and 35 min, it rained 39,8 mm with a mean rainfall intensity of 1,62 mm/hr. Then, at 05/10 there was another rainfall event, not as major as the 03 to 04/10 event, but an interesting one to evaluate the efficiency of the lysimeter. The efficiency managing rain inflow from this event can be helpful to evaluate the bioretention cell.

The inflow and outflow from this October 2020 rainfall event will be compared to another event from December 2020, 03, 04, 05 and 06/12/2020, where the total rainfall precipitation volume (49,2 mm) is almost the same as the October event (48,6 mm), but in a more distributed way. The December event it is presented in Figure 4.5 c).

The last rainfall event (Figure 4.5 d) to be analysed is a small event (8 mm total rainfall), but it happened when, for the first time, the 5 cm depth reached a zero percentage of water storage. The 5 cm sensor was the only sensor that registered 0% VWC in all nine months data. This event occurred at 27/04/2021 and had a 14-hr duration. The analysis of this event will allow checking if the lysimeter can storage most of the rainfall inflow and, maybe, corroborate with Ahiablame, Engel & Chaubey (2013). The authors state bioretention cells can storage the entire rainfall inflow volume of a small rainfall event.

Although the analysis of all these rainfall events is important to evaluate the bioretention cell lysimeter efficiency, the lysimeter is a street-isolated experiment that does not receive runoff from larger impervious surfaces. As described by the literature in the beginning of this chapter, and later asserted by the nine-month available rainfall data, the rainfall regime of Newcastle upon Tyne is practically homogeneous and well distributed throughout the year, without intense rainstorms. This leads to a doubt of how the same bioretention cell would behave if it was non-isolated and treated runoff from larger impervious surfaces during an intense rainfall event. The next chapter explains how this dissertation will evaluate the lysimeter potential hydrological efficiency managing the hypothetical flow originated from an impervious parking lot with different areas (simulated scenarios).

### 4.1.2. SWMM Bioretention Cell Simulation

Laboratory studies can overcome limitations associated with field studies by performing experiments under carefully controlled conditions, allowing for reliable, replicable results. However, the difficulty then becomes translating results from controlled laboratory conditions to the specific conditions of the field. A significant advancement in bioretention design over the past decade has been the increasing prominence and utility of computer models for predicting, understanding, and improving system performance (Spraakman *et al.*, 2020). These authors reviewed 320 bioretention studies and one of the inclusion/exclusion policies of peer-reviewed scientific articles was: Inclusion - studies that evaluated bioretention cells in the field or through a conceptual model; Exclusion - studies that evaluated bioretention cells in highly controlled environments, such as a laboratory. The US EPA’s Stormwater Management Model (SWMM) was the most used model (31% of the studies).

SWMM is freely available and open-source software. The model is used in the evaluation of stormwater runoff systems its LID Editor can be used to represent a variety of technologies for reducing runoff, including bioretention. It can be used to assess drainage, infiltration, evapotranspiration, overflow, exfiltration, and interception (USEPA, 2021).

The SWMM analysis and simulations of the Lysimeter 3B are based on the study of De-Ville *et al.* (2021), that also analysed the same lysimeter with SWMM.

This dissertation simulates the potential bioretention cell Lysimeter 3B runoff treatment of a hypothetical pavement parking lot. The 1-min time-step and the 1-storm are the same as used by De-Ville *et al.* (2021), but this dissertation analyses only the 10-year return rainfall for Newcastle, UK (total rainfall depth of 22,67 mm). Six different parking lot (sizes) scenarios are simulated to assess the bioretention runoff management, which drain directly into the lysimeters (flowing from the impervious surface to the bioretention cell), aiming to find a relation between impervious surface-bioretention surface area ratio and its consequences for stormwater runoff management. Figure 4.6 shows the hyetograph for the1-min time-step, 1-hour, 10-year period designed storm event.

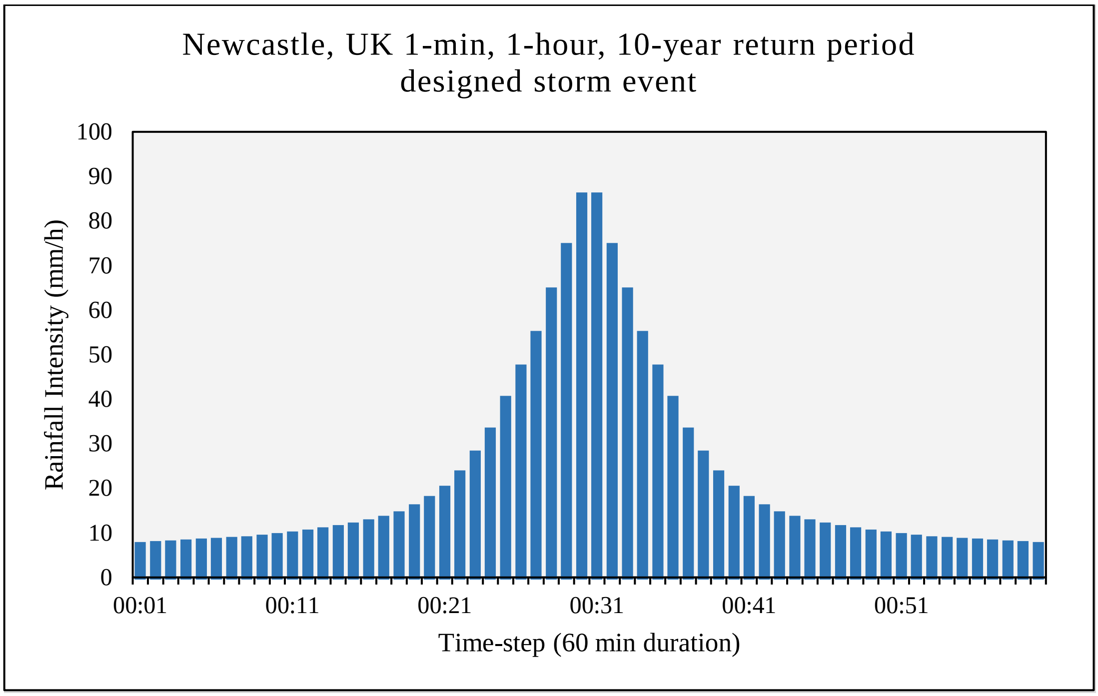


**Figure 4.6** Newcastle, UK 1-min, 1-hour, 10-year return period designed storm event (Source: adapted from De-Ville *et al.*, 2021).

The chosen parking lot sizes scenarios to simulate stormwater runoff are showed in Table 4.2.

**Table 4.2** Pavement parking lot characteristics (Source: USEPA, 2015; Stirling *et al.*, 2021; De-Ville *et al.*, 2021).

| **Parking lot area** | **Parking lot width** | **Bioretention cell area** | **Ratio (parking lot/bioretention cell)** | **Parking lot slope** | **Parking lot imperviousness percentage** | **Parking lot Manning (n)** |
|---|---|---|---|---|---|---|
| 10 $m^2$ | 5 m | 2 $m^2$ | **5:1** | 0,5% | 100% | 0,011 |
| 25 $m^2$ | 5 m | 2 $m^2$ | **12,5:1** | 0,5% | 100% | 0,011 |
| 50 $m^2$ | 5 m | 2 $m^2$ | **25:1** | 0,5% | 100% | 0,011 |
| 100 $m^2$ | 10 m | 2 $m^2$ | **50:1** | 0,5% | 100% | 0,011 |
| 150 $m^2$ | 10 m | 2 $m^2$ | **75:1** | 0,5% | 100% | 0,011 |
| 200 $m^2$ | 10 m | 2 $m^2$ | **100:1** | 0,5% | 100% | 0,011 |

Figure 4.7 presents the SWMM's model layout of the design created.and describes the proposed design for the scenarios modelled with SWMM, with the different parking lot areas where, all rainfall runoff from the impervious parking is going to be directed to the bioretention cell surface.

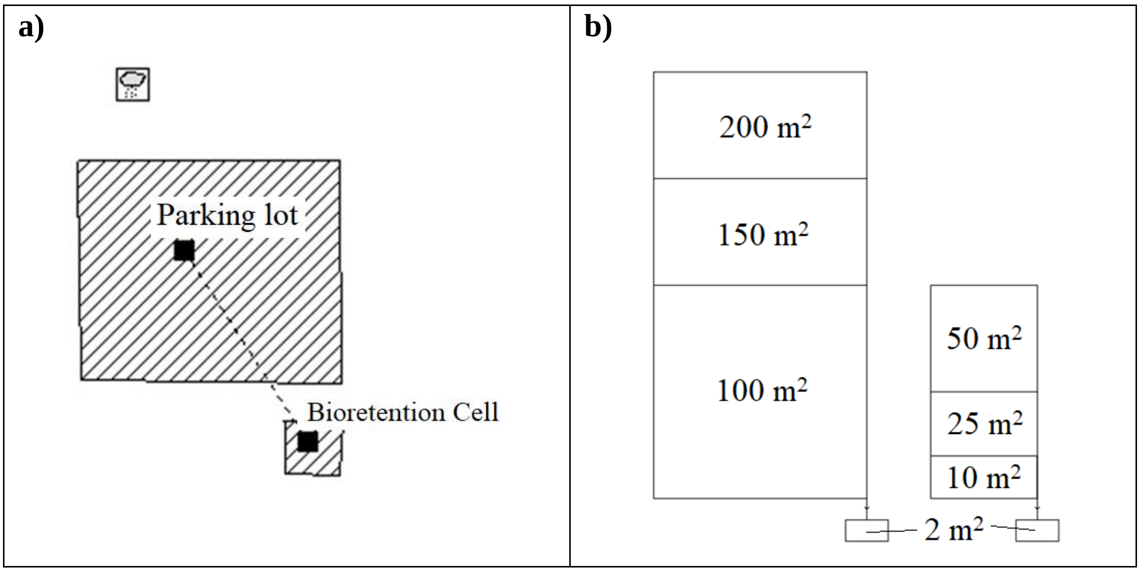


**Figure 4.7** a) Layout of SWMM model and b) Proposed design for SWMM with the different parking lot areas and the 2 $m^2$ bioretention cell from NGIF.

To simulate a GI in SWMM it is necessary to fill in the physical properties of the desired GI. In this case, the simulated GIis the bioretention cell lysimeter. The actual lab-parameters of fill media and design of the Lysimeter 3B and their respective details are in Table 4.3.

**Table 4.3** Bioretention cell Lysimeter 3 Cell B fill media characteristics (Source: adapted from USEPA, 2015; De-Ville *et al.*, 2021).

| **Parameter** | **Unit** | **SuDS substrate media** | **Parameter definition** | **Notes** |
|---|---|---|---|---|
| **Surface** | | | | |
| Berm height | mm | 100 | It is the maximum depth to which water can pond above the surface of the unit before overflow occurs. | Ponding design depth |
| Vegetation volume fraction | $m^3/m^3$ | 0 | The fraction of the volume within the storage depth filled with vegetation. | No vegetation |
| Surface roughness | - | 0 | Manning's n for overland flow over surface soil cover, pavement, roof surface or vegetative swale. Use 0 for other types of GI. | Smooth surface |
| Surface slope | % | 0 | Slope of a roof surface, pavement surface or vegetative swale (percent). Use 0 for other types of GI. | Flat surface |
| **Soil** | | | | |
| Thickness, D | mm | 700 | The thickness of the soil layer | Fill media design depth |
| Porosity, ρ | $m^3/m^3$ | 0,44 | The volume of pore space relative to total volume of soil (as a fraction). | From SuDS substrate characterization |

**Table 4.3** Bioretention cell Lysimeter 3 Cell B fill media characteristics (Source: adapted from USEPA, 2015; De-Ville et al., 2021) – continuation.

| Parameter | Unit | SuDS substrate media | Parameter definition | Notes |
|---|---|---|---|---|
| **Soil** | | | | |
| Field capacity, $\Phi_{fc}$ | $m^3/m^3$ | 0,15 | Volume of pore water relative to total volume after the soil has been allowed to drain fully (as a fraction). Below this level, vertical drainage of water through the soil layer does not occur. | From SuDS substrate characterization |
| Wilting point, $\Phi_w$ | $m^3/m^3$ | 0,12 | Volume of pore water relative to total volume for a well dried soil where only bound water remains (as a fraction). The moisture content of the soil cannot fall below this limit. | From SuDS substrate characterization |
| Conductivity, Ks | mm/h | 101 | Hydraulic conductivity for the fully saturated soil. | From SuDS substrate characterization |
| Conductivity slope | - | 26,1 | Slope of the curve of log (conductivity) versus soil moisture content (dimensionless). | From PSD = 0,48 x (% sand) + 0,85 x (% clay) |
| Suction head | mm | 49,8 | The average value of soil capillary suction along the wetting front. | From Ks = 226,44 x $Ks^{-0,328}$ |
| **Storage** | | | | |
| Thickness | mm | 300 | This is the thickness of a gravel layer. | Drainage layer design depth |
| Void ratio | - | 0,756 | The volume of void space relative to the volume of solids in the layer. | Drainage gravel layer characterization |
| Seepage rate | mm/h | 0 | The rate at which water seeps into the native soil below the layer. | No exfiltration |
| Clogging factor | - | 0 | Total volume of treated runoff it takes to completely clog the bottom of the layer divided by the void volume of the layer. | Not exploring clogging effects |
| **Drain** | | | | |
| Flow coefficient, C | - | 99,999 | The drain coefficient C and exponent n determines the rate of flow through a drain as a function of the height of stored water above the drain's offset. | No impedance to outflow |
| Flow exponent, n | - | 0 | | No impedance to outflow |
| Offset | mm | 0 | This is the height of the drain line above the bottom of a storage layer. | Drain at base of system |

SWMM's model user interface permits the editing of the main characteristics of the parking lot and the bioretention cell, such as area, slope, percentage of impervious surface, *etc*. The area is in hectare, and it is changed for every different parking area scenario tested, while the bioretention cell area remains the same. The impervious surface is set in percentage, where 100% means a surface full waterproofed. As much as these properties in the model user interface are important for the characterisation of the parking lot, the major bioretention cell characterisation needs to be done in the SWMM's LID Editor functionality of SWMM. In this functionality all properties and characteristics presented in Table 4.3. are defined. These properties are shown in Figure 4.8.

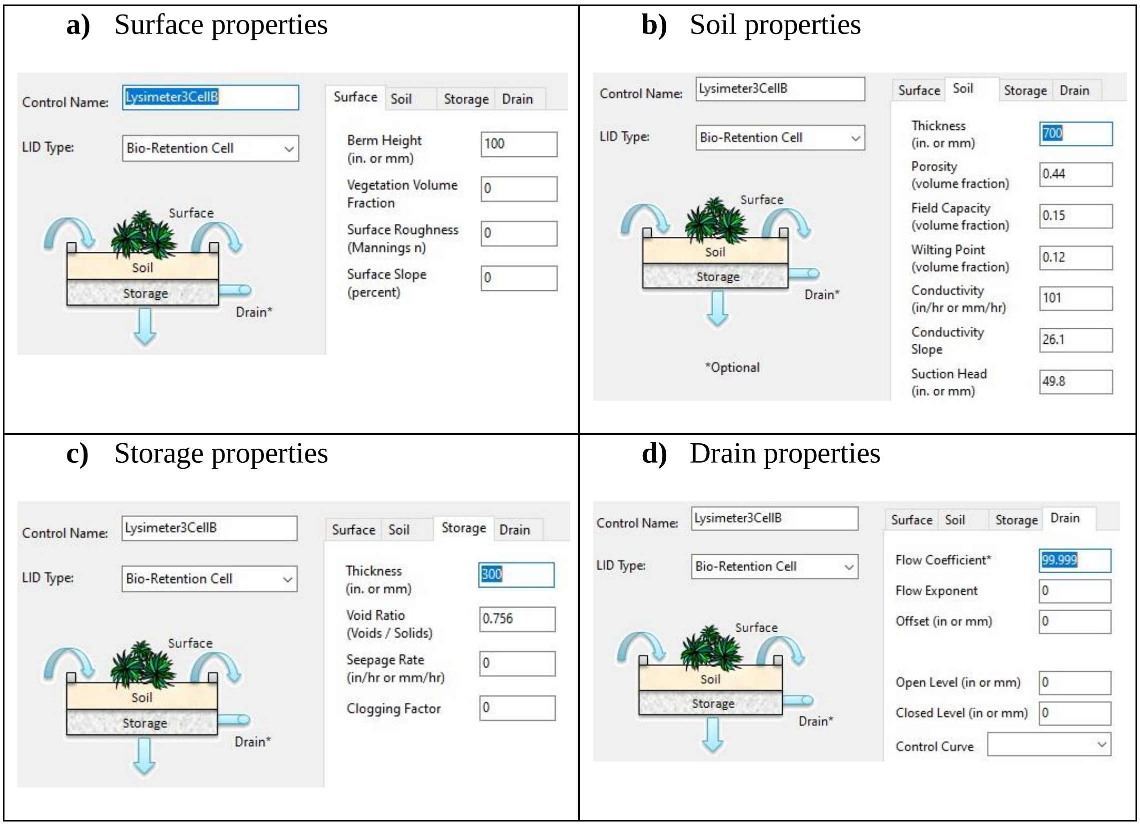


**Figure 4.8** Bioretention cell properties in SWMM's LID Editor.

SWMM lets the user choose some important properties. For this simulation only the bioretention cell area and the soil initial saturation percentage are important. The bioretention surface area was fixed in 2 $m^2$ for every scenario. The initial saturation is important to define how much percentage of water is stored inside the bioretention cell in the beginning of the simulation. A value of 14,7% was extracted from De-Ville *et al.* (2021), but this value is derived from laboratory values and is likely to be different when assessed in-situ, especially after exposure to weather conditions.

This (saturation) property is justifiable only if validated to corroborate with real values. To this end, simulations were performed with the four real rainfall events presented in the previous subchapter 4.1.1. The real inflow and outflow values and inflow and outflow values from the simulations were compared. For the simulations, the properties presented in Figure 4.8 were used. The design was changed for the bioretention cell to manage only the inflow from the rainfall events, as the cell designed in NGIF facilities and is isolated from external runoff. The simulations were first performed for the saturation value of 14,7%. Afterwards, simulations were performed changing only the saturation value and keeping all laboratory characteristics fixed, to find what percentage of saturation is needed to achieve the actual outflows in SWMM simulations. Results from the simulations are presented in Table 4.4.

**Table 4.4** SWMM model and initial bioretention cell saturation validation with De-Ville *et al.* (2021).

| **Real rainfall events data** | | | | |
|---|---|---|---|---|
| **Rainfall event date** | **September 2020** | **October 2020** | **December 2020** | **April 2021** |
| **Total rainfall (mm)** | 26,2 | 48,6 | 49,2 | 8 |
| **Inflow (L)** | 52,4 | 97,2 | 98,4 | 16 |
| **Outflow (L)** | 10,1 | 77,9 | 74 | 0,1 |
| **Simulations with saturation percentage from De-Ville *et al.* (2021)** | | | | |
| **Total rainfall (mm)** | 26,2 | 48,6 | 49,2 | 8 |
| **Initial saturation (%)** | 14,7 | 14,7 | 14,7 | 14,7 |
| **Inflow (L)** | 52,4 | 97,2 | 98,4 | 16 |
| **Outflow (L)** | 52,64 | 81,06 | 77,2 | 41,46 |
| **Outflow error (%)** | 421,19% | 4,06% | 4,32% | 41360% |
| **Simulation with final saturation** | | | | |
| **Total rainfall (mm)** | 26,2 | 48,6 | 49,2 | 8 |
| **Initial saturation (%)** | 2,14 | 14,075 | 14 | 0,04 |
| **Inflow (L)** | 52,4 | 97,2 | 98,4 | 16 |
| **Outflow (L)** | 10,1 | 77,9 | 73,8 | 0,1 |
| **Outflow error (%)** | 0 | 0 | -0,27 | 0 |
| **Initial saturation error (%)** | -85,44 | -4,25 | -4,76 | -99,73 |

Validating the bioretention cell initial saturation was important to choose a reasonable value to be used in target scenarios for this dissertation. The saturation from the events of September 2020 and April 2021 were discard, although it is possible with them to reach the real outflow value, but, with high error percentage compared to the saturation percentage from De-Ville *et al.* (2021). The initial saturation of the events from October and December of 2020 are, respectively, only 4,25% (14,075%) and 4,76% (14%) below the laboratory measured 14,7% saturation. In this dissertation the 14,7% initial saturation from De-Ville *et al.* (2021) will be used to simulate the six different scenarios, as this value indicated a higher outflow volume for all rainfall events and only 4,06% higher than the most intensity rainfall event. Using this value will give the simulated bioretention cell a lower efficiency, thus making the simulated model a little more conservative.

The next chapter will present the results from the NGIF Lysimeter with the real rainfall events showed in subchapter 4.1.1, and its impacts measured with volumetric water content sensors. The SWMM scenarios simulations will be presented later, after the lysimeter VWC results.

# 5. Results

This next chapter will present the obtained results from the NGIF Bioretention Cell Lysimeter 3B volumetric water content sensors and the real rainfall events captured by the experiment, and the results from the SWMM simulations of different parking lot size scenarios and the NGIF Bioretention Cell.

## 5.1. Bioretention Cell Lysimeter 3B VWC Results

This chapter assesses the inflow-outflow efficiency and evaluates lysimeter soil-water storages under varying rainfall precipitation events to determine if more intense rainfall influences and/or undermines the efficiency of a bioretention cell. Further, the influence of a dry period before a rainfall (*i.e.*, antecedent conditions), among other perspectives related individually to each rainfall event are assessed.

### 5.1.1. Lysimeter: September 2020 Rainfall Event

This subchapter presents the VWC analysis from 23/09 and 24/09 rainfall event (Figure 4.5 a) in terms of rainfall inflow and lysimeter outflow volume and volumetric water content variation in each soil depth sensor. This is the first rainfall event captured by the lysimeter, with a total rainfall depth of 26,2 mm. On the 23/09 rained a total of 20,4 mm in 21 hours, which resulted in a mean intensity of 0,97 mm/h, and on 24/09 rained a total of just 5,8 mm. Based on the rainfall distribution along time, it will be possible to identify and discuss the impact of this first and more intense rainfall on the bioretention cell efficiency to manage the second inflow, from the 5,8 mm rain. From 19/09 to 23/09 the lysimeter rain gauge did not registered any rain depth, so, the bioretention cell VWC remained stable and did not influence the substrate depths capability to capture and storage rainfall inflow. Figure 5.1 shows the rainfall inflow and lysimeter outflow of this event.

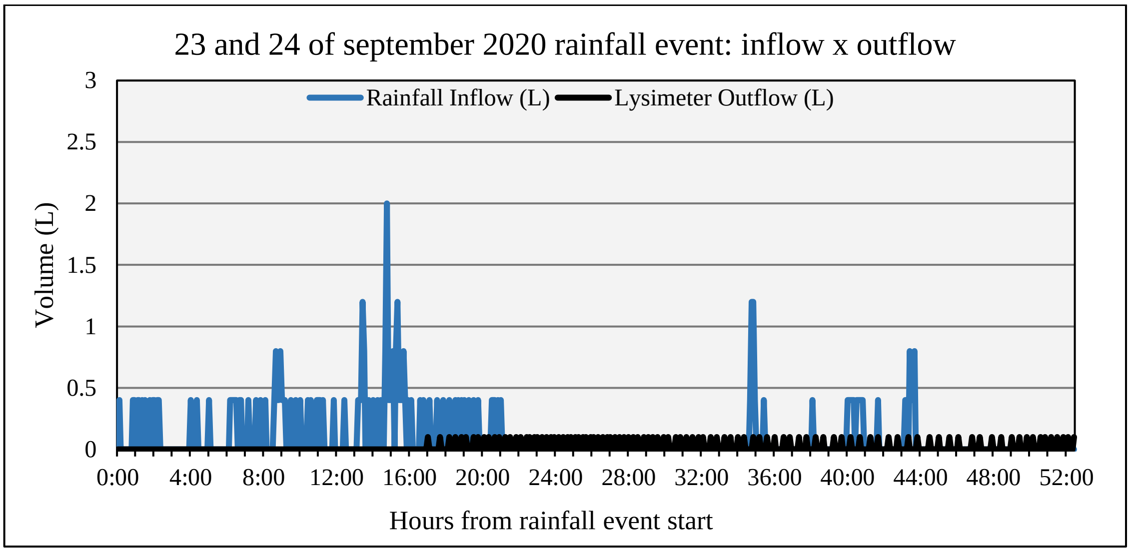


**Figure 5.1** Rainfall inflow and lysimeter outflow from September 2020 26,2 mm rainfall event.

It is possible to observe that the lysimeter delayed the outflow for approximately 17 hours since the rainfall start. The GI also influenced the non-existence of an outflow peak, because the outflow was stable at a maximum of only 0,1 L, in each timestep. The outflow remained practically constant at 0,1 L until 8 hours after the second (5,8 mm) rain event ended. It is possible to make a relation, but unfortunately not to be sure, that the first intense rainfall (20,4 mm in 21 hours) affected the inflow storage from the second less intense rainfall, since the first rainfall had an inflow of 40,8 L and an outflow of 6,2 L (84,8% efficiency), and the second event had an inflow of 11,6 L and an outflow of 3,9 L (66,4% efficiency). Figure 5.2 presents the cumulative inflow and outflow for this same September event.

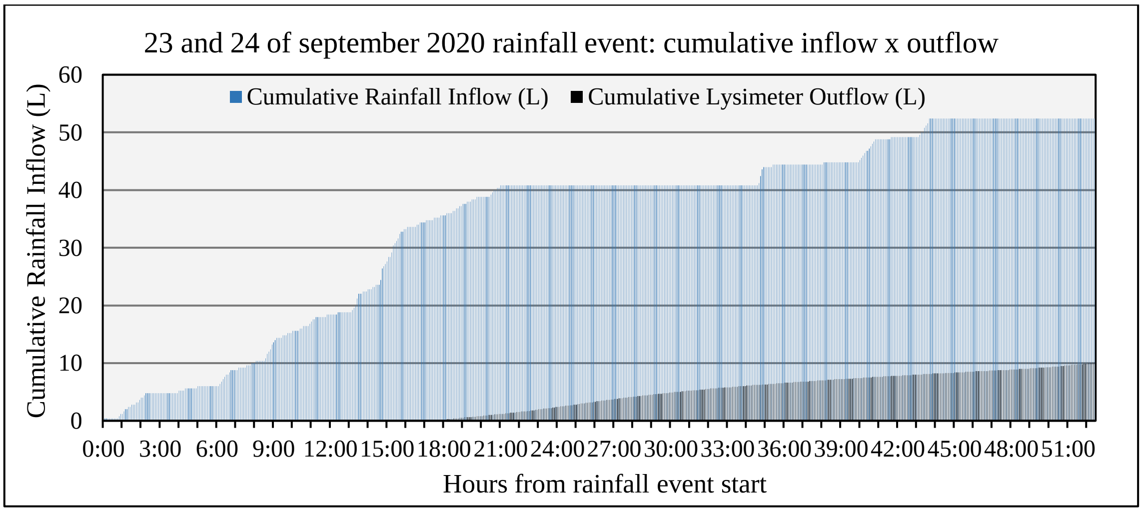


**Figure 5.2** Rainfall cumulative inflow and lysimeter outflow from September 2020 26,2 mm rainfall event.

From Figure 5.1 and Figure 5.2 it is possible to identify an easing, not only in volume, but in the intensity of runoff (a consequence of retaining water volume), allowing the drainage systems to manage more efficiently the rainfall runoff. At total, there was an inflow of 52,4 L and an outflow of 10,1 L with a total event efficiency of 80,7%.

Figure 5.3 presents the VWC for each lysimeter depth and it shows the layer sensors from 19/09 to 24/09; the figure also displays the rain inflow and lysimeter outflow.

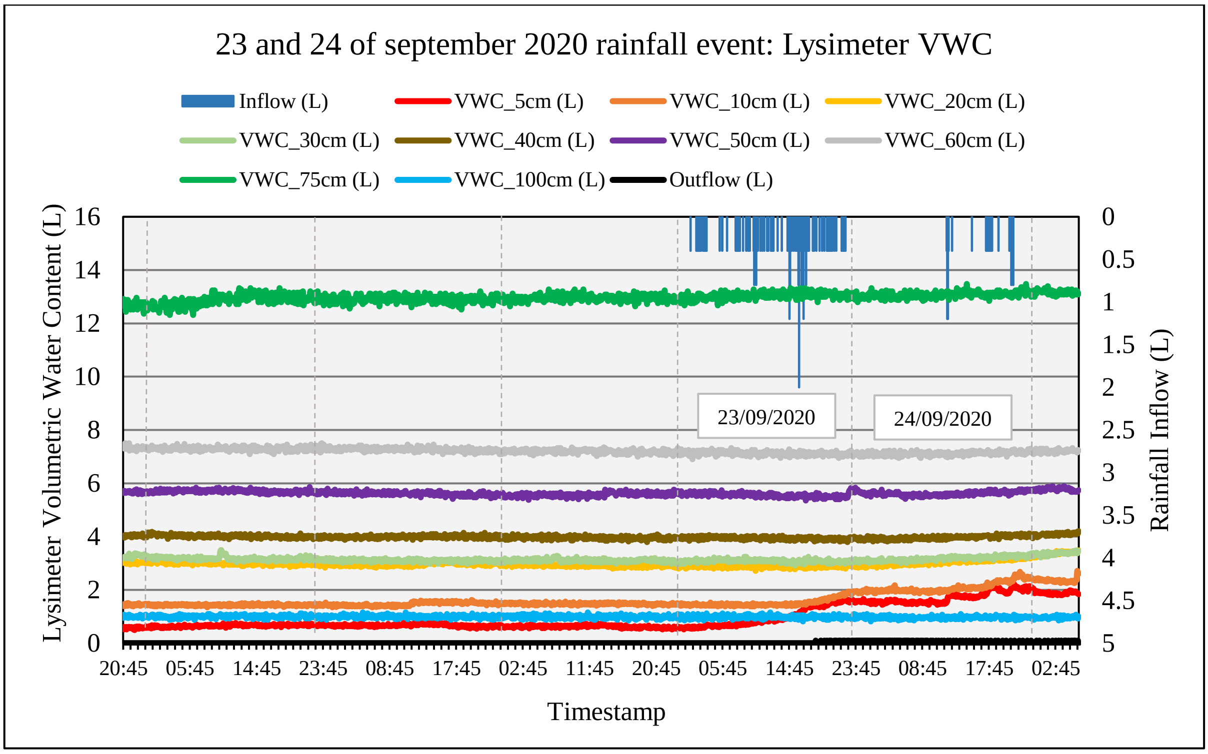


**Figure 5.3** Lysimeter VWC performance from September 2020 26,2 mm rainfall event.

It is possible to observe that the depths 5, 10, 20, 30, 50 and 60 cm from 19/09 to right before the beginning of the rainfall are very slowly decreasing its water content. The other 3 depths 40, 75 and 100 cm are also varying, slowly increasing and decreasing its VWC, so it can be considered stable most of the time. Initially the 5 cm depth had about 0,6 L storage, 10 cm had 1,5 L, 20 cm had 3 L, 30 cm had about 3,5 L, 50 cm had 5,66 L and the 60 cm depth had 7,2 L storage. Right before the rainfall event beginning these storages were respectively around 0,5 L, 1,4 L, 2,8 L, 3 L, 5,5 L and 6,9 L. When the rainfall gets to its peak inflow, it is possible to observe an immediately response on 5 and 10 cm depths. The VWC increase can be seen in Figure 5.3, note that the 5 cm depth rouse from 0,5 to 1,1 L and the 10 cm depth rouse from 1,4 to 1,9 L. The VWC in 20 and 30 cm depths only starts to increase when the second rainfall event begins, where the 20 cm depth rouse from 2,8 to 3,2 L and the 30 cm depth from 3 to 3,3 L. The 50 cm depth right after the end of the first rainfall event shows a quick variation, increasing, then decreasing, and stabilising its water storage, then begins to increase VWC again during the second rainfall event, while the 60 cm depth remains stable until the end of both rain events.

By the end of the period presented in Figure 5.3, the 5 cm depth begins a timid decrease. In contrast, the 10 cm depth continues to increase along with 20, 30, 40, 50 and this time also the 60 cm, that begin a timid increase, with a 0,1-0,15 L addition. The other depths (75 and 100 cm) virtually kept the same VWC since the beginning. This indicates that the surface layers, such as 5 and 10 cm, have a flashier behaviour than the other ones. The 20 and 30 cm depths only suffer increase because of the second event, while the 50 cm layer had a singular behaviour, responding to the first rainfall event after it ended and increasing in fact its VWC during the second one. If the 5,8 mm rain event did not occur, possibly these more superficial depths could have had the same pattern than the other deeper depths, that needs more time to show any significant change in their volumetric water content. Figure 5.4 shows the net change of each layer for the same timestamp.

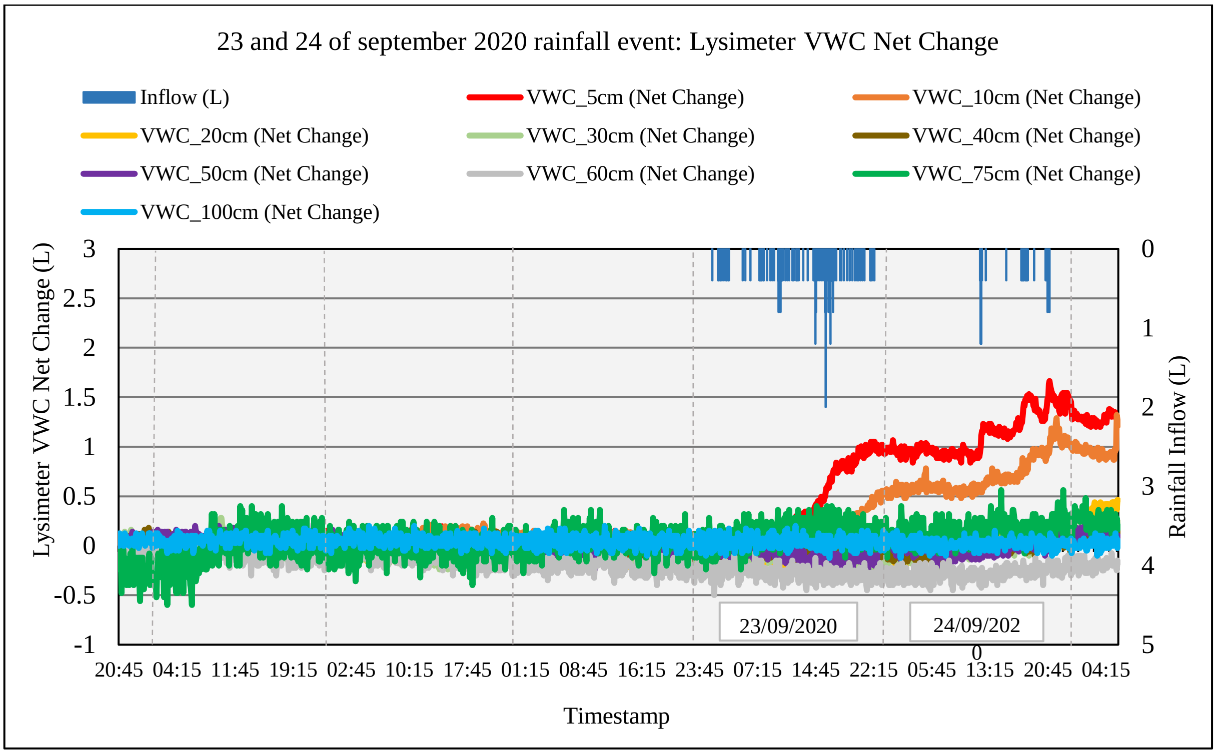


**Figure 5.4** Lysimeter VWC net change performance from September 2020 26,2 mm rainfall event.

The net change performance is a way to compare the variation of VWC along the time with the first VWC data-value from the initial timestamp chosen. In this September 2020 event, all VWC net changes are based on the first volumetric water content value of each depth from 19/09/2020 at 20:45. It is possible to observe from Figure 5.4 that the 100 cm depth (gravel storage depth of the lysimeter) remains the same; it makes sense since this depth is always storing and freeing water. It is also possible to observe the rapid water storage increase in the 5 and 10 cm depth, and for the second rainfall event the 5 and 10 cm depth volumetric water content increased even more. The 75 cm depth resulted into an interesting behaviour, where at start the data indicates a water dry out. Without any rainfall, its VWC begins to increase and then remains stable. This can indicate, as mentioned above, that the other depths were drying out and some volumes of water were infiltrating to deeper depths.

### 5.1.2. Lysimeter: October and December 2020 Rainfall Events

After the 24/09 rainfall event, no rainfall was registered by the lysimeter rain gauge for 8 days. The rain period of 03/10 and 04/10 was one of the most intense events in all nine months of available data, with 39,8 mm distributed in 24 hours and 35 minutes, corresponding to a mean rainfall intensity of 1,62 mm/hr. Although this rain event is the most intense from all nine month monitored data, it is still considered as a low intensity event (because it is below 5 mm/hr). The October rainfall event began in 03/10 and ended in 05/10, and had a total rain depth of 48,6 mm (Figure 4.5 b). Figure 5.5 presents its rainfall inflow and outflow volume.

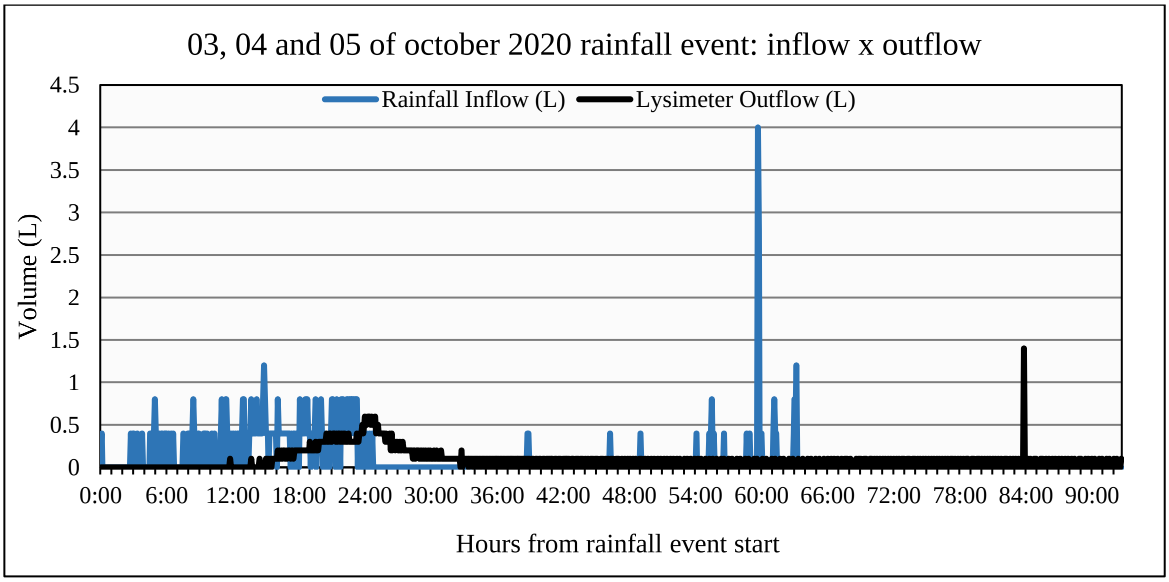


**Figure 5.5** Rainfall inflow and lysimeter outflow from October 2020 48,6 mm rainfall event.

As we can see from Figure 5.5, the behaviour is different from the September 2020 hydrograph response presented in the subchapter above (Figure 5.1). In the October event it is possible to observe a delay between rainfall begin and outflow discharge, but still generated outflow peak volumes in the first and second rainfall period. The first rainfall has a 1,2 L inflow peak volume and a 0,6 L outflow peak volume (50% reduction), while the second rain period has a 4 L inflow peak and a 1,4 L outflow peak (65% reduction).

The outflow delay is about 12 hours and the lag time (peak outflow delay) is about 11 hours. When the outflow discharge reaches its falling limb, it descends to 0,1 L and then becomes stable in these values, even though another rainfall period begins. For the second rainfall, the lag time was 27 hours. Figure 5.6 shows the cumulative inflow and outflow for this October event.

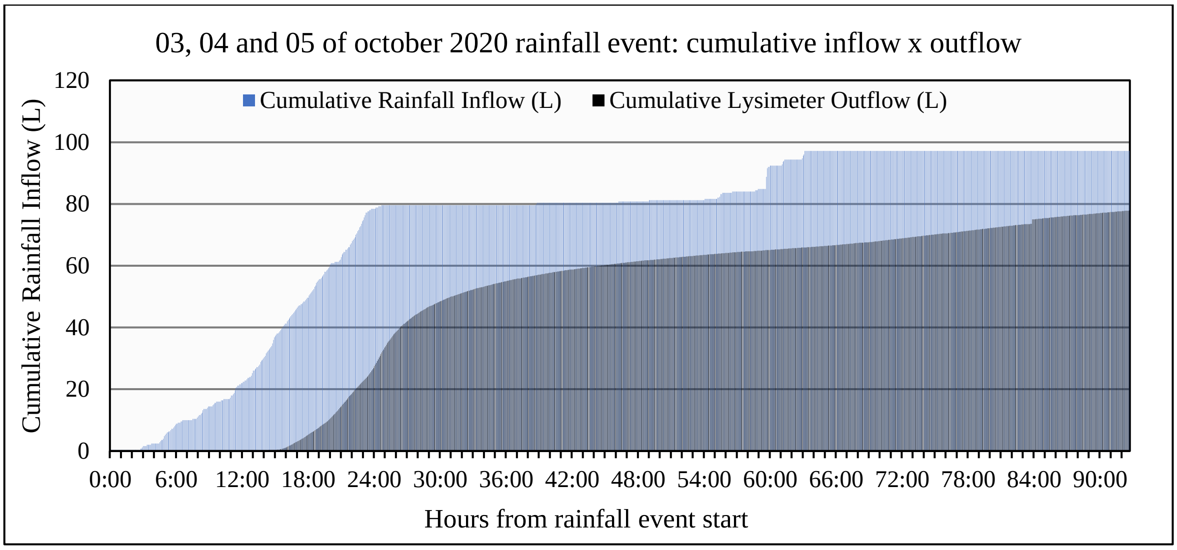


**Figure 5.6** Rainfall cumulative inflow and lysimeter outflow from October 2020 48,6 mm rainfall event.

The total inflow from the first 24,5-hr rainfall event (between 03/10 and 04/10 only) was 79,6 L, and the outflow discharge (total outflow volume until the beginning of the second rainfall period) is 56,9 L, which gives an efficiency of 28,5%. The efficiency is different from the inflow volume reduction from the subchapter 5.1.1. Later, in this same 5.1.2 subchapter, a possible negative influence of intense events in this monitored bioretention cell will be discussed.

Regarding the rainfall from the remaining days (04/10 and 05/10), the total inflow was 17,6 L but, it is not possible to measure for sure the outflow discharge amount due to the

24,5-hr earlier intense event. It possible to say that from time 38:40 until 92:35 the rainfall inflow was 17,6 L and the outflow discharge 21 L.

Although the bioretention cell delayed outflow discharge and peak, its efficiency for this rainfall event suffered a major decrease. The total event (three days rainfall) inflow was 97,2 L, while outflow discharge was of 77,9 L. This gives an efficiency of 19,9%, about 61% less than the September 2020 event from subchapter 5.1.1. Figure 5.7 presents the VWC of the lysimeter for the October 2020 rainfall precipitation event.

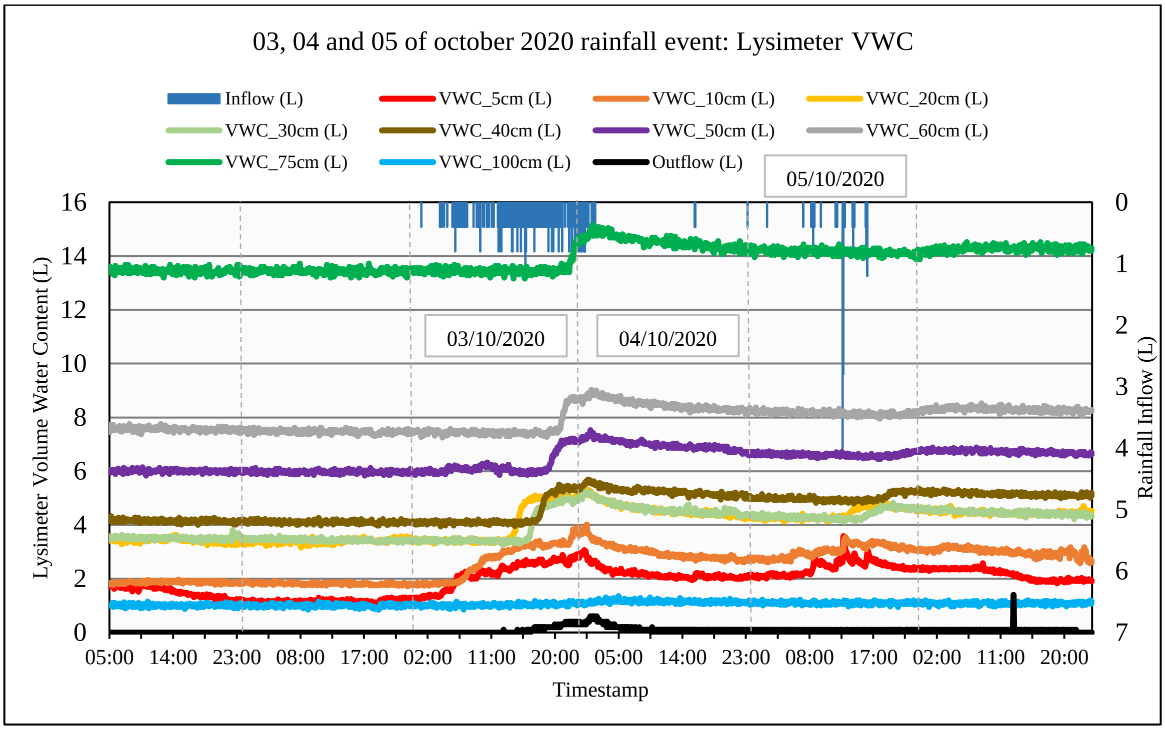


**Figure 5.7** Lysimeter VWC performance from October 2020 48,6 mm rainfall event.

Differently from the September rainfall event, in the October rainfall event we have almost all nine depths responding simultaneously to the 24,5-hr rainfall from 03/10. The 5 cm depth is the only that begins indicating a visible descend, reaching 1 L VWC right before the rainfall start. The first depths that respond to rainfall, as expected, are the 5 and 10 cm, about six hours after the first rain registered. 11 hours later, the 20, 30 and 40 cm depths increased their VWC, and six hours later the 50, 60 and 75 cm depths began to rise its water content. The 100 cm depth is the only remaining virtually stabilised with the same value of VWC, of about 0,9-1,2 L. All the other eight depths rouse the VWC in about 1,2 to 2,2 L after the first rainfall event. Regarding the second event, only the 5 cm depth still varies its volumetric water content, reaching the same 3-3,1 L peak from the previously event. After the second rainfall peak, there is some VWC increase in the 10, 20, 30, and 40 cm depths, while the rainfall peak inflow impact in the 50, 60 and 75 cm depths are timid. The first layer VWC begins to decrease is the 5 cm depth, about 18 hours after the end of the rainfall. However, overall, the VWC is basically influenced by the first intense event. Figure 5.8 presents the VWC net change.

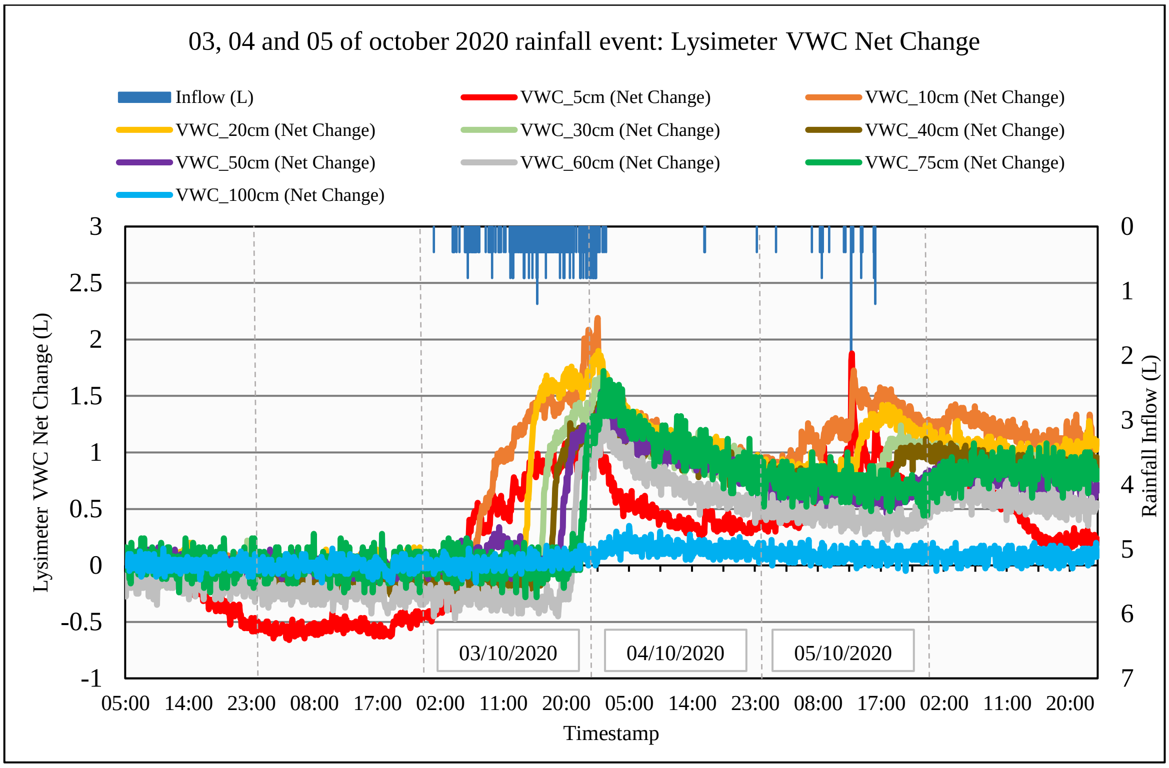


**Figure 5.8** Lysimeter VWC net change performance from October 2020 48,6 mm rainfall event.

The VWC net change has the first volumetric water content value from 01/10/2020 at 05:00 as reference. It is observed a drying behaviour from the 5 cm depth. The other depths maintain basically the same VWC variation since the beginning but, after the rainfall start every depth responds to it, even the 100 cm depth increases its water content a little timidly, but it still grew. It was not possible to observe this behaviour in Figure 5.7. Also, it is possible to corroborate with the 1,2 L to 2,2 L VWC increase after the rainfall inflow peak volume. For the second rainfall the impact is a little more attenuated and all depths, the 100 cm included, starts its falling limb, with the 5 cm layer being the fastest to present a decrease.

In order to evaluate the influence of rainfall intensity on the efficiency of inflow management of this monitored bioretention cell, a rainfall event from December was also analysed, already presented in chapter 4.1.1 and Figure 4.5 c). The 4-day event has practically the same total rainfall volume of the 3 days rainfall of October analysed above, however; it has a more equal distribution among the days. Figure 5.9 shows the rainfall inflow and lysimeter outflow volume of the rainfall December event.

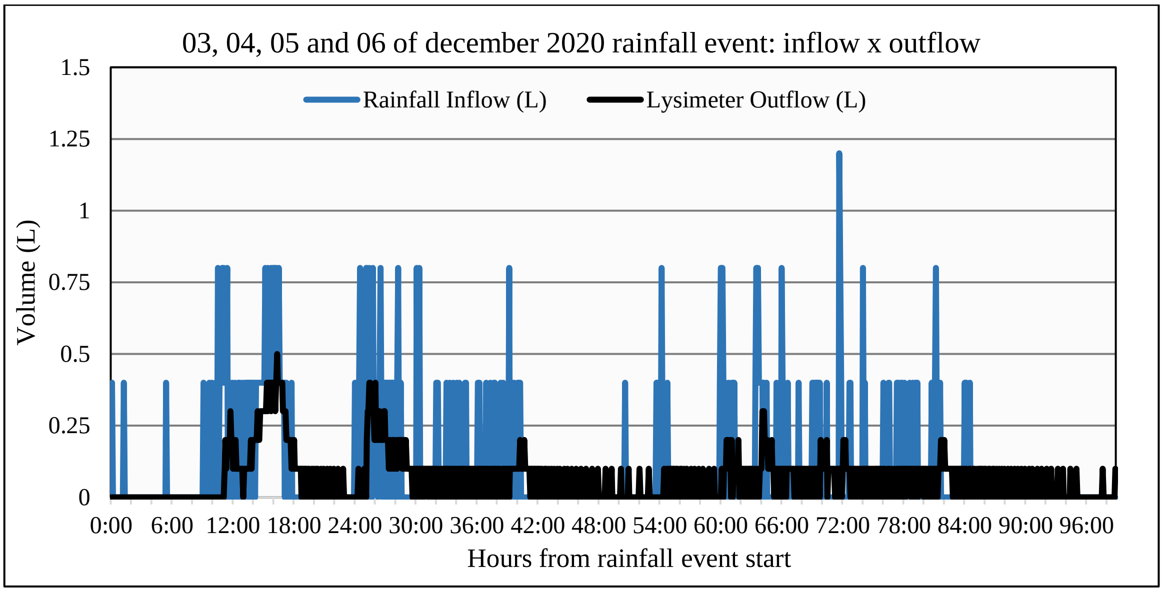


**Figure 5.9** Rainfall inflow and lysimeter outflow from December 2020 49,2 mm rainfall event.

The December 2020 event has a total rainfall depth of 49,2 mm, distributed along 4 days. The October 2020 event had 48,6 mm in 3 days but about 81,9% of its rainfall depth occurred in the first 24,5 hours with a mean intensity of 1,62 mm/hr. In the meantime, the most intensity rainfall from this December event is the rainfall from 04/12 which had a mean intensity of 1,3 mm/hr. In this event it is possible to observe a representative delayed outflow discharge and lag time, as the October rainfall precipitation event.

Overall, from 03/12 to 06/12 the inflow was 98,4 L, about 1,2% greater than the 97,2 L from October. The outflow discharge was 74 L, about 5% lower than the 77,9 L from October. The efficiency for the December event was 24,8%, about 5% higher from October. For all that, for this particular analysed bioretention cell, as important as the total volume of rainfall of any event is, it is important to have knowledge of the amount of time that this total volume occurred. In this event it was observed an inverse relation between intensity and efficiency to manage rainfall inflow.

### 5.1.3. Lysimeter: April 2021 Rainfall Event

In this subchapter it will be presented and discussed the 14-hr rainfall event from 27/04. This rainfall event had a total depth of only 8 mm. It is a really small intense rainfall with a mean intensity of 0,57 mm/h. However, this event happened at one of the few times the

5 cm depth was completely dry, with zero litres of water stored. The zero storage only occurred after about 43 days without any rain registered by the lysimeter rain gauge.

If in the other rainfall events this dissertation discussed the impact of humid substrate and the impacts of sequential rainfall, with this 8 mm in 14-hr rainfall precipitation the objective is to discuss and assess the benefits of a drier soil. Figure 5.10 presents the 27/04 rainfall inflow and lysimeter registered outflow volume.

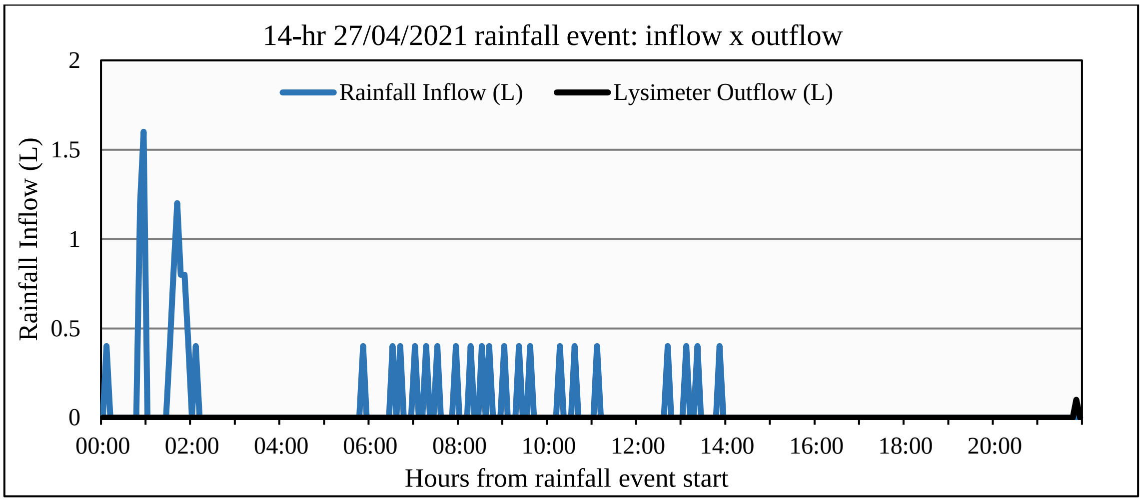


**Figure 5.10** Rainfall inflow and lysimeter outflow from 14-hr April 2020 8 mm rainfall event.

The outflow discharge was delayed about nine hours from the end of the rainfall. It is fair to state that it did not have any outflow, since the only outflow registered were 100 mL. The bioretention cell really absorbed the rainfall inflow from this event. Figure 5.11 shows the cumulative inflow and outflow.

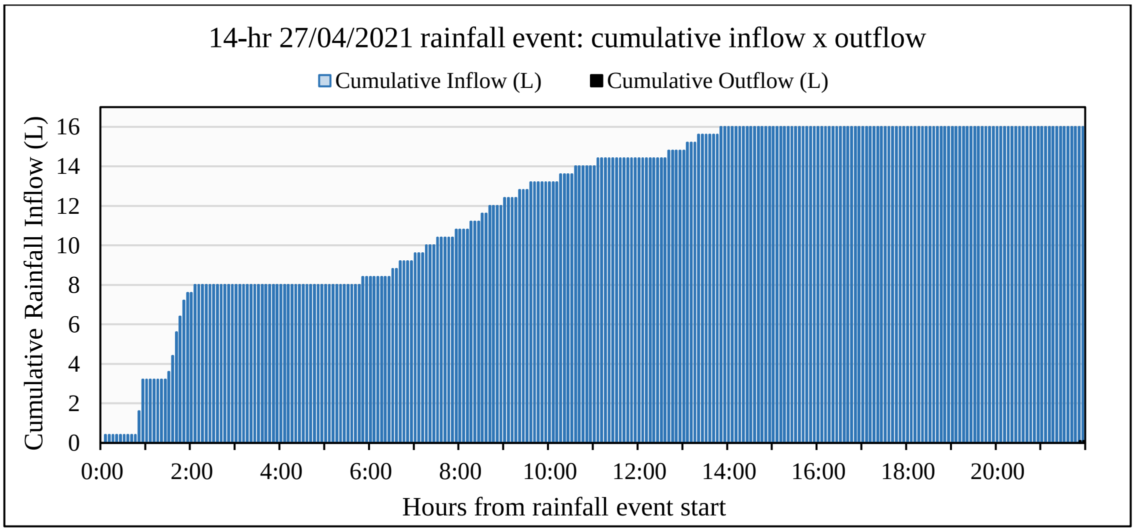


**Figure 5.11** Rainfall cumulative inflow and lysimeter outflow from 14-hr April 2021 8 mm rainfall event.

The total rainfall inflow of this event was 16 L and the outflow registered by the flow gauge at the bottom of the lysimeter was 0,1 L, which results in an efficiency of 99,4% managing rainfall inflow.

For a small rainfall depth and for intense rainfall events, after a long period of sunny days, this bioretention cell was able to manage rainfall inflow and runoff almost by itself or, at least, helped to greatly reduce the runoff that would traditionally go into grey drainage systems. This result is important to corroborate with Ahiablame, Engel & Chaubey (2013) founds on bioretention cell's efficiency for small rainfall events, stating that for small events bioretention cell can capture almost all inflow. Figure 5.12 presents the lysimeter VWC depth performance.

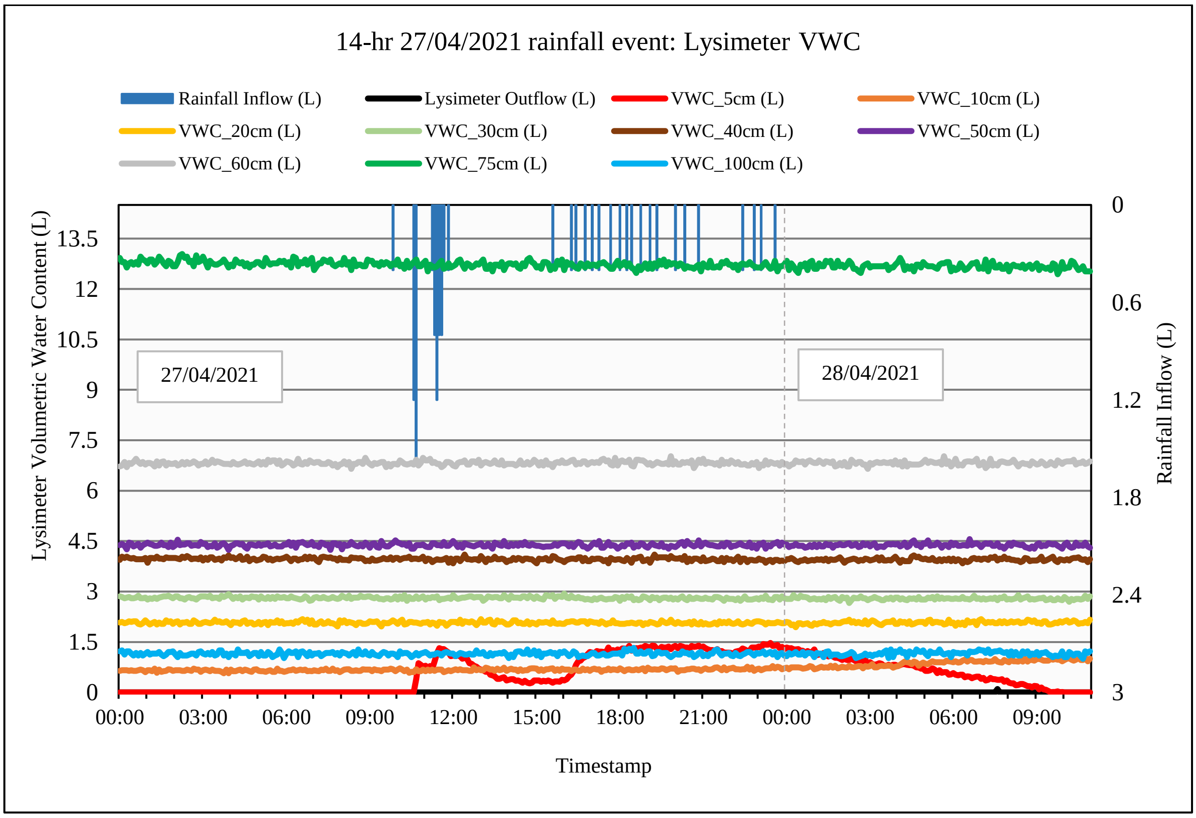


**Figure 5.12** Lysimeter VWC performance from 14-hr April 2021 8 mm rainfall event.

The volumetric water content behaviour for this particular event is different from the other rainfall events already presented in this 5.1 results chapter. Virtually only the 5 cm depth responded to the rainfall inflow. This response is clearly seen at the first rainfall peak at 10:40, when the 5 cm depth increased its storage to 0,7 L. The others 10, 20, 30, 40, 50, 60, 75 and 100 cm depth remained practically the same from the beginning of the rain event. After the second rainfall peak (at 11:25) the 5 cm depth reaches its maximum

VWC, about 1,32 L, and then begins to decrease and almost reaches zero liters again. The 5 cm depth reached the minimum of 0,27 L before the beginning of the second rainfall period, when the VWC rose again.

In the second rainfall period, the 5 cm depth storages more water content than in the first, since in the first one the depth was zero VWC and in the second the VWC already starts at 0,27 L. This second rainfall was well distributed, and the 5 cm depth stayed virtually with the same water content from the rainfall beginning to its end, about 1,37 L. After eight hours of the rainfall end, the 5 cm depth reaches zero liters again. By the time the most superficial layer reaches 0,4-0,3 L, the 10 cm depth starts a timid increase. Probably with small rainfall after long periods without rain the depths behaviour are sequential, after one depth starts to finally decrease, the layer below begins to increase its VWC. Figure 5.13 shows the VWC net change.

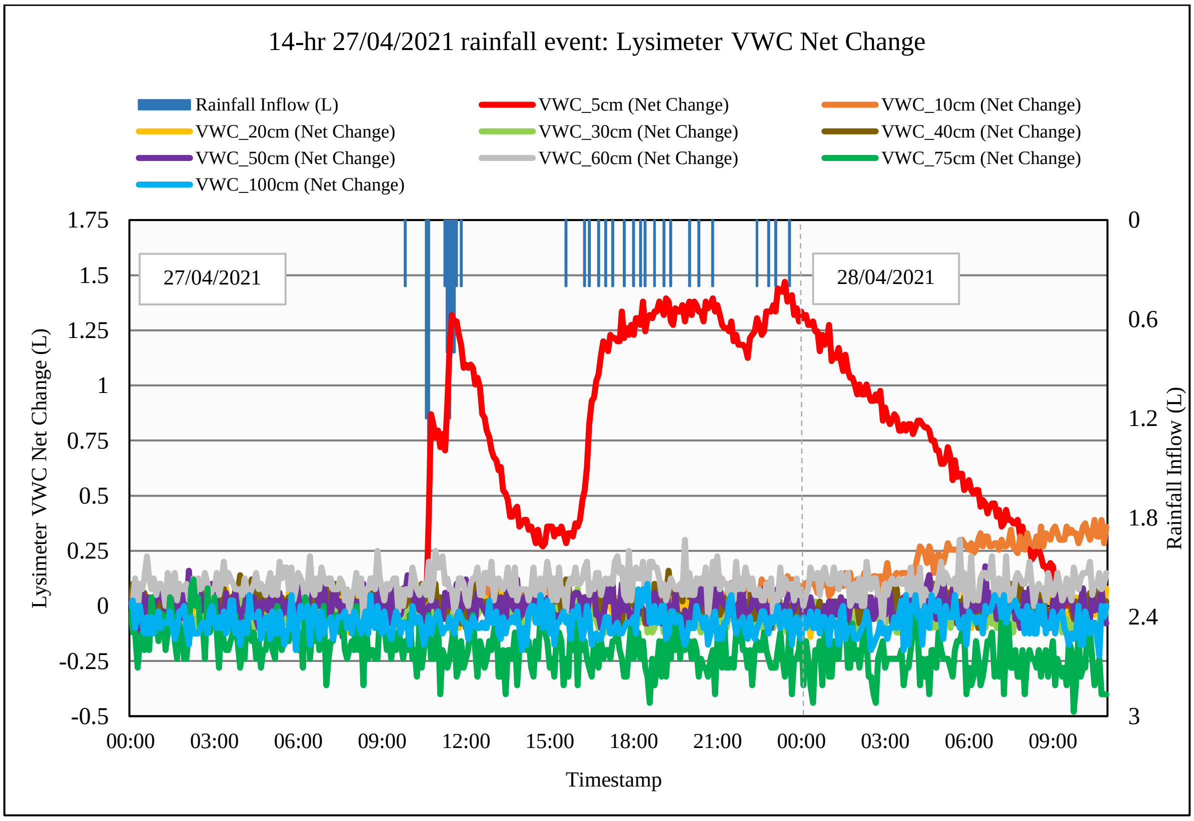


**Figure 5.13** Lysimeter VWC net change performance from 14-hr April 2021 8 mm rainfall event.

The VWC net change graph represents the 27/04/2021 rainfall event, starting at 00:00 and ending in the next day at 10:55. It is possible to observe that the volumetric water variation of all the other depths besides the 5 cm are virtually stable and have the same behaviour from the beginning to the end. Figure 5.13 shows the high impact the rain generated in the 5 cm depth, going from zero to 1,32 L in less than 40 minutes, and how the constant second rainfall period kept VWC high compared to other layers. It is also possible to observe the actual time where the 5 and 10 cm depth intersect each other. The intersection happens about 9 hours after the end of the rainfall. For this bioretention cell and this rainfall event, maybe the 10 and 20 cm depth would intersect as well, many hours later and so on, but it is not possible to assure it since by the end of the 28/04 starts raining again.

## 5.2. SWMM Simulation Scenarios Results

As already explained in subchapter 4.1.2, six different scenarios to be simulated on SWMM were designed. The bioretention cell lysimeter from NGIF, with actual laboratory founded physical characteristics (already validated) was simulated for managing runoff from different impervious surfaces areas (referred in this dissertation as parking lot). With the simulation it will be possible to discuss the potential efficiency of bioretention cells managing stormwater and find the best impervious surface-bioretention cell area ratio to get the most benefits as possible in urban areas.

### 5.2.1. Sensitivity to Catchment Drainage Area

This subchapter will present the founding results from the six different scenarios simulated with the SWMM model, as a form to evaluate the bioretention cell sensitivity to different catchment sizes drainage areas. To asses this sensitivity, runoff volume and peak flow management will be analysed and discussed. The impervious parking lot surface runoff and the bioretention cell runoff for all six impervious-bioretention cell area ratio scenarios hydrograph is presented by Figure 5.14.

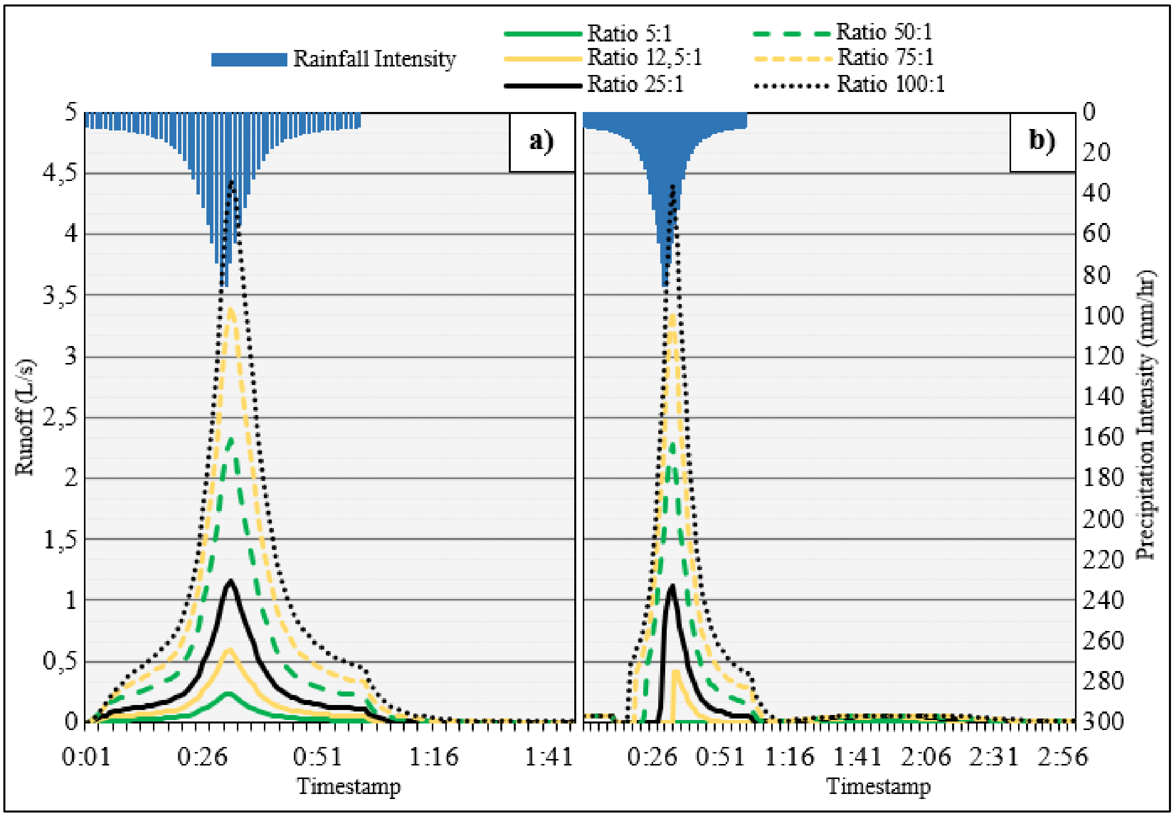


**Figure 5.14 a)** Parking lot runoff from every six different scenarios. **b)** Bioretention cell runoff for every six different scenarios. Disclaimer: the bioretention runoff from the ratio 5:1 ended at 1:46 hours; ratio 12,5:1 ended at 4:36 hours; ratio 25:1 ended at 4:44 hours; ratio 50:1 ended at 4:50 hours; ratio 75:1 ended at 4:59 hours; and ratio 100:1 ended at 5:08 hours.

As presented in Table 4.2, the ratios are related to the bioretention cell surface area and to the hypothetical catchment area of six different sizes impervious parking lots (10, 25, 50, 100, 150 and 200 m$^2$). In Figure 5.14 **a)** Parking lot runoff from every six different scenarios. **b)** Bioretention cell runoff for every six different scenarios. Disclaimer: the bioretention runoff from the ratio 5:1 ended at 1:46 hours; ratio 12,5:1 ended at 4:36 hours; ratio 25:1 ended at 4:44 hours; ratio 50:1 ended at 4:50 hours; ratio 75:1 ended at 4:59 hours; and ratio 100:1 ended at 5:08 hoursis also possible to see the designed 10-year return period rainfall, for the city of Newcastle.

In the simulation for the ratio 5:1 scenario (solid green), the parking lot starts generating runoff 1 minute after the rainfall beginning, and it shows virtually the same behaviour as the rainfall, with a flashy response to the rain and a runoff peak of 0,24 L/s. There is also some amount of runoff discharged by the bioretention cell underdrain in the beginning of the rainfall. During 10 min, a runoff of 0,06 L/s is freed and then it stops. The runoff remains to zero until the time 01:13. This could be a reflex from the initial saturation percentage of the bioretention cell.

Overall, looking just to the GI runoff performance it is possible to state that it managed impervious runoff efficiently, since there is not any runoff peak and the outflow discharge, apart from the initial outflow, was delayed about 13 minutes after the rainfall ended. Curiously, the peak outflow was the 0,06 L/s (75% reducing efficiency) from the beginning of the rainfall event.

For the 12,5:1 ratio scenario (solid yellow), the rainfall runoff flow has a similar performance as the 10 $m^2$ parking (ratio 5:1). The peak flow value increased from 0,24 to 0,59 L/s. In this 12,5:1 scenario there is also the presence of a 0,06 L/s outflow discharge in the beginning of the rainfall. However, there is a 0,41 L/s peak runoff from the bioretention cell with a runoff peak delay of 3 minutes. After the peak flow the bioretention cell runoff enters in its falling limb, attenuating the rest of remaining outflow discharges. It is possible to state that the runoff peak flow was reduced by 30,5% (0,59 L/s parking lot runoff to 0,41 L/s bioretention cell runoff).

In the third 25:1 ratio scenario (solid black), the runoff from the parking lot remained with the same flashy behaviour related to rainfall intensity, but now with bigger flow values and a bigger peak flow of 1,16 L/s. The initial 0,06 L/s runoff from the bioretention cell it is still the same as the other scenarios as well. The 25:1 ratio scenario presented a bioretention cell peak runoff of 1,12 L/s (a 3,45% reducing efficiency). The runoff peak delay between the parking runoff and the GI runoff is 2 minutes. After its peak flow, the same outflow attenuation previously observed happens and the runoff discharge lasts until 3 hours and 44 minutes after the 1-hr rainfall ends. The disappointing result in this 25:1 ratio scenario is the peak runoff reduction (just 3,45%). A 50 $m^2$ impervious surface begins to generate runoff that makes a peak runoff reduction not so attractive as in the other two previously simulated scenarios.

The parking lot in ratio 50:1 scenario (dashed green) had a peak runoff of 2,32 L/s. The bioretention cell still showed the same 0,06 L/s outflow runoff in the beginning of the event, and the runoff peak delay between both hydrographs decreased to 1 minute, resulting in a flash flow like an impervious surface. However, the GI cannot still be considered ineffective, because the outflow discharges continue up to 3 hours and 50 minutes after the end of the rainfall. Although the bioretention cell still manages to attenuate the outflow discharge, the runoff peak flow was reduced by only 1,72% (2,32 L/s parking peak runoff to 2,28 L/s bioretention cell peak runoff).

The simulated ratio 75:1 scenario (dashed yellow) presented a parking lot peak runoff of 3,41 L/s. The bioretention cell remained discharging 0,06 L/s of outflow in the beginning of the rainfall. The GI peak flow is 3,37 L/s (1,17% reducing efficiency) and the runoff peak delay is 1 minute, as the 50:1 scenario. The outflow discharge after the falling limb increased from 3:50 to 3:59 hours. For the 75:1 scenario as well, the peak runoff reduction can be considered unsatisfactory when compared to the other impervious area ratio simulations, as well as the peak runoff flow.

For the ratio 100:1 scenario (dashed black), the parking lot had a peak runoff of 4,44 L/s. The bioretention cell remained discharging 0,06 L/s of outflow in the beginning of the rainfall. At this point it is possible to conclude that this outflow runoff is not related to the impervious surface runoff generated, but with physical properties of the bioretention cell (maybe the saturation percentage), since all other variables increased their values and their efficiencies reduced as impervious areas were getting bigger, but this GI outflow in the beginning of the rainfall kept the same value and duration. The GI for the ratio 100:1 peak flow is 4,4 L/s (insignificant 0,09% reducing efficiency) and the runoff peak delay is also 1 minute. The outflow discharge after the falling limb was increased by 9 minutes (4:08 hours after rainfall ended).

Since ratio 50:1 scenario (dashed green), the bioretention cell runoff hydrograph is becoming more like the parking lot runoff distribution. In the 100:1 simulated scenario, both runoff hydrographs are basically the same.

Figure 5.15 shows the different cumulative runoffs for all ratio scenarios and Table 5.1 presents important summary results from the impervious parking lot and the bioretention cell.

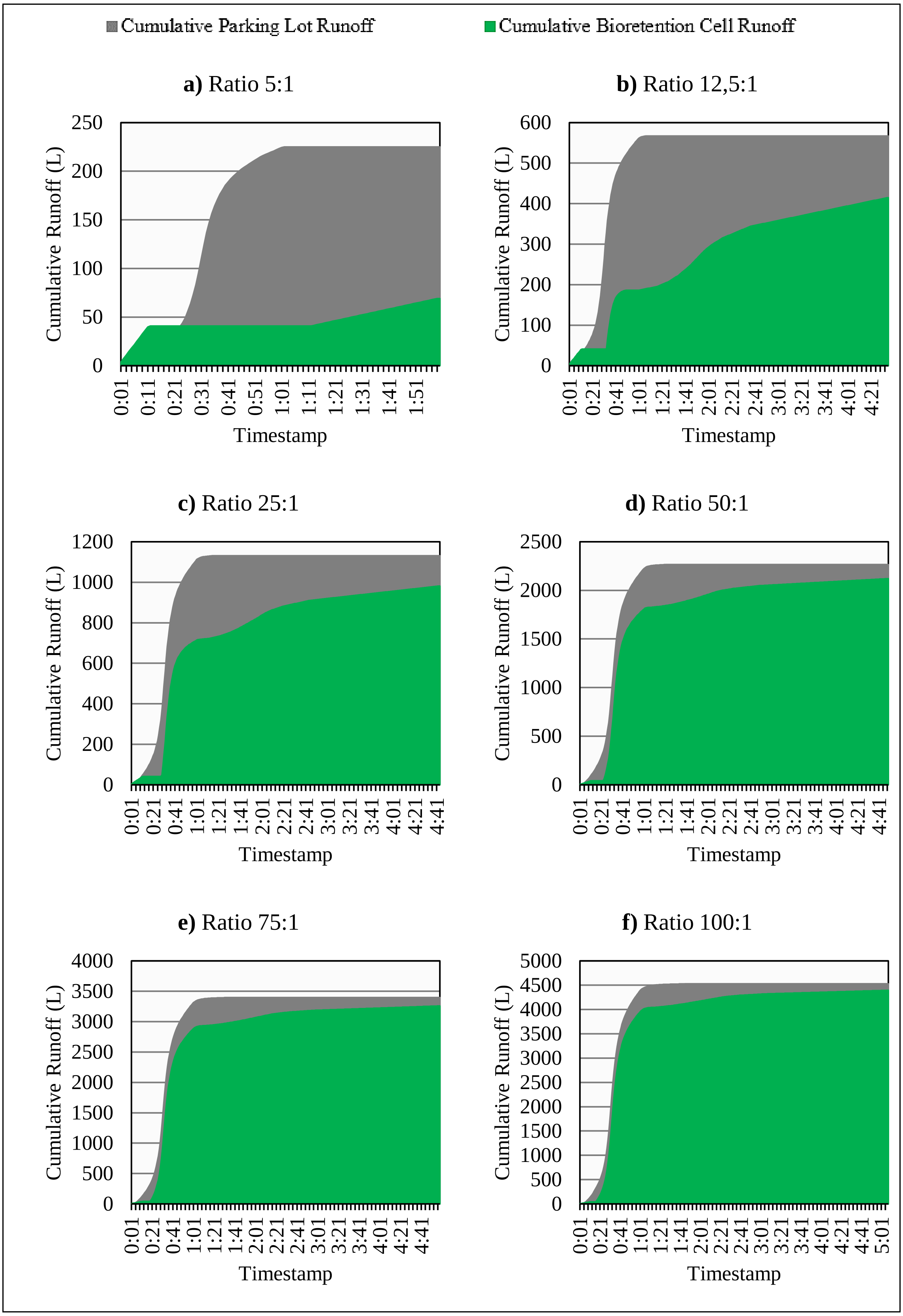


**Figure 5.15** Parking lot and bioretention cell cumulative runoff for the six different ratios scenarios simulated.

**Table 5.1** Parking lot and bioretention cell SWMM summary results for a total rainfall of 22,67 mm.

| Ratio | Impervious surface (m²) | Peak runoff (L/s) | Bioretention cell summary results | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Total runoff (inflow) received (L) | Peak runoff (outflow discharge) (L/s) | Surface overflow (L) | Storage runoff (L) | Drain outflow (L) | Runoff management efficiency (%) | Peak runoff reduction (%) |
| 5:1 | 10 | 0,24 | 272,22 | 0,06 | 0 | 168,66 | 103,7 | 61,91 | 75 |
| 12,5:1 | 25 | 0,59 | 612,5 | 0,41 | 143,92 | 193,74 | 275,06 | 31,6 | 30,51 |
| 25:1 | 50 | 1,16 | 1179,54 | 1,12 | 670,92 | 195,4 | 313,44 | 16,55 | 3,45 |
| 50:1 | 100 | 2,32 | 2313,72 | 2,28 | 1773,64 | 196,6 | 343,7 | 8,49 | 1,72 |
| 75:1 | 150 | 3,41 | 3447,6 | 3,37 | 2876,88 | 198,62 | 372,32 | 5,75 | 1,17 |
| 100:1 | 200 | 4,44 | 4581,26 | 4,4 | 3981,6 | 200,88 | 399,02 | 4,38 | 0,09 |

For the ratio 5:1 scenario, the parking lot generated 272,2 L of runoff volume which was directed to the bioretention cell surface. The GI managed to storage 168,8 L of the impervious inflow, reducing 61,9% of the runoff volume. The bioretention cell did not have any surface overflow.

The impervious area in ratio 12,5:1 simulation generated 612,5 L of runoff volume and the bioretention cell managed to storage 193,74 L of the impervious inflow, reducing 31,60% of its volume. Differently from the previous scenario (5:1), this one showed a surface overflow volume of 143,92 L which was the amount of runoff that passed by the bioretention cell without any management. If this scenario was a real rainfall event, in a real urban area, this overflow volume would be directed to the drainage system. The flashy and high bioretention peak flow probably was caused by this overflow since it is the only different runoff behaviour from the 5:1 impervious area scenario and the outflow discharge attenuation is even similar. Despite runoff management efficiency decreased from the 5:1 ratio scenario (about 30,31% less), its efficiency is better than the real 24,5-hr intense rainfall event from October 2020 (Subchapter 5.1.2).

Scenario 25:1 generated a 1179,54 L impervious runoff volume and the bioretention cell managed to storage 195,40 L of this inflow, reducing 16,55% of the runoff volume. The runoff managing can still be considered a reasonable efficiency since it is only 3,31% lower than the efficiency observed on the real 24,5-hr intense rainfall event from October 2020 (Subchapter 5.1.2). This scenario could represent the boundary impervious-bioretention cell area ratio. The 25:1 ratio also presented a surface overflow volume of 670,92 L. This overflow volume is the alleged responsible for the bioretention cell flashy runoff behaviour (quickly reaches its peak runoff) noted in Figure 5.14, differently from what happens in 5:1 scenario (without overflow) and 12,5:1 scenario (still a small amount of overflow volume). The outflow discharge attenuation still behaves like the other two previously scenarios, but with higher flow values.

For the ratio 50:1 scenario, the parking generated 2313,72 L runoff volume and the bioretention cell managed to storage 196,60 L, reducing 8,49% of the inflow volume. For this scenario the runoff reduction can be considered unsatisfactory when compared to the other impervious area ratio simulations (5:1, 12,5:1 and 25:1). The surface outflow volume for this scenario is high, about 1773 L. The only result that remained the same in all simulated scenarios is the bioretention cell outflow discharge attenuation after its falling limb. Basically, in this simulated scenario the bioretention cell starts to get overwhelmed by the parking lot impervious runoff. However, this scenario results are beyond the design specifications of the GI, it is more related to the 50:1 impervious-bioretention cell ratio. The UK CIRIA SuDS Manual (2015) for example, indicates a 10:1 ratio for bioretention cells, so, this 50:1 ratio is beyond the recommended by literature.

The parking lot in ratio 75:1 scenario generated 3447,60 L of runoff volume and the bioretention cell managed to storage 198,62 L, reducing the volume by 5,75%. The surface outflow volume for this scenario is also very high, 2876,88 L. The outflow discharge attenuation still behaves like the other scenarios after the bioretention cell runoff falling limb.

In the last scenario (ratio 100:1), the parking generated 4.581,26 L of runoff volume and the bioretention cell managed to storage 200,88 L (only 4,38% reducing efficiency). For this scenario, as for the 50:1 and 75:1 ratio, the runoff reduction can be considered unsatisfactory when compared to the other impervious area ratio simulations, the runoff volume is not satisfactory as the first two simulated scenarios (5:1 and 12,5:1), and not even close to the reduction efficiency from the 25:1 ratio simulation (this scenario also had an unattractive peak runoff reduction). The surface outflow volume for this scenario is much higher, 3981,60 L (more than three times the overflow from the ratio 50:1 scenario). The only result that remained the same in all simulated scenarios is the bioretention cell outflow discharge attenuation, after its falling limb.

## 6. Conclusions

Increasing the resilience of urban areas to cope better with flooding, *i.e.*, to maintain their properties, and public and private infrastructures functioning properly during floods, has become increasingly important in a world with more and more population living in urban areas. Also, it is crucial to make space for rainwater, making the urban spaces able to live with it, and no longer treat it as unwanted. To accomplish this difficult task, stormwater management plans can implement one of the best possible urban planning strategies, Green Infrastructure (GI). Stormwater management must fulfill requirements for environmental quality and flood safety, and GI aims to mimic natural processes by improving water management, quality, social, economic and health aspects. GI have both green actions and soft actions, and combining them with grey infrastructures can increase resilience against flooding by de-stressing below-ground traditional drainage infrastructures. However, soft actions still need to go a long way to be implemented efficiently as they involve social and political factors.

This dissertation brought as a successful GI implementation the awarded Spanish city of Vitoria-Gasteiz, where the Green Belt project and execution triggered the City Council to implement other green infrastructures as well. As so, the city managed to improve and correct historical problems regarding urban flooding water quality, preserving its environment and landscapes, and improving biodiversity. The implemented GI was well accepted by the general public, since 99% of the city population agrees that the Green Belt and its GI improved life quality and increased the number of green spaces, parks, and urban gardens. The Vitoria-Gasteiz success can inspire other municipalities to do the same, since, despite the need of hard work, it is possible to implement green and soft GI actions aiming to improve the life of future generations.

Aiming to assess GI stormwater management efficiency, Volumetric Water Content (VWC) data from a real small-scale bioretention cell lysimeter experiment was analysed. Overall, nine months of records were available, in which the bioretention cell received 1.211,2 L of inflow and managed efficiently 52,68% of it. The rainfall event chosen from September 2020 had a total rainfall of 26,2 mm distributed along two days. The GI performed well with rainfall events within the instrumented period, as it did not have any runoff peak and the outflow was delayed by 17 hours. The bioretention cell received a total of 52,4 L of inflow and managed to storage 80,7% of it. The first rainfall period had an 85% efficiency, while the second one (with a total rainfall depth of 5,8 mm) had a 66%

efficiency. In this particular analysis, the rainfall intensity of the first rainfall event, as well as a more saturated soil, negatively influenced the efficiency of the bioretention cell. The impact of this more intense rainfall event can be seen in the difference in inflow management efficiency between the two rainfall periods. In the first period, rainfall was 3,5 times more than in the second, and the efficiency was 85% versus 66% (almost 1,5 times more efficiency). Between the end of the first rainfall period and the beginning of the second one, there are practically 14 hours without any rainfall, and even then, the impact of the first rainfall is observed in the reduction of efficiency.

The rainfall event chosen from October 2020 had a total rainfall depth of 48,6 mm distributed along three days. Also, the chosen period had the most intense rainfall event out of all nine-month data (39,8 mm in 24,5 hours). For these intense 24,5 hours event, the lysimeter responded with a lag time of 8 hours, a 50% runoff peak reduction and an efficiency managing inflow of 28,5%. For all three-days rainfall event, the GI was able to delay the outflow in 12 hours and managed 20% of total 97,2 L inflow volume. For this event, the first intense rainfall could have decreased the experiment efficiency. This October 2020 event was compared to an event from December 2020 where the total rainfall depth was 49,2 mm distributed in four days. Virtually, the rainfall depth was the same, but in the December event rainfall was more uniform along time and less intense. The inflow was 98,4 L and the bioretention cell managed to reduce 25% of the total inflow. Even though knowing the total rainfall depth is important, rainfall intensity was the main property influencing the efficiency of this particular bioretention cell, with an inverse relationship, *i.e.*, the higher the intensity, the lower the efficiency.

The last event, of April 2021, had a total rainfall precipitation of 8 mm distributed in 14 hours. Before this small rainfall event it did not rain for 43 days, so the lysimeter substrate was dry. The lysimeter received 16 L of inflow and discharged an insignificant 100 mL of outflow, resulting in 99% efficiency. After a long period of sunny days, for a small rainfall depth and for intense rainfall events, this particular bioretention cell was able to manage and store most of the rainfall inflow volume.

Results from the different Storm Water Management Model (SWMM) scenarios suggested that the best-found ratio for an optimal impervious-bioretention cell area ratio was 5:1. The 5:1 ratio did not generate runoff peak and surface overflow and efficiently managed 62% of total runoff inflow. However, urban areas are densely urbanised and populated, making it almost impossible to implement such small ratio, where every 5 $m^2$

would need a 1 $m^2$ bioretention cell infrastructure. With that in mind, impervious-bioretention cell area ratios between 12,5:1 and 25:1 can be appropriate solutions for urban areas. The 12,5:1 scenario showed a 30% runoff peak reduction and a 32% runoff volume reduction, and the 25:1 scenario presented a 3,45% runoff peak reduction and a 16,5% runoff volume reduction. These efficiencies are placed between the real lysimeter efficiencies from the October 2020 rainfall event (the most intense registered) and the December 2020 rainfall event (with the same total rainfall depth from October event). Also, both of these ratios can be fitted into the UK CIRIA SuDS Manual (2015), suggesting that GI should be designed for a 10:1 ratio.

Overall, the results, both real and simulated, have demonstrated that bioretention cells are green infrastructures that can help urban areas to manage its urban floods events and increase the flood resilience. The results showed that the bioretention cell analysed can delay runoff peak flow and outflow volume, thus de-stressing traditional drainage systems. The lysimeter analysed is a bare earth unvegetated control, and vegetated bioretention systems are expected to perform more successfully due to the increased losses due to evapotranspiration.

Further work should explore the extent to which evapotranspiration increases drying of GI systems. The possibility of simulating the 1-hr rainfall event used in the SWMM simulations with the rainwater tank for rainfall simulations from the NGIF would be interesting to compare real to simulated results from this dissertation and understand more deeply about this bioretention cell performance and, consequently, about bioretention systems.

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