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Sustainable Urban Drainage: Green roofs

Dissertation presented to obtain the degree of Master in Environment Engineering on the specialty of Territory and Management of the Environment

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ABSTRACT

Recent flooding all over the world have shown how vulnerable are urban areas to extreme hydrologic conditions. Urban sprawl combined with climate change increase rainfall runoff thus causing recurrent flooding. Rebuilding the drainage system may not be efficient or feasible, either technically or economically, to address this problem. Innovative techniques such as green roofs, pervious surfaces, swales, retention basins, among others, mitigate flood peaks thus reducing flood risk, and reduce the concentration of pollutants in rainfall runoff.

In this study is analysed the potential of green roofs in reducing peak flow and rainfall runoff as well as the sustainability of this technology, economically, socially and environmentally. The analysis was performed considering the application of this technology in the Campus II of the University of Coimbra using the hydraulic-hydrological modelling program Storm Water Management Model (SWMM), of the Environmental Protection Agency (EPA) of the United States of America (USA).

Results showed a peak flow reduction of 94-100% and rainfall runoff reduction of approximately 97%, concerning subcatchments with green roofs and by using the Low Impact Development (LID) control tool of SWMM. However, considering the entire area of the case study the reduction is of 13-15% due to the low area available to insert green roofs, in the large area of the case study.

Keywords: green roofs, SWMM, LID control tool, sustainability, reduction of peak flow, reduction of rainfall runoff.

RESUMO

As recentes inundações em todo o mundo mostram a vulnerabilidade dos ambientes urbanos às condições hidrológicas extremas. O aumento da urbanização, sem o devido planeamento, combinado com as alterações climáticas levam ao aumento dos caudais superficiais provocando, assim, recorrentes inundações. Reconstruir o sistema de drenagem para fazer face a este problema pode não ser eficiente ou viável, quer tecnicamente quer economicamente. Técnicas inovadoras como a dos telhados verdes, construção de pavimentos permeáveis, canais abertos com vegetação, bacias de retenção, entre outros, atenuam os picos de cheia, diminuindo o risco de cheia, e reduzem a concentração de poluentes das águas de chuva nas áreas urbanas.

Neste estudo é analisado o potencial dos telhados verdes na redução do pico de cheia e da quantidade de caudal superficial, bem como a sustentabilidade desta tecnologia, economicamente, socialmente e ambientalmente. A análise da redução do pico de cheia e da quantidade de caudal superficial foi efetuada considerando a aplicação desta tecnologia na área do Pólo II da Universidade de Coimbra, recorrendo ao programa de modelação hidráulica-hidrológica Storm Water Management Model (SWMM), da Environmental Protection Agency (EPA) dos Estados Unidos da América (EUA).

Os resultados obtidos indicam uma redução do pico de cheia entre os 94-100%,e da quantidade de caudal superficial em aproximadamente 97%, ao nível da área de telhado verde, ao utilizar a ferramenta de controlo LID. No entanto, do ponto de vista da área de estudo a redução é na ordem dos 13-15% devido à grande dimensão da área de estudo, que possui uma baixa área de telhados que pode ser convertida em telhado verde.

Palavras-chave: telhados verdes, SWMM, ferramenta de controlo LID, sustentabilidade, redução do pico de cheia, redução do caudal de precipitação.

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ACRONYM

BMP – Best Management Practices
CMS – Cubic Meter per Second
EEA – European Environment Agency
GHG – Green House Gas
GI – Green Infrastructure
LID – Low Impact Development
SUDS – Sustainable Urban Drainage System
SWMM – Storm Water Management Model
UHI – Urban Heat Island
WSUD – Water Sensitive Urban Design

1 INTRODUCTION

1.1. Context

Flooding is the most frequent form of natural disaster in the last 20 years and has increased significantly worldwide (Graceson et al., 2013). There are four main types of flooding: fluvial, coastal, groundwater and pluvial; that vary according to their nature. Sayers et al. (2013) mentions that coastal flood occurs due to storm surge, wave overtopping and tsunamis, as well as a result of sea level rises along coastal communities. Groundwater flooding because of the inability for water to continue to soak into the ground mainly in low lying communities. Fluvial flooding is caused by water breaking out of waterways when the amount of water has reached the carrying capacity of that waterway. And pluvial floods as a result of rainfall directly on the urban area. Pluvial flooding is often exacerbated by increased development - water does not have enough room to find its way through an urban environment – or by increased rainfall intensity – becoming more frequent due to climate change. By 2030 the level of urbanisation is expected to reach 83% in developed countries (Mohammad et al., 2012). With the surface in urban areas growing rapidly combined with climate change, urban areas will deal with the increased risk of flooding (due to drainage system surcharge) (Berretta et al., 2014), bringing many problems for residents.

Typically the goal of a drainage system is to convey the excess surface water – through underground pipe systems – away as quickly as possible not having been designed with sustainability in mind. Effective control of rainfall runoff at-source minimises the necessity of large flow structures. In most developed cities, approximately 40-50% of the impervious urban surface area are roofs (Stovin, 2009), existing a great potential to develop green roofs as an at-source solution. According to Stovin (2009) "any technique that reduces the rate and volume of roof runoff has the potential to contribute to improved storm water management".

Green roofs replace traditional black roofs and are minimally invasive. They can enhance evapotranspiration (Marasco et al., 2014), thereby decreasing local air temperatures and pose as a solution to the Urban Heat Island (UHI) effect, as well as reduce rainfall runoff and peak flow, being an at-source detention and retention technology. At the same time increase vegetated areas in cities as many other benefits, regarding water quantity and quality.

1.2. Dissertation goal and motivation

The present dissertation intends to assess the potential of green roofs through a case study in the SWMM software. The goals are:

- literature review and legal background of green roofs up to the present time,
- evaluate the improvement on peak flow by installing green roofs,
- evaluate the improvement on runoff volume by installing green roofs.

In Portugal, green roofs are not an ordinary technology having few examples of this technology, mostly due to the investment that has to be done. The building of Calouste Gulbenkian Foundation, ETAR of Alcântara (Fig 1.1. A) and the Praça de Lisboa in Porto (Fig 1.1. B) are some of the examples of green roofs in Portugal.

Figure 1.1 - Examples of green roofs in Portugal. (A) ETAR of Alcântara, Lisbon (OE@, 2015); (B) Praça de Lisboa, OPorto (Blog@, 2015).

This study can provide a valuable contribution in a sense that can add information to this recent and in need to develop field of study, whether with a literature review that gathers information from several sources about green roofs, whether with the development of the simulation model with the recent tool from SWMM.

1.3. Dissertation structure

This study is divided in 6 chapters:

- chapter 1: is an introduction to the field of study and presents the goal and motivation of this dissertation;
- chapter 2: provides a literature review of green roofs, as well as urban drainage. An overview about the environmental impacts associated to green roofs are also indicated;
- chapter 3: describes the case study and presents the methodology adopted;
- chapter 4: demonstrates an application example of a SWMM simulation;
- chapter 5: shows and contains a critical analysis of the results of the study case;
- chapter 6: analyses the goals accomplished and suggests future work to be developed.

2 LITERATURE REVIEW

The present chapter exposes the current knowledge regarding green roofs providing context to the study made. First is presented urban drainage, the issue to be solved, and how and in which way urbanisation and climate change have influenced it. After that the different terminologies commonly found in the literature are explained and putted into context in order to reduce the confusion that exist due to such diverse terms. Posteriorly the philosophy adopted to address the issue is explained and the technologies that it uses are mentioned, thus introducing green roofs – how they are made, what are they made of, which benefits do they have, what are the disadvantages, among others.

2.1. Urban drainage

2.1.1. Historical context

Traditionally, the excess surface water from built-up areas is drained through constructed channels, natural waterways or underground pipe systems, conveying the water away as quickly as possible and consequently preventing local flooding (Wong, 2007).

The pipe systems can be separate or combined with the sewer system (Sá Marques et Sousa, 2011). Due to the unpredictable load on wastewater treatment, leading sometimes to spills of untreated sewage into receiving watercourses and cause pollution, combined pipe system are no longer used in the construction of new pipe system but exist in some cities, or parts of it, in the world. Separate surface water runoff pipe system is the current approach when building these systems thus the wastewater is piped to the treatment station and the surface water runoff is piped to the nearest watercourse. Although reducing the risk of spills, the separate systems transfer the existing pollutants in the runoff from the urban surface straight to the receiving watercourse and with the growing urbanisation rate the pollutant load in this runoff is also increasing (Woods Ballard, 2007).

2.1.2. Impacts of urbanisation

In 2014 the urban population was 54% of the total global population and is expected to grow approximately 1.84% per year between 2015 and 2020, 1.63% per year between 2020 and 2025 and 1.44% per year between 2025 and 2030 (WHO@, 2015). In Portugal, by 2011, approximately 43% of the population lived in urban areas (PORDATA@, 2015).

As cities sprawl the intrinsic characteristics of the original land and the surrounding areas are altered (Davis and McCuen, 2005). In several situations, forest and open space are replaced by houses, roadways and commercial and industrial areas (Figure 2.1). This transition in land has environmental impacts. For instance watershed storage (interception, infiltration and depression storage) is greatly modified (Figure 2.1), peak flow and runoff increase and water quality decreases.

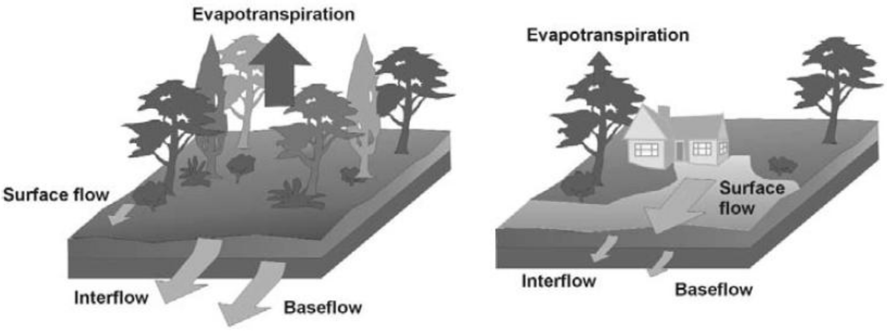


Figure 2.1 – Pre- and post-development changes in water balance (Woods Ballard, 2007).

a) Rainfall runoff

So far urban development is diminishing the permeability of land surface due to the replacement of draining ground with impermeable roads, paved areas and roofs. Roof surfaces are 40-50% of the existent impervious surfaces in the city (Stovin 2009). Figure 2.2 shows how runoff, evapotranspiration, deep infiltration and shallow infiltration percentages are affected while the percentage of impervious surfaces increases.

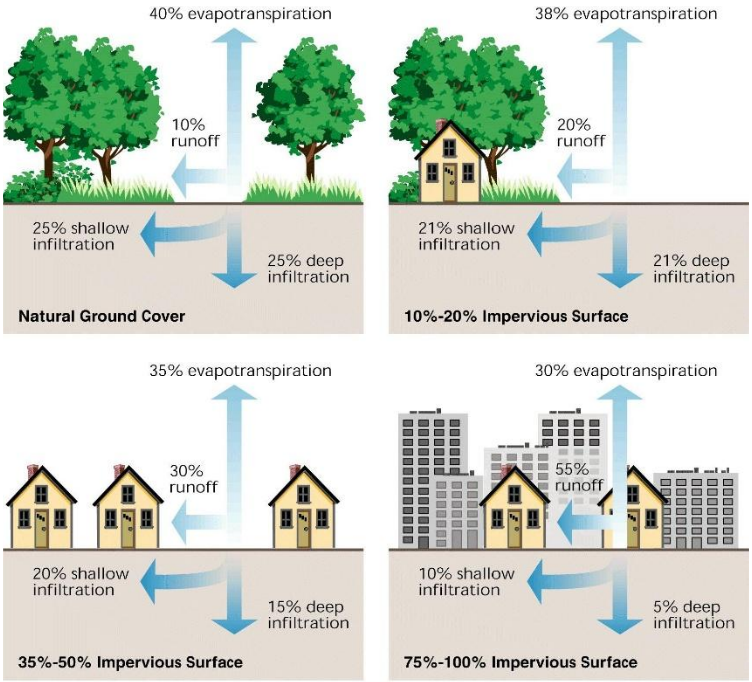


Figure 2.2 - Changes in water balance as impervious surface percentage increases (Auburnhills, 2015).

As can be seen (Figure 2.2), with the increase of impermeable surfaces the runoff percentage also increases whereas shallow infiltration, deep infiltration and evapotranspiration decrease. These alteration to the natural flow patterns can lead to floods or channel erosion downstream of the development (Woods Ballard, 2007) and the increase of the city temperature due to the loss of moisture from the decrease of evapotranspiration, causing the Urban Heat Island (UHI) effect. Figure 2.3 shows the pre- and post-development runoff hydrographs after a storm rainfall event over an urban area.

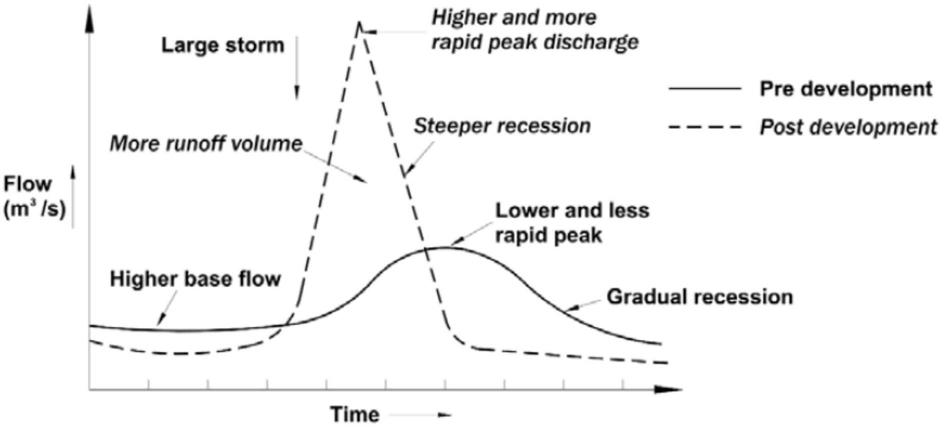


Figure 2.3 - Pre- and post-development runoff hydrographs after a storm rainfall over an urban area (Woods Ballard, 2007).

While grass and forested areas allow 70 to 90% of the rainfall to infiltrate, roofs, sidewalks, driveways and roads do not allow infiltration or only a small amount due to cracks and small openings (Davis and McCuen, 2005). Thus post-development produces more direct runoff from a site at the expense of infiltration, as can be seen (Figure 2.3) the alterations in infiltration also lead to a decrease in percolation which can cause low baseflows in watercourses, reduced aquifer recharge, and damage to in-stream streamside habitats (Woods Ballard, 2007). Table 2.1 summarizes the impacts of development regarding quantity of water.

Table 2.1 - Quantity impacts of development (adapted from Woods Ballard, 2007).

Processes		Impacts
Changes to stream flow	▪ reduced infiltration and evapotranspiration; ▪ rapid urban area drainage; ▪ reduced infiltration, interflow, recharge.	▪ increased runoff volumes; ▪ increased peak runoff rates; ▪ increased downstream flooding; ▪ reduced baseflows.
Changes to stream morphology	▪ increased stream profile instability; ▪ increased erosion rates; ▪ sediment deposition; ▪ increased flow rates and flood frequency; ▪ floodplain development (including in-channel structures, bridges, culverts).	▪ stream widening; ▪ stream erosion; ▪ loss of streamside tree cover; ▪ changes in channel bed profiles.
Impacts to aquatic habitat	▪ Increased flow rates and flood frequency; ▪ loss of riparian vegetation; ▪ increased erosion rates; ▪ sediment deposition; ▪ reduced habitat variability; ▪ reduced baseflows; ▪ stored runoff, from warm urban areas.	▪ degradation to habitat structure; ▪ loss of pool-riffle structure; ▪ increased stream temperatures; ▪ decline in abundance and biodiversity; ▪ sedimentation.

b) Water quality

In developed areas there are numerous sources of pollution: atmospheric deposition, leaks and spillages, litter/animal faeces, illegal disposal of chemicals and oil, etc. When it rains these pollutants are washed into surface water sewers and eventually into rivers, or into groundwater (Woods Ballard, 2007). Also as runoff volumes increase, topsoil and vegetation are lost removing a valuable filtering mechanism for runoff. Table 2.2 summarises the impacts of urbanisation on runoff quality.

Table 2.2 - Quality impacts of development (adapted from Woods Ballard, 2007)

	Processes	Impacts
Water quality impacts	▪ decomposition of organic matter present in runoff; ▪ wash-off of fertiliser, vegetative litter, animal wastes, sewer overflows, sewage spills, detergents; ▪ dash-off of oils, greases, diesel/petrol; ▪ wash-off from industrial and commercial sites, rooftops, vehicles, household chemicals, landfills, hazardous waste sites.	▪ reduced oxygen in receiving waters; ▪ nutrient enrichment (raised nitrogen, phosphorus concentrations); ▪ pathogen contamination; ▪ hydrocarbon contamination; ▪ increased levels of toxic materials (metals, pesticides, cyanides); ▪ raised sediment loads, sedimentation; ▪ raised water temperatures; ▪ litter and debris; ▪ weed and algal growth.

2.1.3. Impacts of climate change

Environmental systems, economic sectors and human health have had several impacts due to climate change. These impacts vary depending on climatic, geographic and social-economic conditions (EEA@, 2015). According to the European Environment Agency (EEA, 2015), “even if greenhouse gas (GHG) emissions were to stop today, climate change would continue for many decades as a result of past emissions and the inertia of the climate system. It is therefore necessary to adapt to the changes that have already occurred and to prepare for plausible scenarios of future climate change”. However, the magnitude rate of climate change depends on future global GHG emissions.

Regarding Europe and the annual mean temperature and annual precipitation, the EEA@ (2015), based on studies, projects for 2071-2100 that average land temperatures over Europe will continue to increase by more than global average temperature. The largest temperature increases will be over eastern and northern Europe in winter, and over southern Europe in summer (Figure 2.4). Annual precipitation will increase in northern Europe and decrease in southern Europe, enhancing the differences between currently wet regions and currently dry regions (Figure 2.4).

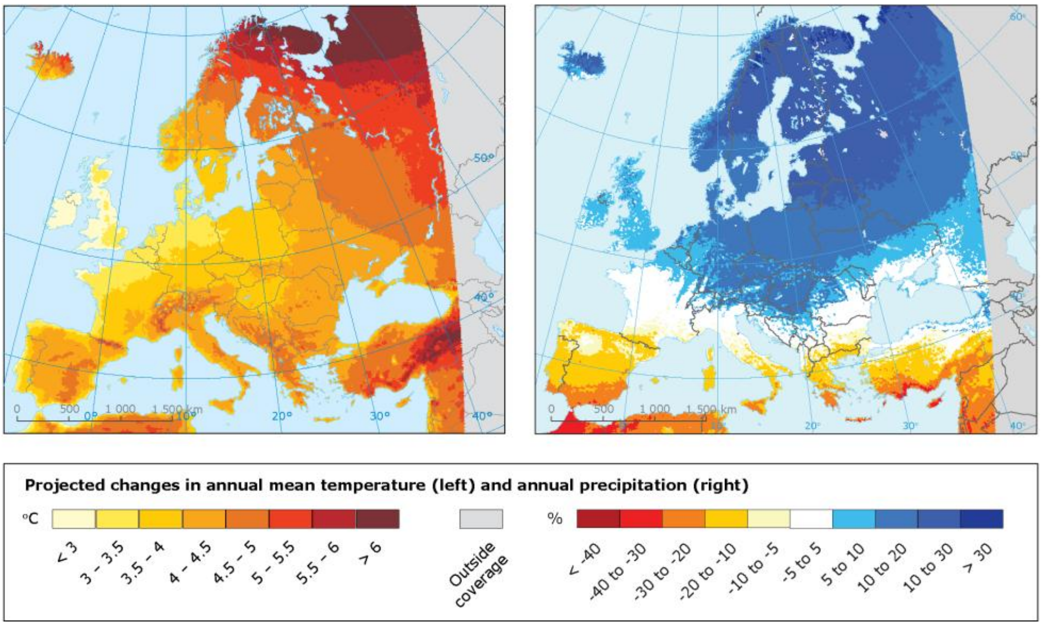


Figure 2.4 - Projected changes in annual mean temperature (left) and annual precipitation (right) (EEA, 2015).

Although the annual precipitation decrease in southern Europe, the intensity of those events will increase. In other words, the number of days with high precipitation is projected to increase (EEA@, 2012). According to Dias (2014), the 5th Assessment Report of the Intergovernmental Panel for Climate Change (IPCC) estimates that, for the Mediterranean region, a precipitation with a return period of 20 years will now occur within 15 to 18 years and that the precipitation intensity will increase 10 to 20% in the future. For a return period of one year it is expected an increase of 20% in the intensity of precipitation whereas a return period of two years an increase of 30% is estimated. These alterations will restrict the behaviour of the urban drainage systems leading to an increase of floods.

2.2. SUDS, LID, BMPs and WSUD

In the last several decades urban drainage has undergone significant change, “moving from an approach largely focussed on flood mitigation and health protection to one in which a wide range of environmental, sanitary, social and economic considerations are taken into account.” (Fletcher et al., 2014). With this evolution several terms such as Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID) techniques, Best Management Practices (BMP) and Water Sensitive Urban Design (WSUD) emerged in several literature related to urban drainage.

The terminology varies according to the country: SUDS is more common in the United Kingdom, WSUD in Australia and LID and BMP in North America. But they all have one thing in common: achieve better urban drainage management. However, WSUD is a philosophy to manage urban drainage whereas SUDS, LIDS and BMP are technologies to achieve that same purpose. This means that WSUD uses SUDS, LID and BMP technologies to achieve its goals.

2.3. Water Sensitive Urban Design (WSUD),

2.3.1. Definition

Water Sensitive Urban Design (WSUD) integrates urban planning with the management, protection and conservation of the urban water cycle, ensuring that urban water management is sensitive to natural hydrological and ecological processes (Wong, 2007).

According to Wong (2007) the International Water Association (IWA)/International Association of Hydraulic Engineering and Research (IAHR) Joint Committee on Urban Drainage state that WSUD “comprises two parts – ‘Water Sensitive’ and ‘Urban Design’. Urban Design is a well recognised field associated with the planning and architectural design of urban environments, covering issues that have traditionally appeared outside of the water field but nevertheless interact or have implications to environmental effects on land and water. WSUD brings ‘sensitivity to water’ into urban design, i.e. it aims to ensure that water is given due prominence within the urban design processes. The words ‘Water Sensitive’ define a new paradigm in integrated urban water cycle management that integrates the various disciplines of engineering and environmental sciences associated with the provision of water services including the protection of aquatic environments in urban areas. Community values and aspirations of urban places necessarily govern urban design decisions and therefore water management practices. Collectively WSUDS integrates the social and physical sciences”.

2.3.2. Principles

“WSUD encompasses all aspects of integrated urban water cycle management, including water supply, water sewerage and storm water management” (Fletcher et al., 2014) and intends to create water sensitive cities that, in the face of population growth and climate change impacts, are sustainable, resilient and liveable.

- Liveable – the comfort capacity of the city (basic needs of water and food; protection from flooding; public health; public safety).
- Resilience – city’s capacity to adapt, withstand and recover from climatic extremes (floods and droughts, heat and pollution).
- Sustainability – carrying capacity of the city. In other words, the city’s ability to sustain (i.e. ecological footprint and planetary boundaries).

2.3.3. Goals

WSUD began to be used in the 1990s in Australia. In 1994 Whelans et al. listed the objectives of WSUD as being (Fletcher et al., 2014):

1. "Manage the water balance (considering groundwater and stream flows, along with flood damage and waterway erosion),
2. Maintain and where possible enhance water quality (including sediment, protection of riparian vegetation, and minimise the export of pollutants to surface and groundwater's),
3. Encourage water conservation (minimizing the import of potable water supply, through the harvesting of storm water and the recycling of wastewater, and reductions in irrigation requirements), and
4. Maintain water-related environmental and recreational opportunities".

However, since 1994, these goals have been reformulated. In 2012, Fletcher et al. presented the following goals:

- "Manage type urban water cycle in a sustainable manner (considering both surface water and ground water, along with flooding and impacts on erosion of waterways),
- Maintain or return the flow regime as close as possible to the natural level,
- Protect and where possible restore water quality (of both surface and ground waters),
- Protect and where possible restore the health of receiving waters,
- Conserve water resources (consider storm water as a resource rather than a nuisance),
- Enhance the urban landscape and amenity by incorporating storm water management measures which offer multiple benefits into the landscape".

2.3.4. Technologies/Infrastructures used by WSUD

WSUD is an approach of planning and design. The planning is made having in mind the community values and aspirations of urban places whereas the design, concerning storm water runoff, is done regarding the best opportunities and multiple benefit outcomes while managing storm water impacts. Green wall, green roofs, bioswales, permeable pavements, among others are examples of Green Infrastructure (GI) used by WSUD. A GI is a tried and tested tool that uses nature to provide ecological, economic and social benefits. In this dissertation only green roofs are studied being analysed in section 2.3.

2.3.5. Benefits of WSUD

WSUD has several benefits (Wong et al., 2013):

- the total storm water runoff decreases and flow regimes for urban waterways improve,
- productive vegetation and increased carbon sequestration,
- air quality improves;
- reduced atmospheric heating,

- reduced daytime heat storage,
- increased shading,
- evapotranspiration increases,
- amenity of the landscape improves,
- urban heat is mitigated and human thermal comfort is improved,
- support vegetation health,
- they are an at-source solution avoiding problems downstream.

Figure 2.5 is a schematic representation WSUD elements at the micro-scale and its benefits.

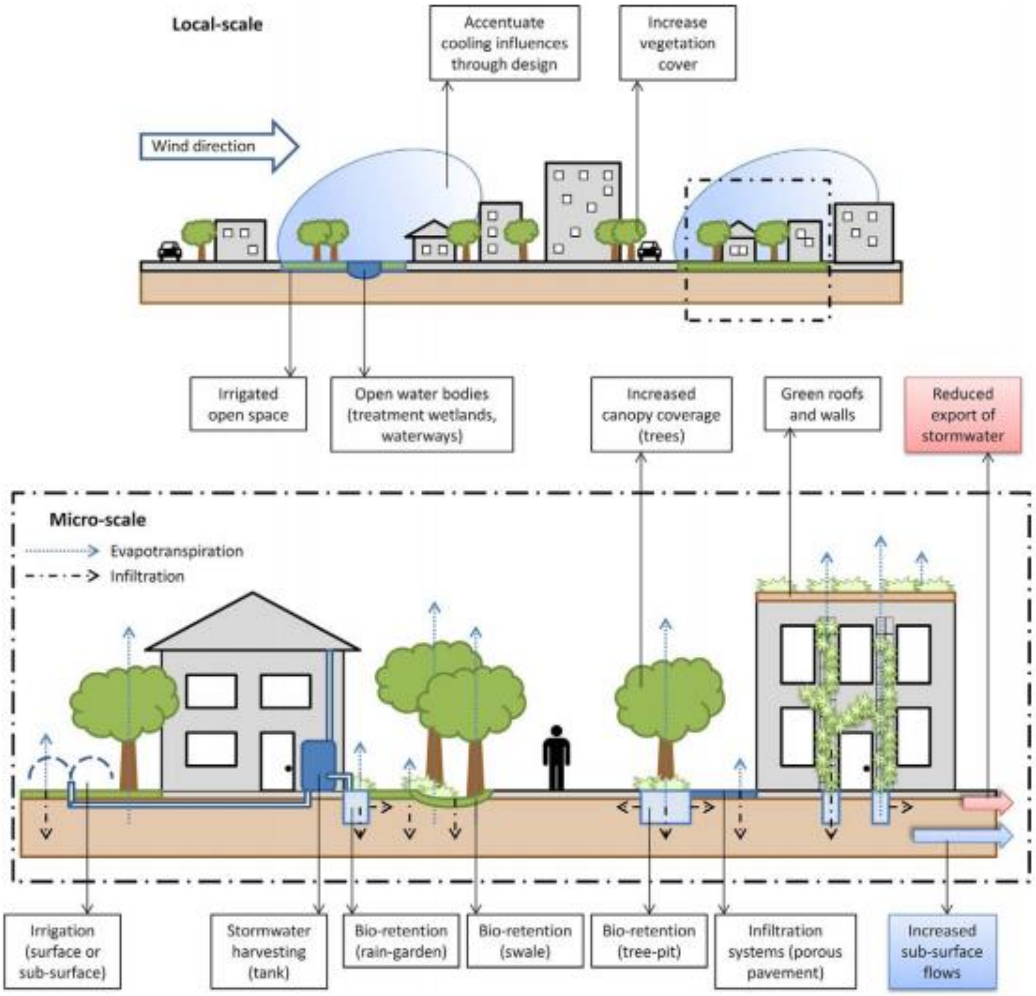


Figure 2.5 – "Schematic representation of widespread implementation of storm water harvesting and Water Sensitive Urban Design elements at the micro-scale in the restoration of a more natural water balance, along with increased vegetation cover." (Coutts et al., 2013).

2.3.6. Difficulties

Although WSUD poses as a good solution there are difficulties when trying to implement this approach. Regulatory framework, technology and design, construction and maintenance practices and community acceptance are recurring impediments to the effective implementation of these designs.

Traditionally water planners are invited to design their systems after transport, industry and energy planning have set the shape and form of the city. WSUD require city and water system planners to work together from the beginning of the planning processes.

2.4. Green roofs

A green roof is an engineered multi-layered structure which covers a building's roof with vegetation (Razzaghmanesh, 2014 and Woods Ballard, 2007). The Chicago City Hall (Figure 2.6 A) and the Ford Motor Company's in River Rouge (USA) (Figure 2.6 B) are examples of green roofs.

Figure 2.6 - Examples of green roofs. (A) Chicago City Hall (Wikipedia@, 2015); (B) Ford Motor Company's (ASG@, 2015).

Several authors have studied and stated benefits regarding the green roof technology however it must be taken into account that those benefits depend on two factors: (i) the green roof characteristics and (ii) the weather conditions concerning the location of the green roof (Berndtsson, 2010). A further analysis of these factors will be made in order to introduce and understand the potential benefits of this technology.

2.4.1. Green roof characteristics

The construction techniques of a green roof are versatile, from the number of layers, the material and thickness of the layer as well as the roof slope, the roof age and position to the way the system is installed: complete system, modular system or pre-cultivated blankets (Table 2.3) (Berardi et al., 2014); there are a number of possibilities and each one influences the outcome benefits.

Table 2.3 - Design construction classification of green roof systems, adapted from Berardi et al. (2014)

	Pre-cultivated system	**Modular system**	**Complete system**
System	Pre-planted	Pre-planted	Layered system
Weight	Low	Average	Generally high
Installation	Simple and fast	Simple and fast	Complex
Maintenance	Simple	Simple	Complex
Cost	Low	Average	High

a) Layered system

The layered system commonly comprises four layers: a waterproofing membrane, a drainage layer, a growing medium or soil layer and a vegetation layer (Figure 2.7) (Berardi et al., 2014) and Woods Ballard (2007)). However other layers are frequently required, such as supplementary filters, a root barrier (between the growing medium and the drainage layer) and an irrigation system (within or above the growing medium).

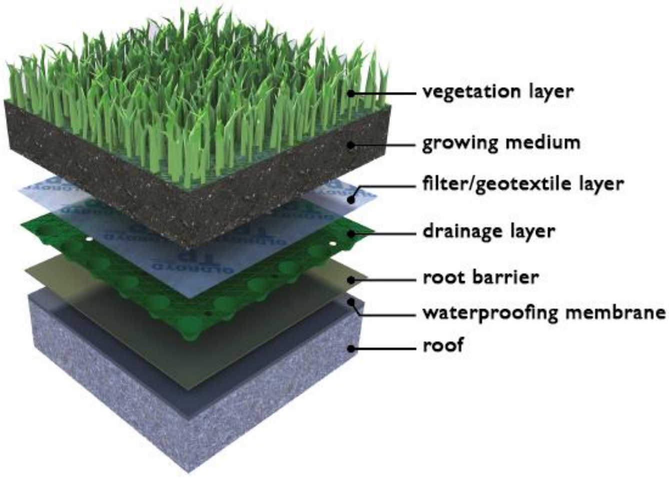


Figure 2.7 - Typical green roof structure (adapted from Safeguard@, 2015).

Waterproofing membrane

Water leakage is one of the main concerns regarding the installation of a green roof since this may compromise the roof structure of the building. It is the waterproofing membrane that stands between the green roof and the roof. This layer is responsible to guarantee that the installation of the green roof won't compromise in anyway the structure of the building. Therefore, as mentioned by (Woods Ballard, 2007), the waterproofing membrane is a vital component of the layer system. It ought to be root resistant and should be properly protected from mechanical damage and temperature changes.

The reliability of the membrane must be taken care since once the green roof is completed repairs are difficult to be (Woods Ballard, 2007).

Root barrier

Intends to protect the waterproofing membrane from roots thus guaranteeing no harm to the membrane (Baldessar 2012 e Silva 2012). Some membranes have root barrier characteristics having then no need to add another layer to the system.

Drainage layer

According to Woods Ballard (2007), located over the waterproofing layer, the drainage layer underlies the entire green roof and is meant to keep the growing medium aerated, to drain the excess water and to hold amounts of water for times of drought, enhancing the retaining capacity of the green roof and acting as a reservoir storage. The flow capacity of the layer must be sufficient to carry the necessary volume of water from the roof and to prevent ponding of water over the waterproofing membrane. Low flow capacity may originate water deposition in the vegetation layer thus enhancing the weight of the green roof system on the roof, dragging of the growing medium and vegetation death by drowning (Silva 2012).

Filter/geotextile layer

Separates the lower part of the growing medium layer from the drainage layer and its purpose is to prevent the loss of soil particles (Berndtsson, 2010) and the clogging of the drainage layer due to small particles from the growing medium layer, allowing water passage (Baldessar, 2012 and Woods Ballard, 2007).

Growing medium or soil layer

The composition of the layer is fitted according to the vegetation layer and must provide for oxygen, nutrient and moisture needs of plants. Its materials need to be low density soils, water permeable, water and air retentive, resistant to rot, heat, frost and shrinkage, chemically and physically stable, high in nutrients and a good rooting medium (Baldessar 2012 and Woods Ballard, 2007).

The soil layer allows the absorption of rainfall, infiltrating and storing the water (Berardi et al., 2014 and Stovin 2009). Several authors' state that this layer is responsible for most of the water retaining capacity of the green roof thus reducing a portion of the runoff, Berndtsson, (2010) refers that the thickness of the soil is one of the characteristics that influences the reduction effect of the runoff. This layer is also the heaviest, needing to be taken into account the load that can be putted into the structure when saturated with water (maximum load expected).

Vegetation layer

The type of vegetation names the type of green roof. There are two main categories (i) intensive and (ii) extensive green roofs and a not so referenced and most commonly not mentioned third category, (iii) simple-intensive (semi-intensive) green roof (Berndtsson, 2010).

(i) Intensive green roof – landscaped environment that is prepared for access and use. Various types of plants can be implemented from lawn and shrubs to trees thus being the type of green roof more complex and with more depth of soil layer (Figure 2.8, C);

(ii) Extensive green roof – typically cover the entire roof area with low growing, maintenance and water needs plants such as moss or *sedum* (Figure 2.8, A). Their construction process is technically simple and uses a thin layer of soil. Can be implemented in sloped roofs;

(iii) Simple-intensive – combination of extensive with intensive green roof characteristics (Figure 2.8, B).

Figure 2.8 - Different types of green roofs. (A) extensive green roof (Neoturf@, 2015); (B) simple-intensive (IGRA (a), 2015) ; (C) intensive green roof (IGRA (b), 2015).

Table 2.4 synopsis the types of green roof:

Table 2.4 - Synopsis of the green roof types, adapted from IGRA(c)@(2015).

	Type of green roof:		
	Extensive	**Semi-Intensive**	**Intensive**
Maintenance	Low	Periodically	High
Irrigation	No	Periodically	Regularly
Plant communities	Moss, Sedum, Herbs and Grasses	Grass, Herbs and Shrubs	Lawn or Perennials, Shrubs and Trees
System build-up height (mm)	60 - 200	120 - 250	>150 (above 300 may require reinforced structure)
Weight (kg/m^2)	60 - 150	120 - 200	180 - 500
Accessibility	Inaccessible (fragile roots)	-	Accessible
Use	Ecological protection layer	Designed Green Roof	Park like garden/recreation purpose
Costs	Low	Middle	High

The following Table 2.5 presents a comparison of extensive and intensive green roof systems.

Table 2.5 - Comparison of extensive and intensive green roof systems adapted from Woods Ballard (2007).

	Extensive green roof	**Intensive green roof**
Advantages	▪ Lightweight: generally not requiring significant structural reinforcement; ▪ Suitable for large areas; ▪ Low maintenance and long life; ▪ Little or no need of irrigation and specialised drainage systems; ▪ Less technical expertise required; ▪ Often suitable for retrofits; ▪ Vegetation self-management; ▪ Relatively inexpensive; ▪ Looks more natural; ▪ Easier for planning authority to demand as a condition of planning; ▪ Storm water retention.	▪ Greater diversity of plants and habitats; ▪ Good insulation properties; ▪ Can simulate a wildlife garden; ▪ Can be made very attractive; ▪ Often accessible, with opportunities for recreation and amenity benefits; ▪ High energy efficiency and good storm water retention capability; ▪ Longer membrane life.
Disadvantages	▪ Limited plant variety and ecological value; ▪ Limited or negative aesthetic benefits;	▪ Greater loading on roof structure; ▪ Need for irrigation and drainage systems requiring energy, water, materials; ▪ Higher capital and maintenance costs; ▪ Frequent maintenance required; ▪ Greater technical expertise required to implement and operate.

b) Roof slope

According to IGRA(c)@ (2015), only roofs with slope over 10° need to have special technical precautions in order to mitigate the existing shear forces and erosion. Roofs with a slope of less than 2% are likely to develop puddles thus needing specific arrangements for the roof drainage. If the slope of a roof is more than 45° then it is not suitable to implement a green roof. When in the presence of slope the green roof should be extensive whereas intensive roofs should be relatively flat (EPA (a)).

c) Roof age and position

With time the vegetated layer undergoes various chemical and physical changes: organic content may increase, the porosity of the soil changes, soil particles may be lost, dissolvable substances are washed off with water (Berndtsson, 2010).

Wind and sunlight position also influence the green roof system. Wind can compromise the security of the structure and the vegetation layer. Sunlight influences the evapotranspiration rate, the photosynthesis and the growing of the plants thus affecting the maintenance and the benefits that can be taken from this technology since the vegetation layer has a major role in this advantages as will be further explained.

2.4.2. Weather conditions

Season/climate (air temperature, wind conditions and humidity), characteristics of rain event (intensity and duration) influence the entire green roof system (Stovin 2009), from the type of vegetation to be used to the type of drainage system and layer.

2.4.3. Benefits of green roofs

Mostly, green roofs have been developed for their benefits in retaining precipitation, reducing the volume of runoff and attenuating peak flows. However, several other benefits have been found to be associated to this technology. Table 2.6 presents in a brief manner the environmental benefits of green roofs. These benefits will be further analysed in order to better understand them and how their beneficial can vary according to the green roof system.

Table 2.6 - Environmental benefits of green roofs, adapted from Berardi et al. (2014).

Environmental benefits of green roofs	
Water management	Storm water management Enhanced water runoff quality Improved use of rainwater Enhancement of urban hydrology
Energy consumption reduction	Decreasing cooling and heating loads Improvement of air temperature
Urban heat island	Decrease of the urban heat island effect Reduction of carbon footprints
Air pollution mitigation	Enhanced urban air quality Mitigation of air pollution
Sound absorption	Sound insulation Noise absorption
Ecological preservation	Reduction of habitat lost Biodiversity and improved landscape

Water management

Considered as a Sustainable Urban Drainage System (SUDS) green roofs benefits are mainly associated with the improvement in water management (e.g. storm water management and enhancement of the water runoff quality).

a) Storm water management

Underground pipe systems have been the traditional drainage systems for excess surface water from urban areas, conveying the water away as quickly as possible. However due to the increase of impervious areas caused by urbanisation and the rain precipitation intensities and frequencies as a result of climate change these drainage systems are facing difficulties in managing such amount of water. Green roofs present as a solution because they can capture some of the precipitation and delay the peak flow, avoiding the pipe systems to be overflown, since the enlargement of the pipe system would be physically and economically not feasible.

Acting at-source, many studies have demonstrated the benefits of this technology in storm water management, they can reduce storm water runoff in the order of 40-100% of the total rainfall (Berardi et al 2014; Fletcher et al. 2013 and Mohammad et al 2012);However the reduction depends on the type of roof system, growing medium depth and composition, vegetation layer (e.g. extensive or intensive), roof slope, the intensity and duration of the rainfall, the climate conditions and the green roof design, thus the large range of possibilities in the percentage of runoff that can be reduced. Figure 2.9 compares the runoff between a conventional roof and a green roof during a rainfall event whereas Figure 2.10 schematises the impact of this technology on the resulting hydrograph.

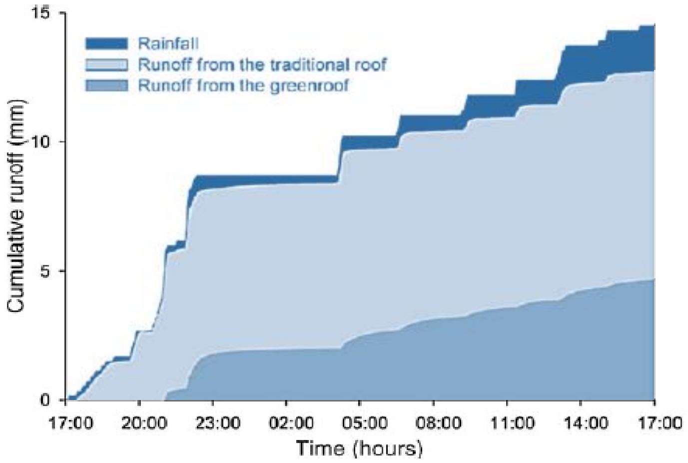


Figure 2.9 - Comparison of the runoff between a conventional roof and a green roof during a rainfall event (Mentens et al. 2005).

Though the amount of storm water runoff that can be reduced by a green roof is not very accurate, the peak flow that can be reduced has a smaller range of possibilities. 60-80% seems to be very consensual amongst experts of the area (Bengtsson et al. 2005; VanWoert et al 2005). This impact in the runoff hydrograph can be perceptible in Figure 2.10. The peak flow also varies with the green roof design for instance extensive roofs have obtained a peak runoff reduction of approximately 57% whereas intensive roofs have verified a reduction to 71,7% (Kikuchi and Koshimizu 2013).

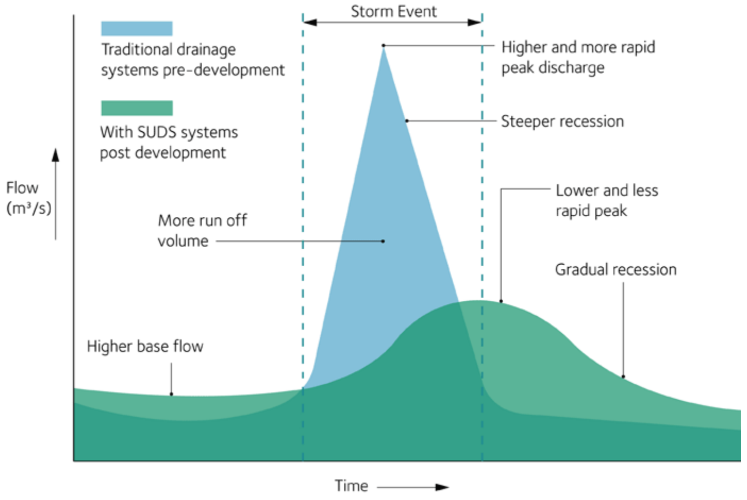


Figure 2.10 - Schematic rainfall runoff response comparison between traditional drainage systems and SUDS systems (Permcalc@, 2015).

As mentioned, several characteristics influence the green roof outcome. Regarding the climatic effect it has been shown that in the winter the green roof is less efficient whereas the summer. This is due to the bigger precipitation associated with winter that saturates the soil and plants and thus lessens the retaining capability of the technology whereas in the summer due to the less precipitation usually verified the retaining capability enhances in comparison with the winter season (Silva 2012).

b) Enhanced water runoff quality

In urban areas pollutants do not come from a single source or activity, but are a result of all the land use and human activity – urban diffuse pollution - (Woods Ballard, 2007). When precipitation occurs these pollutants are washed into the drainage system that eventually leads to rivers, or into groundwater. Usually the initial runoff from impervious surfaces after a dry period is more contaminated than the subsequent runoff due to the accumulation of atmospheric particles and debris such as leaves, bird droppings, and vegetation (Berndtsson, 2010). This “first flush” is recognized to have low water standards. Thus, conventional roof tops surfaces are significant sources of storm water pollutants (Stovin 2009). However, Bliss et al. (2009) found no signs of first flush effect on green roofs.

Also, one of the main concerns in urban areas is acid rain. According to several authors (Bliss et al., 2009; Berndtsson et al., 2009; Teemusk and Mander, 2007) green roofs are mitigating mild acid rain since they increase pH levels from values between 5 and 6 in rain water to over 7 and 8 in the green roof runoff water.

Regarding heavy metals, these concentrations are generally lower than in urban runoff from conventional roof tops (Berndtsson et al. 2009).

Even though numerous benefits in water quality are granted to green roofs there are concerns about their contribution to the release of nutrients (e.g. phosphorus and nitrogen) linked to the use of fertilizers and soil material (Berndtsson, 2010). However it is mentioned that this is only verified in the first years of age of the roof and that subsequently an annual loss of these nutrients are lost. Further research should be developed to better understand this contribution.

The green roof components and nutrition concentrations vary the specific nature of the runoff.

Energy consumption reduction

Both in warm or cold climates, green roofs are highly efficient in reducing the variation of indoor temperature and decreasing the level of building energy consumption. The building characteristics play an important role, the better the insulation of the roof, the lower the contribution of the green roof. In summer the heat gain decreases due to the shading cover and by preventing the direct influence of solar radiations, approximately 70-90%, whereas in winter heat loss decreased due to the insulation effect, approximately 10-30%. However these results vary according to the soil material and depth and the vegetation layer plants (e.g. coverage ratio and leaf thickness) (Berardi et al., 2014).

Figure 2.11 presents a thermal scan of a conventional roof and a green roof, the temperature difference is clear between them.

Figure 2.11 - Thermal scan of a conventional roof and a green roof (EPA a, 2008).

Urban heat island

The urban heat island (UHI) effect is a phenomenon in which urban areas experience warmer temperatures than their surrounding countryside (EPA b, 2008). This occurs due to the large areas of hard reflective surfaces (typically with an albedo of 0.1 to 0.2) existent on urban areas which absorb solar radiation and reflect this heat back into the atmosphere (EFB 2015). According to IGRA (2015), the UHI effect drastically reduce the quality of life and impairs health of the city’s inhabitants and in summer the UHI effect can reach nearly 10°C.

Since the albedo of green roofs ranges from 0.7 to 0.85 (Berardi et al., 2014), they can be a solution to this problem. The vegetation layer absorbs the heat and then uses it through evapotranspiration, humidifying the dry existing air. However the highest impacts on the UHI effect from green roofs occurred in the hottest and driest climates (EFB 2015).

Air pollution mitigation

There have been studies that state air pollution mitigation regarding the use of green roofs being intensive green roofs the most efficient in this field due to its type of vegetation, Currie and Bass (2005) refer that trees are the most influential plants for reducing air pollution (NO_x, SO_2 and PM_{10}). Currie and Bass (2005) and Deutsch et al (2005) both confirm the potential of green roofs for pollution removal based on an urban forest effect model with Currie and Bass (2005) referring that 109 ha of green roofs would contribute to 7,87 metric tons of air pollution removal per year. Also by reducing the UHI effect and the building energy consumption, green roofs indirectly decrease air pollution.

Sound absorption

The vegetation layer and the growing medium present a high absorption coefficient and therefore considerably reduce the noises at street level in urban areas. Connelly and Hodgson (2008) made an empirical analysis and concluded that green roofs decrease the sound level from 5 to 13 dB at low and mid frequencies, and from 2 dB to 8 dB at high frequencies.

Ecological preservation

It has been indicated that green roofs, mostly large-scale, enhance the environment quality and ecological preservation by reducing the habitat lost due to urbanisation and by improving the landscape. However it is difficult to measure those benefits.

Economic benefits

The green roof system, in particular the type of plants influences the economic feasibility of the system. However, in a long term, green roofs are feasible due to the economic gains in the energy saving and the expected endurance of the waterproofing membrane that is superior than a normal roof layer thus not needing an intervention to the building structure earlier than in average 50 years (Berardi et. al, 2014).

2.4.4. Disadvantages of green roofs

Although presenting as a promising solution for several issues in urban areas, green roofs also have characteristics that should be taken into account.

Waterproofing integrity

As mentioned earlier, the waterproofing membrane is one of the most important. If this layer is compromised the green roof system is bound to development problems and is also compromising the building structure. To ensure quality control a thorough water flood test needs to be conducted for leaks after installing it.

Load induced by the structure

The green roof system represents extra load to the buildings structure therefore its weight must be taken into account when projecting the building and in already existing buildings extra care must be taken in order to understand if it is capable to support this extra load.

Maintenance

Although extensive roofs are design to have little or no maintenance some is recommended in order to verify the correct functioning of the system (e.g. weed control and irrigation system). For intensive roofs the maintenance is more regular due to the maintenance demand of its vegetation layer.

Resistance

Mostly in intensive roofs, the wind shear and negative wind pressures may compromise the resistance of the layers thus a correct installation and taking into account these criteria must be made.

Vegetation layer

As several times mentioned, the vegetation layer plays an important role in the green roof system. However, this role cannot be performed if the plants are not suitable to the climate region and to the growing medium layer characteristics (e.g. depth and materials).

Expertise

The use of green roofs is becoming more frequent and present in our lives, however there are lacking experts for this technology which influences the costs associated to this technology and may imply low quality green roofs systems.

Economic

The high costs of this technology due to the lack of experts and the type of material are delaying its widespread. However it is expected that with an increase in experts and in demands for this systems the prices will decrease since the materials will be produced in mass scale thus reducing the production costs. Currently the price of an extensive roof is 55 €/m^2, whereas an intensive is hard to determine since it depends on the complexity that is envisioned for that roof.

Although green roofs system have so much benefits most of them are difficult to economically quantify their value thus being difficult to appeal to this technology and to accurately determine their economic benefit.

2.4.5. Legal background of green roofs

According to Woods Ballard (2007), the European Union (EU) Water Framework Directive precludes the use of the traditional approach to drainage since this framework intends that all discharges of urban runoff must be managed so that their impact on the receiving environment is mitigated. In Portugal this framework was transposed into the national legislation in 2005 (Law no. 58/2005, December 29th). Regarding green roofs, at the current time, there is no legislation or regulation for the EU. However, through Europe we can see a development on this subject.

On May 6th of 2013 the European Commission (EC@, 2015) issued a press release in which states that a new strategy was adopted by the EC, a strategy that encourages the use of green infrastructure (GI) to ensure that the enhancement of natural processes becomes a systematic part of spatial planning. The strategy intends to: promote green infrastructure in the main policy areas, improve research and data, improve access to finance for GI projects and to support European Union-level GI projects.

Regarding regulation, the first ever originated in Germany in the decade of 1980-1990 (Ngan, 2004). In 2007, Germany was supporting the construction of 13.5 million m^2 of green roofs per year (Oberndorfer 2007). The policies of Esselingen, Darmstadt and Munich are examples of how this country is the number one in this technology. Esselingen pays the owners 50% of the costs of green roofs, in Darmstadt users can receive a maximum of 5 000 € for planting a green roof and in Munich all suitable flat roofs with a surface area >100 m^2 are obliged to be landscape. Nowadays, the German FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau) publishes guides for the understanding of green roof being updated and improved since the beginning and are used and referenced in numerous other guides from other countries. More recently, on 19th of March, France passed a law that requires new commercial buildings to have partially covered roofs with green roofs or solar panels (TheGuardian, 2015)

Worldwide there have been policies in favour of green roofs: a law in Tokyo requires that built areas larger than 1000 m^2 and in public buildings with built areas larger than 250 m^2 green roofs must be installed; in Basel, Switzerland users are repaid 20% of the cost of a green roof; In Toronto, Canada, policies were developed to promote green roofs in buildings with the ratio of 50-70% of the entire building coverage; In the United States of America, some states also developed policies, for instance New York City gives an one year tax credit for green roofs that encompass at least 50% of available roof space (Berardi et al., 2014). As can be seen, the existing legal policies are at a city level and not at a national level, each city has its own documents and initiative.

3 METHODOLOGY

Green roofs are a technology that still need to develop research in order to better understand and quantify its benefits due to the large amount of variables that can influence the behave and the efficiency in several aspects, as can be perceived in section 2.

This study will focus on the action of green roofs in reducing the peak flow and the quantity of rainfall runoff that can be retained by it. The current chapter contains the methods and materials used to determine the mentioned benefits. Two case study were made resorting to the Storm Water Management Model.

3.1. Storm Water Management Model (SWMM)

Storm Water Management Model (SWMM) is a dynamic hydrology-hydraulic water quality simulation model developed by the United States Environmental Protection Agency (EPA) and is used for planning, analysis and design, mainly in urban areas, of storm water runoff, combined and sanitary sewers and other drainage systems. SWMM can be used for single event or long-term (continuous) simulation of runoff quantity and quality. The runoff component operates on a collection of sub catchment areas that receive precipitation and generate runoff and pollutant loads. This enables to track the quantity and quality runoff made within each sub catchment during a simulation period in each pipe and channel (Rossman, 2010).

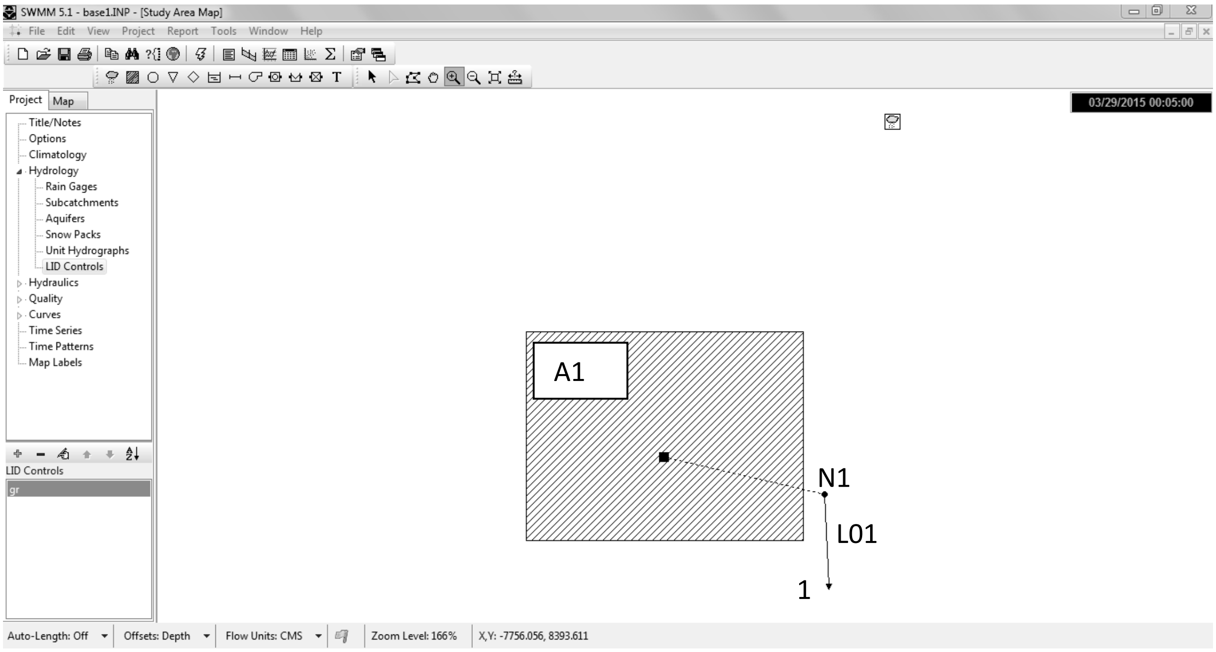
The latest version 5.1. allows to model the hydrologic performance of specific types of green infrastructure (GI) such as green roofs and was released in March 2014. This new tool allows engineers and planners to determine GI effectiveness in managing storm water and will be used for the purpose of this dissertation regarding storm water runoff and peak flow.

3.2. Case study I

In order to understand how the LID control tool influences a simulation model a simple application example was made. First of all, a search was done to discover the typical range for each of the parameters of the LID tool. Secondly, several scenarios of study were developed in order to understand how parameters influence the outcomes. Also a scenario without LID but by assuming 25% imperviousness in the roof in order to simulate a green roof was made, this is a simplified approach to the introduction of green roofs.

3.2.1. Simulation data for case study I

The application example is a simple simulation model – 1 subcatchment (A1), 2 nodes (N1 and Outfall 1) and 1 conduits (L01) – based on an UNESCO-IHE SWMM tutorial (SWMM quick start tutorial, 2015). Figure 3.1 is a screen shot of the model.



Auto-Length: Off | Offsets: Depth | Flow Units: CMS | Zoom Level: 166% | X,Y: -7756.056, 8393.611

Figure 3.1 - Screen shot of the SWMM model used to determine how the parameter of LID control tool influences the outcome - case study I.

The data used for the subcatchment is exposed in Table 3.1, the nodes' information is in Table 3.2, the outfall data is in Table 3.3, the conduit information is in Table 3.4 and the time event simulated is in Table 3.5.

Table 3.1 - Input parameters of the subcatchment for case study I.

	Subcatchment	A1
Subcatchment	**Outlet**	N1
	Area (ha)	1
	% Imperv	60
	Width	50
	%slope	2
Subareas	**N-Imperv**	0.01
	N-Perv	0.1
	S-Imperv	1.25
	S-Perv	0.05
	PctZero	25
	Routeto	OUTLET
Infiltration	**Max Rate**	83
	Min Rate	0.5
	Decay	7
	Dry Time	7
	Max Infil	0

Table 3.2 - Nodes input parameters for case study I.

Node	N1
Invert (m)	17.159
MaxDepth (m)	1.80
Initdepth	0
SurDepth	0
Aponded	0

Table 3.3 - Outfall input data for case study I.

Outfall	Invert	Type	Gated
1	17	FREE	NO

Table 3.4 - Conduits input data for case study I.

Conduits	L01
From Node	N1
To Node	1
Length	20
Roughness	0.01
Inoffset	0
Outoffset	0
InitFlow	0
MaxFlow	0
Shape	Circular
Geom1 (diameter)	0.5

Table 3.5 - Time event information for case study I.

	Time (h:m)	Precipitation (mm/h)
Rainfall	00:00	11.57
	00:05	12.16
	00:10	12.85
	00:15	13.67
	00:20	14.65
	00:25	15.87
	00:30	17.43
	00:35	19.54
	00:40	22.58
	00:45	27.54
	00:50	37.93
	00:55	133.67
	01:00	50.45
	01:05	31.56
	01:10	24.71
	01:15	20.9
	01:20	18.4
	01:25	16.6
	01:30	15.23
	01:35	14.14
	01:40	13.24
	01:45	12.49
	01:50	11.85
	01:55	11.3
	02:00	0

3.2.2. Scenarios of study

In order to understand how each parameter of the LID control tool influences the outcome several scenarios were studied. A scenario with the default parameters of the LID control tool of SWMM was made, as well as several other scenarios considering the existing data range for each parameter, according to Rossman (2010). This allowed to better analyse which model specifications benefit most the installation of green roofs. Only the scenarios with the best outcomes will be here presented since several scenarios were created and developed and some did not show differences between them or from the default parameters model.

Scenario 1

Simulation model with the data from Table 3.1 to 3.5.

Scenario 2

Simulation model with the same data as in scenario 1 but with the information that roofs now have 25% imperviousness in order to simulate the existence of a green roof, a simplified approach.

Scenario 3

Simulation model with the same information as in scenario 1 but with the introduction of the LID control tool in subcatchment A1. The data for this LID is in Table 3.6 and is the default charactheristics of SWMM for green roofs LID control tool.

Table 3.6 - LID control tool data for case study I.

Layer	Parameter	Value	Unit
Surface	Berm height	0	mm
	Vegetation Volume Fraction	0	
	Roughness (mannings n)	0.1	
	Surface slope (percent)	1	
Soil	Thickness	12	mm
	Porosity (volume fraction)	0.5	
	Field Capacity (volume fraction)	0.2	
	Wilting Point (volume fraction)	0.1	
	Conductivity	0.5	mm/h
	Conductivity Slope	10	
Drainage Mat	Thickness	3	mm
	Void Fraction	0.5	
	Roughness (mannings n)	0.1	

Scenario 4

Simulation model equal to scenario 3 but with a berm height of 20 mm.

Scenario 5

Simulation model equal to scenario 3 but with a berm height of 30 mm.

Scenario 6

Simulation model equal to scenario 3 but with a berm height of 50 mm.

Scenario 7

Simulation model equal to scenario 3 but with a berm height of 30 mm and a soil thickness of 75 mm.

Scenario 8

Simulation model equal to scenario 3 but with a berm height of 30 mm and a soil thickness of 150 mm.

According to Rossman (2010), the berm height is the height of the confining walls or berms, being the maximum depth to which water can pond above the surface of the unit before overflow.

3.2.3. LID placement

In order to understand how the LID tool influences the outcome we need to understand how the tool works. The LID controls can be inserted by two different approaches: (1) “place one or more controls in an existing subcatchment that will displace an equal amount of non-LID area from the subcatchment”, (2) “create a new subcatchment devoted entirely to just a single LID practice” (Rossman, 2010). Figure 3.2 shows the before and after of LIDs in a subcatchment.

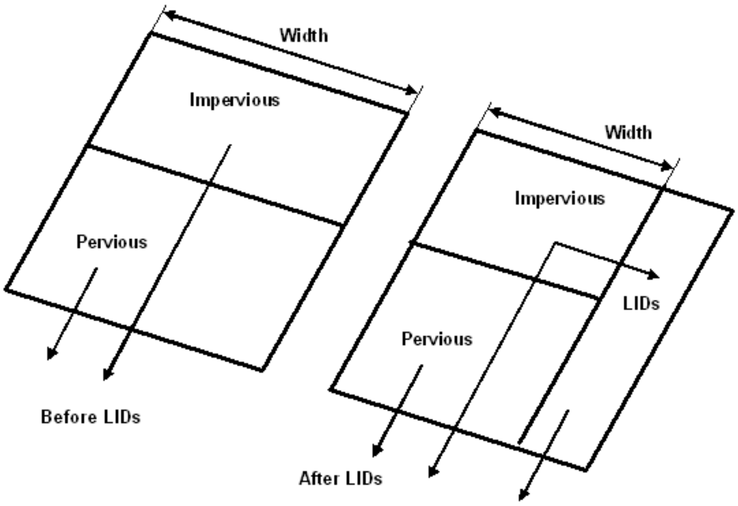


Figure 3.2 - Before and after adding LIDs to a subcatchment (Rossman, 2010).

“The first approach allows a mix of LIDs to be placed into a subcatchment each treating a different portion of the runoff generated from the non-LID fraction of the subcatchment. Note that under this option the subcatchment's LIDs act in parallel – it is not possible to make them act in series” (Rossman, 2010). For the application example and for the case study the first approach will be used, considering that the LID occupies the entire area of subcatchment. Concerning the LID tool of green roof, Figure 3.3 shows how SWMM assumes a green roof model.

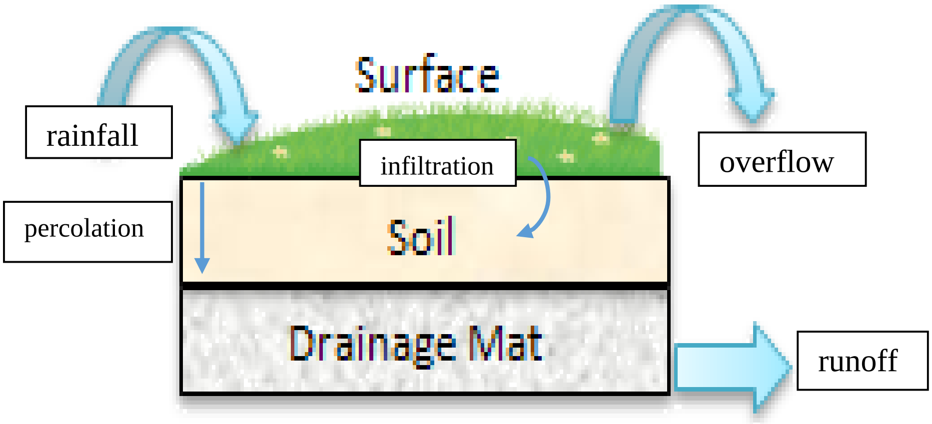


Figure 3.3 - Green roof representation in SWMM (adapted from Rossman, 2010).

3.3. Case study II

The potential use of green roofs to reduce peak flow and rainfall runoff will be studied in the Campus II of the University of Coimbra. Due to its plain roof architecture there is a lot of roof space available to install green roofs. Combined with the transformations made to the initial landscape, forest area converted into roads and facilities' buildings, the Campus is a good case study.

The current landscape of the Campus can be seen in Figure 3.4, the pink and dark blue lines represent the urban drainage system studied. As mentioned, it is composed by roads, facilities' buildings and also green areas, such as meadows, having preserved some of the initial forest.

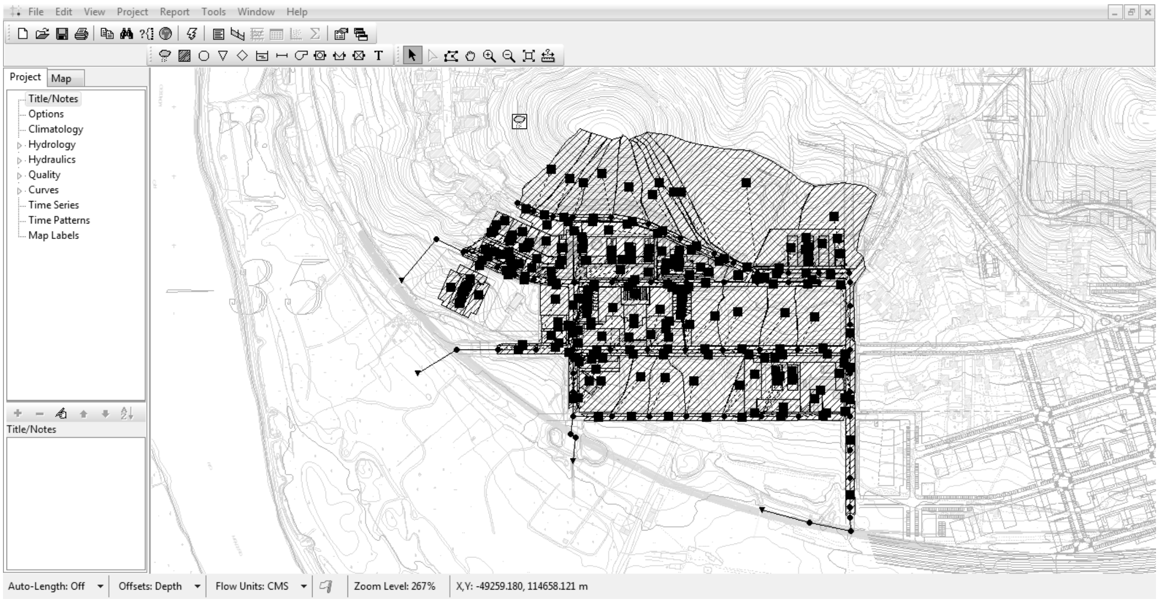
Figure 3.4 – Still of Campus II of the University of Coimbra.

In terms of percentage, only approximately 12,2 % of the entire area of study will be converted into green roofs as will be further mentioned and explained. Figure 3.5 shows a representation of the roofs that will be converted into green roofs from the still of Campus II of the University of Coimbra.

Figure 3.5 – Still of Campus II of the University of Coimbra with a representation of the roofs that will be converted into green roofs.

3.3.1. Simulation data for case study II

For this study a meticulous SWMM model was constructed. The detailed model includes 256 subcatchments, 62 conduits, 62 nodes and 4 outfalls. Figure 3.6 shows a screen shot of this model.



Auto-Length: Off
Offsets: Depth
Flow Units: CMS
Zoom Level: 267%
X,Y: -49259.180, 114658.121 m

Figure 3.6. - Screen shot of the SWMM model for the study area

Subcatchment

For each subcatchment the area, percentual slope, outlet and percentage of impervious area were introduced, the remaining characteristics adopted were the default of the program. The area was obtained according to the auto-length tool since the model was drawn over the real size cartography of the study area. The average slope was calculated based on the cartography, this cartography is not public domain. The outlet was determined according to the areas of influence. The percentage of impervious area was designated according to the runoff coefficient of each area. Since the runoff coefficient represents the amount of precipitation that will generate superficial runoff, in which a larger value is verified for areas with low infiltration and high runoff and lower for permeable areas, the correlation was made for this study. In Table 3.7 the main types of area are presented as well as the percentage of imperviousness area adopted.

Table 3.7 - Percentage of imperviousness of the different types of area of the case study II.

Area type	% imperv	% of area
Roofs	60.0	20.75*
Roads and sidewalks	82.5	22.07
Paved parking lot	70.0	4.21
Forest and empty lots	20.0	52.71
Glass	100.0	0.25
*9.3% can be converted into green roof	**Total**	100.00

The runoff coefficient used for forest and empty lots, roads and sidewalks and for paved parking lots are an average value of the runoff coefficients range for the Rational Method in the book of Pedroso de Lima et al. (2010). For the roofs the coefficient used was based on Sousa (2015), which studied the runoff coefficient of a roof of the study area thus not having the need to use tabulated values, but a better fitted value. The glass runoff coefficient was made according to the material which does not retain any water thus having a runoff coefficient of 1.

Nodes and outfalls

The nodes' information inserted in the model was according to the data existing in the cartography of the study area, which contains the depth of each conduit that is connected to a node. This information is then used to determine the max depth – highest value of the depths of the conduits that are connected to a node – and the invert elevation - elevation of the node, determined by the surface elevation of the node minus the max depth. The remaining characteristics are the default of SWMM.

For the outfalls the only information inserted was the invert elevation which was obtained from the cartography of the study area.

Conduits

The information inserted for the conduits were the inlet and outlet node, the shape, its diameter, length and Manning's roughness coefficient. According with the design in the SWMM program the conduit was connected to the respectively inlet and outlet node. When inserting the conduits in the SWMM the auto-length tool was used to determine its length. The shape assumed was circular because the common practice is circular conduits of concrete (Sá Marques et Sousa, 2011), which has a Manning's roughness number of 0.01. The diameters were in the cartography.

Rainfall event

The precipitation event used in the simulated model was obtained by using the Alternating Block Method, a method that allows to develop a hyetograph from IDF curves. The IDF curves considered were regarding Coimbra with a return period of 5 and 10 years and were taken from Sá Marques et Sousa (2011). The return period chosen intended to test the green roof in order to understand if it is able to subsist such events and also considering the alterations that climate change will make to the return period – the precipitation intensity will increase 10 to 20% in the future (Dias, 2014). Figure 3.7 shows the hyetograph obtained for the return period of five years and Figure 3.8 for a return period of ten years.

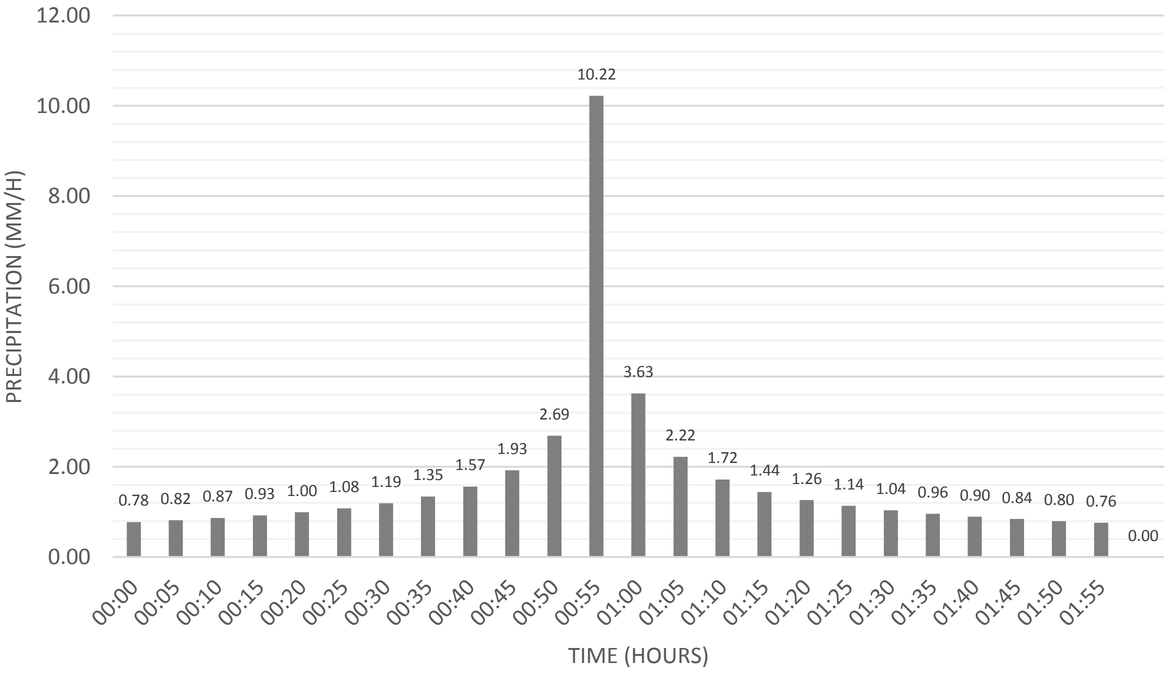


Figure 3.7 - Hyetograph of the precipitation event studied and precipitation values with a return period of five years.

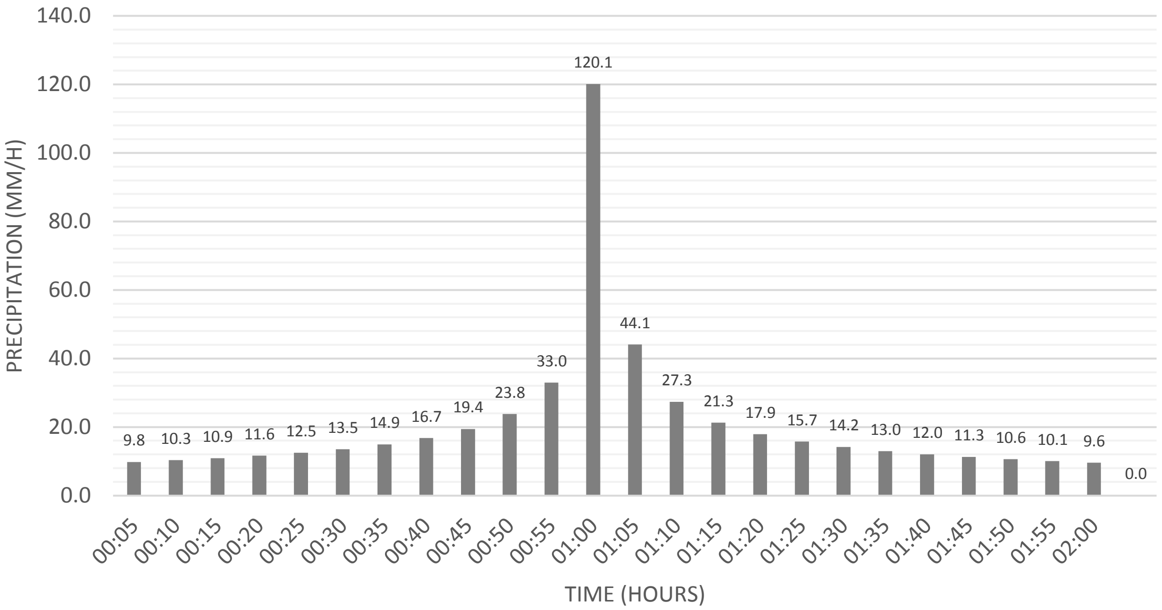


Figure 3.8 - Hyetograph of the precipitation event studied and precipitation values with a return period of ten years.

3.3.2. Scenarios of study

In order to explore the impact of green roof implementation in the study area two physical scenarios were introduced in the SWMM program:

Scenario 1

The study area characteristics are according to the current state and are as mentioned in 3.3.1.

Scenario 2

Green roofs are simulated to be introduced in the roof space that is available by using the LID control tool. The LID control tool option chosen was the green roof and the input characteristics used are in Table 3.8 and result of the analyses of the case study I, in which several scenarios were studied allowing to design a green roof to obtain good outcomes.

Table 3.8 - Input parameters of the green roof LID control in SWMM model for case study II.

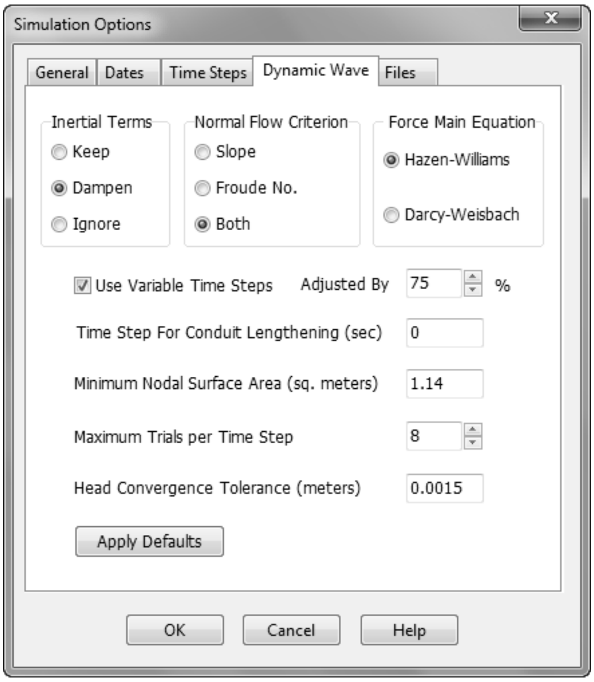
Layer	Parameter	Value	Unit
Surface	Berm height	50	mm
	Vegetation Volume Fraction	0	
	Roughness (mannings n)	0.1	
	Surface slope (percent)	1	
Soil	Thickness	12	mm
	Porosity (volume fraction)	0.5	
	Field Capacity (volume fraction)	0.2	
	Wilting Point (volume fraction)	0.1	
	Conductivity	0.5	mm/h
	Conductivity Slope	10	
Drainage Mat	Thickness	3	mm
	Void Fraction	0.5	
	Roughness (mannings n)	0.1	

As referred in Table 3.7, only 9.3% of the 20.75% of roof space will be converted into green roof. This is due to the fact that the remaining percentage is filled with solar panels or with air conditioner units or are very small areas, less than 5 m^2, therefore the installation of green roof will not be considered.

3.4. Considerations of the SWMM model

As mentioned in section 2.4., green roofs induce an extra load compared with roofs that do not have this technology. However the study developed considered that all available facilities' roofs can sustain the load associated with this technology.

The SWMM software was configured with the Routing Method of Dynamic Wave since it produces the most theoretically accurate results for flow routing (Rossman, 2010). Figure 3.9 shows the Dynamic Wave options set in SWMM.



Inertial Terms
○ Keep
● Dampen
○ Ignore

Normal Flow Criterion
○ Slope
○ Froude No.
● Both

Force Main Equation
● Hazen-Williams
○ Darcy-Weisbach

☑ Use Variable Time Steps Adjusted By 75 %

Time Step For Conduit Lengthening (sec) 0

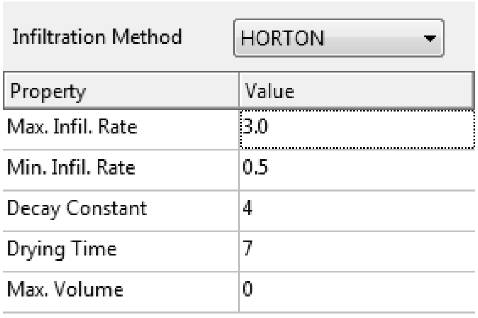
Minimum Nodal Surface Area (sq. meters) 1.14

Maximum Trials per Time Step 8

Head Convergence Tolerance (meters) 0.0015

Figure 3.9 -Dynamic wave simulation options.

The Infiltration Model selected was Horton due to the fact that it is the simpler model in comparison with the remaining others regarding input parameters required as well as for the concept of how the infiltration occurs. The characteristics of the Infiltration Model are presented in Figure 3.10.



Infiltration Method HORTON

Property	Value
Max. Infil. Rate	3.0
Min. Infil. Rate	0.5
Decay Constant	4
Drying Time	7
Max. Volume	0

Figure 3.10 - Screen shot of the Infiltration Model data on SWMM.

4 RESULTS AND DISCUSSION

The present chapter contains the obtained results from the SWMM simulations made as well as a review of them regarding the goals of this dissertation. These results are divided according to the case study, I and II.

4.1. Case study I

4.1.1. Continuity errors

Firstly an analysis of the continuity errors will be made. According to Rossman (2010) the continuity errors “represent the percent difference between initial storage + total inflow and final storage + total outflow for the entire drainage system” and allow us to understand the quality of the simulation. Under 10 percent is a reasonable level and indicate that the results are valid. The negative sign means that the there is more outflow than inflow and vice-versa for the positive sign. Table 4.1 shows the continuity errors obtained.

Table 4.1 - Continuity errors for the scenarios studied in case study I.

	scenarios			
Continuity erros [%]	**1**	**2**	**3**	**4 to 8**
runoff quantity	-0.049	-0.059	0	0
flow routing	0	-0.025	0.01	0

In this case all of the continuity errors are well under 10%, which indicates that the simulation has a good quality and that the system is balanced.

4.1.2. Subcatchment

In order to understand how each scenario influences the subcatchment the following Table 4.2 shows the volume drained from the subcatchment for each scenario.

Table 4.2 – Volume [m^3] simulation results for subcatchment A1.

	scenario							
Volume [m^3]	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Subcatchment A1	427.98	364.53	461.54	290.78	137.47	0	137.47	137.47

From Table 4.2 it can be seen that all scenarios decrease the amount of water that drains except for scenario 3, which is the one with the default characteristics of SWMM for LID control tool. This is due to the lack capability of this scenario to infiltrate water, when comparing with the others, namely scenario 1. Also, by comparing scenario 5, 7 and 8 it can be seen that by changing the thickness of the soil the volume reduction is the same, not affecting the outcomes. In the end scenario 6 is the one that decreases more volume, having a reduction of 100%.

4.1.3. Outfall

The outfall data results will be analysed concerning the flow and the time of max occurrence in outfall 1.

Flow and time of max occurrence

The following Figure 4.1 shows the flow in the outfall 1 during the elapsed time for the several scenarios.

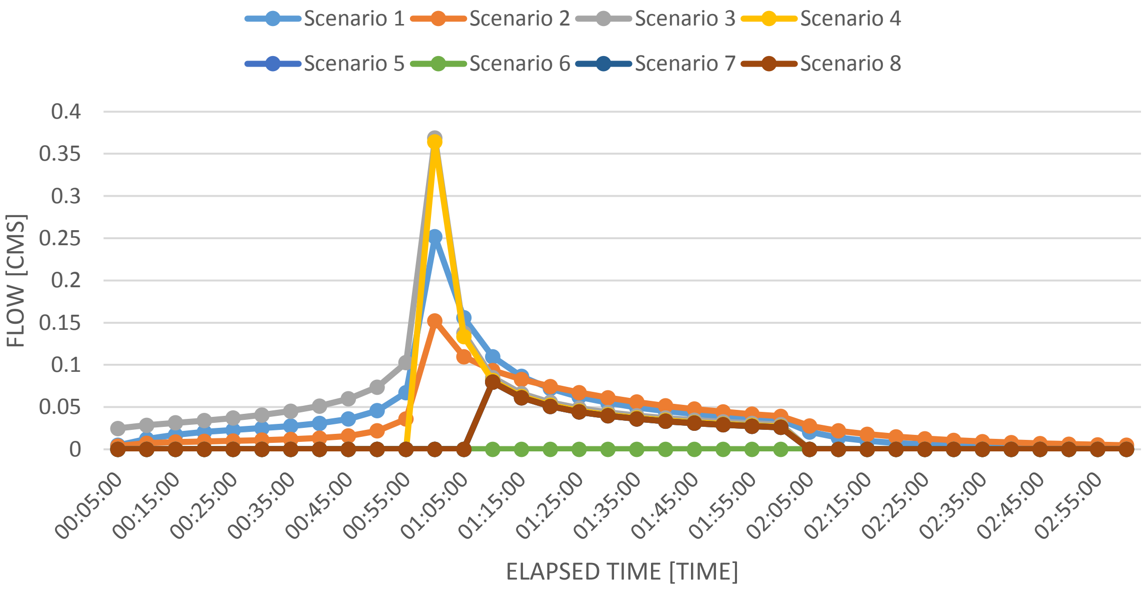


Figure 4.1 - Flow [CMS] of water on outfall 1 through the elapsed time.

From the above figure we can see that the several scenarios have different behaviours. For instance, although scenario 4 had less volume than scenario 1 (Table 4.2) we can now see that it has a higher pick flow when comparing with each other which contributes to pluvial flooding, not presenting as a reliable solution. Scenario 3 had more volume than scenario 1 and the above figure allows to see that difference, also not being a reliable solution.

Scenario 2, a simplified approach to introducing green roofs, has good outcomes when comparing with scenario 1, however not as good as for scenarios 5 to 8, since it does not represent a proper green roof behaviour. Scenario 5, 7 and 8 are overlapped whereas scenario 6 has no flow due to its high berm height. Although they are overlapped this does not mean that they have the same behaviour.

Regarding the time of max occurrence Table 4.3 shows the times verified for each scenario.

Table 4.3 - Time of max occurrence for each scenario.

	scenario							
time of max occurrence (hours)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
outfall 1	01:00	01:00	00:56	00:59	01:07	00:00	01:07	01:07

The above table allows to see more clearly the time of peak flow from Figure 4.1. As mentioned before the scenario with the best outcome is scenario 6.

4.1.4. LID behaviour

As mentioned before, although some scenarios with LID had similar results their behaviour is not the same. Figure 4.2 shows the soil moisture of the soil layer for the scenarios with the LID control tool.

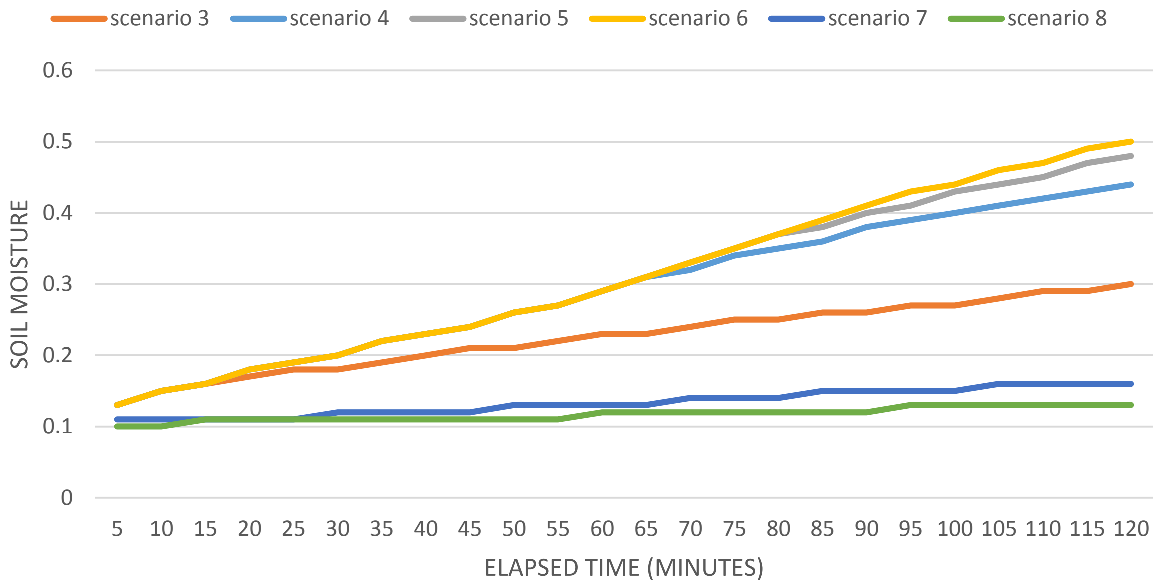


Figure 4.2 - Soil moisture of the LID control tool soil layer for scenarios 3 to 8.

The porosity is the volume of pore space relative to total volume of soil whereas the wilting point is the limit of which the soil moisture cannot fall below (Rossman, 2010). By this being said, it can be seen from the above figure that the information is according to the data of the soil layer for the control tool (Table 3.6), a porosity of 0.5 and a wilting point of 0.1. The soil moisture increases with the amount of water that is retained by the LID control tool, except for scenario 7 and 8 that have a thicker soil layer thus having more soil to retain water, leading to lower soil moisture. Scenario 4 to 6 have a berm height different than scenario 3, which allows the water to pond and consequently have a higher soil moisture.

4.1.5. Overall analysis

As can be seen in the previous sub sections, the introduction of green roofs can have benefits reducing runoff quantity as well as peak flows. Several scenarios were studied, however only the eight showed had the best results and allowed to see how the SWMM simulation behaves concerning the variation of different parameters.

This application example allowed to better understand how the model reacts to several parameters modifications and to design the green roof simulation that will be used for case study II. The simplified version of scenario 2 will not be used for the case study II, although it induces some reduction it does not represent the mechanism of a green roof. Scenario 6 is the more efficient scenario concerning the goal of this dissertation and will be used in case study II.

4.2. Case study II with a return period of 5 years

4.2.1. Continuity errors

As has been made for the application example, an analysis of the continuity errors will be made. Remembering what was said: the continuity errors “represent the percent difference between initial storage + total inflow and final storage + total outflow for the entire drainage system” (Rossman, 2010) and allow us to understand the quality of the simulation. Under 10 percent is a reasonable level and indicates that the results are valid. The negative sign means that there is more outflow than inflow and vice-versa for the positive sign. Table 4.4 presents the continuity errors obtained in the simulation for each scenario.

Table 4.4 - Continuity error (%) in the scenarios of case study II simulation with a return period of five years.

		Scenario 1	**Scenario 2**
Continuity error (%)	**Runoff quantity**	-0.059	-0.046
	Flow Routing	-0.329	-0.152

As can be perceived from Table 4.4 the continuity errors obtained are well under 10 percent indicating a simulation with good quality.

4.2.2. Subcatchments

Due to the amount of subcatchments of the model a thorough analysis, as has been made for the application example, could not be made. However a comparison between scenarios was made for two subcatchments to see how the different scenarios affect the runoff and also an overall analyses to the percentual differences concerning total infiltration, total runoff and peak runoff reduction.

Subcatchment analysis

The two subcatchments analysed were the roof of the no. 2 student residence and one of the Department of Civil Engineering roofs, as indicated on the screenshot of the SWMM interface in green (Figure 4.3). Figure 4.4 shows the runoff [CMS] from the subcatchment for the two scenarios.

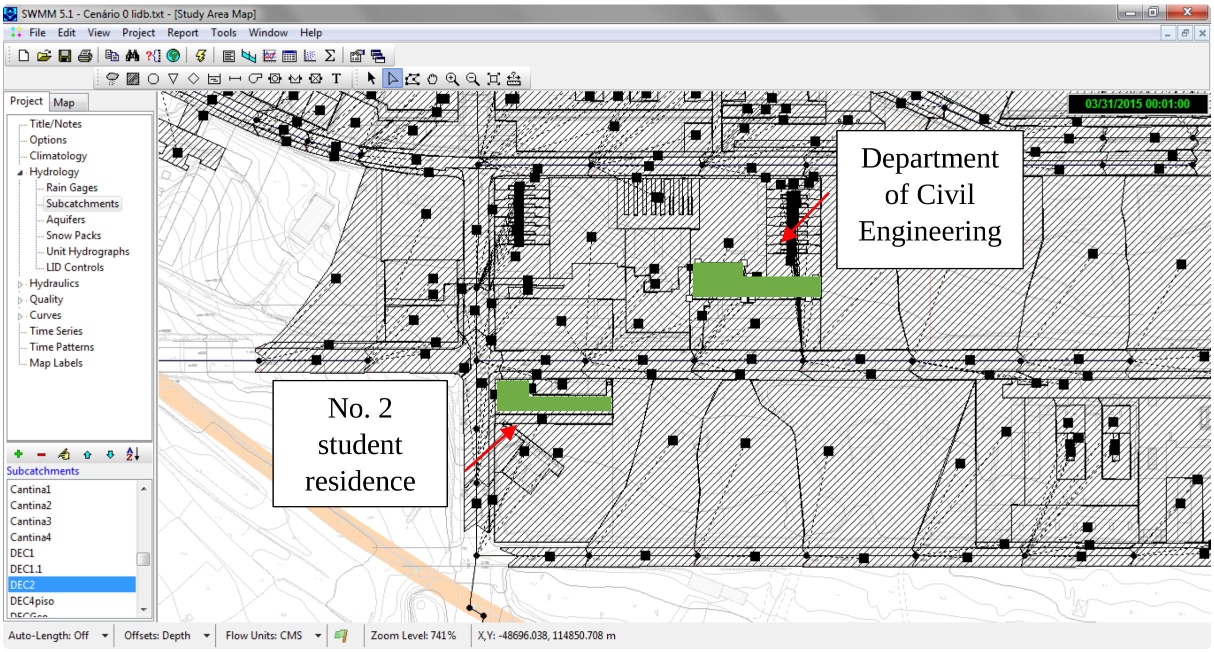


Figure 4.3 - Screenshot of the two subcatchments analysed on the SWMM interface.

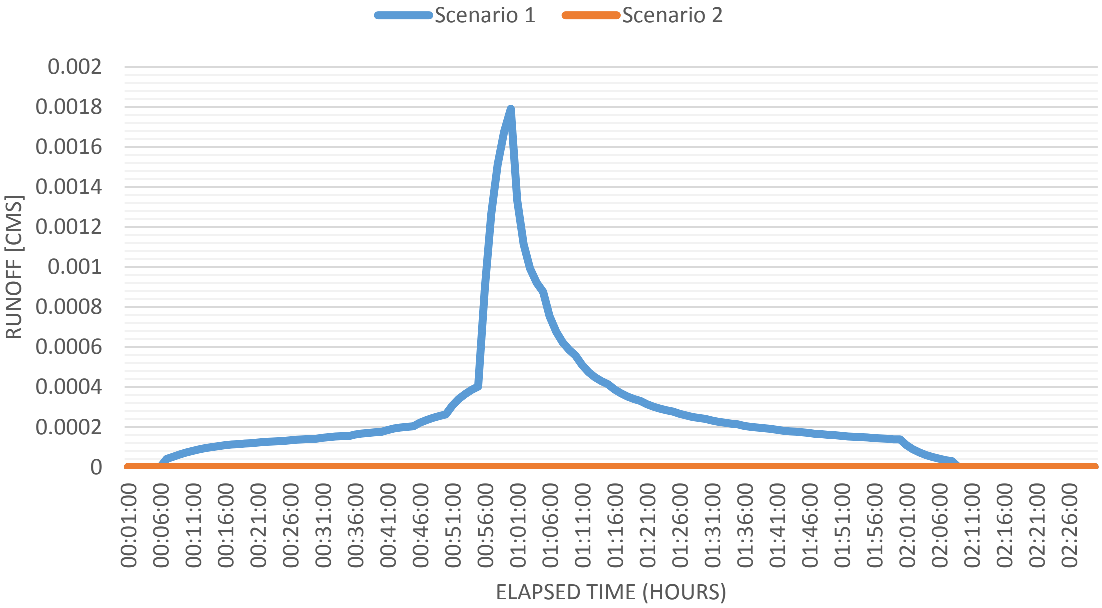


Figure 4.4 - Runoff from subcatchment for the two scenarios for a return period of 5 years.

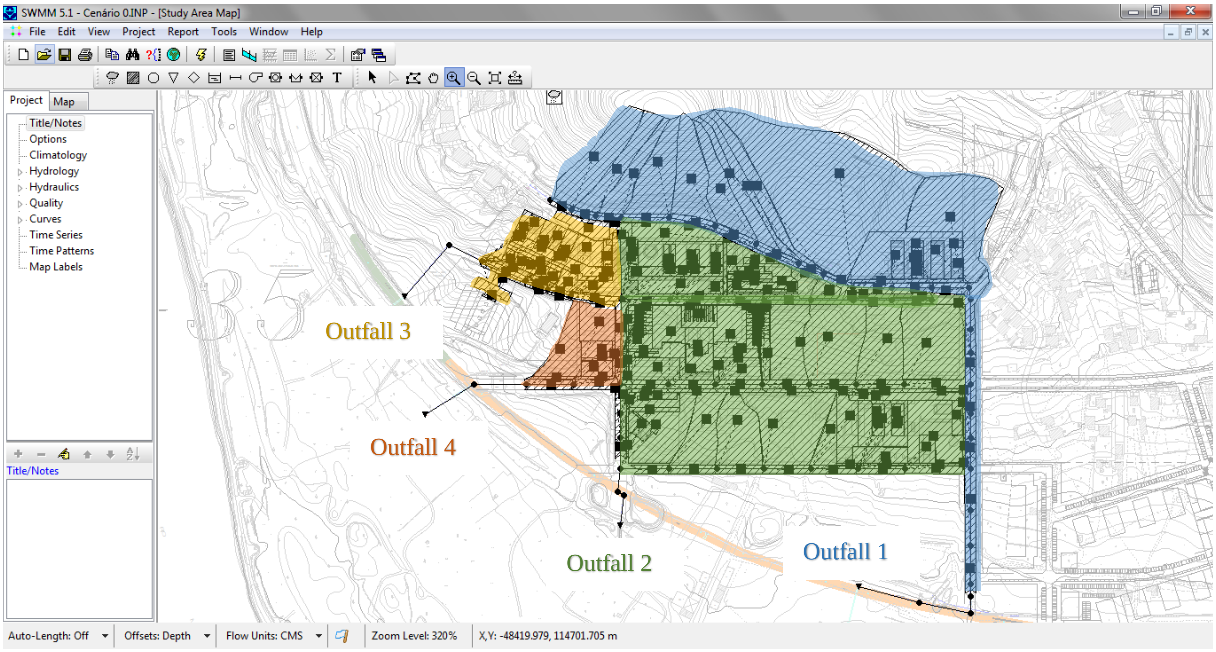
Observing the runoff quantity of the roof over the elapsed time we can see differences between the two scenarios. Although they have different dimensions, both subcatchments have the same behaviour. A behaviour that is according to the example of application: scenario with LID that has no runoff. From this we can conclude that the remaining subcatchments also behave like the above figure.

Overall analysis

As seen for the application example (case study I) the scenario with the LID control tool shows promising results having an overall decrease of approximately 97% of the total runoff and 100% for the peak flow, two of the main data that contribute for pluvial flooding.

4.2.3. Outfalls

Regarding outfalls, the areas that contribute for each one of the four outfalls are shown in Figure 4.5.



Auto-Length: Off
Offsets: Depth
Flow Units: CMS
Zoom Level: 320%
X,Y: -48419.979, 114701.705 m

Figure 4.5 - Screenshot of the SWMM interface with the representation of each area of contribution of each outfall.

As can be seen from the figure, outfall 3 and 4 have small areas of contribution comparing with outfall 1 and 2, these areas are shown in Table 4.5, as well as the area that is possible to convert into green roof.

Table 4.5 - Area of outfall that can be converted into green roof for case study II.

	Area of outfall [m^2]	**Area that can be converted into green roof [m^2]**
Outfall 1	87 010	771
Outfall 2	101 800	12 238
Outfall 3	14 818	6 196
Outfall 4	10 300	700

From the table it is clear the discrepancy between the area of the outfall and the area that can be converted into green roof. This difference will be reflected in the flow of the outfall, since the contribution that a subcatchment with green roof could have will be very small due to the amount of area that does not have sustainable urban drainage systems.

Figure 4.6 to Figure 4.9 show the flow for each outfall through the elapsed time for both scenarios.

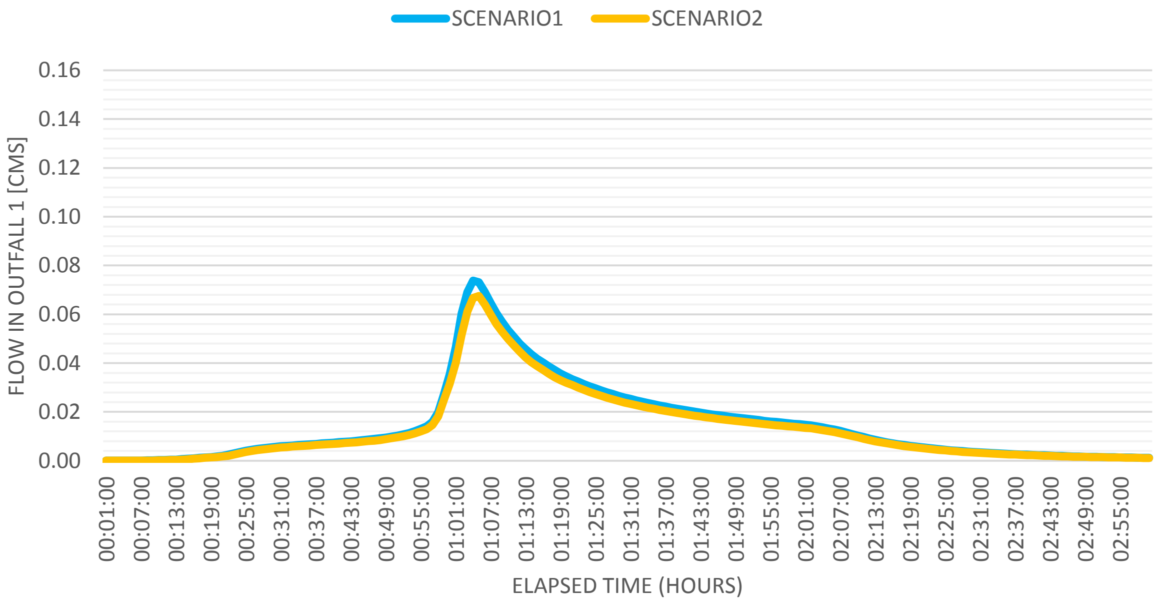


Figure 4.6 - Flow [CMS] in Outfall 1 through the elapsed time for the two scenarios.

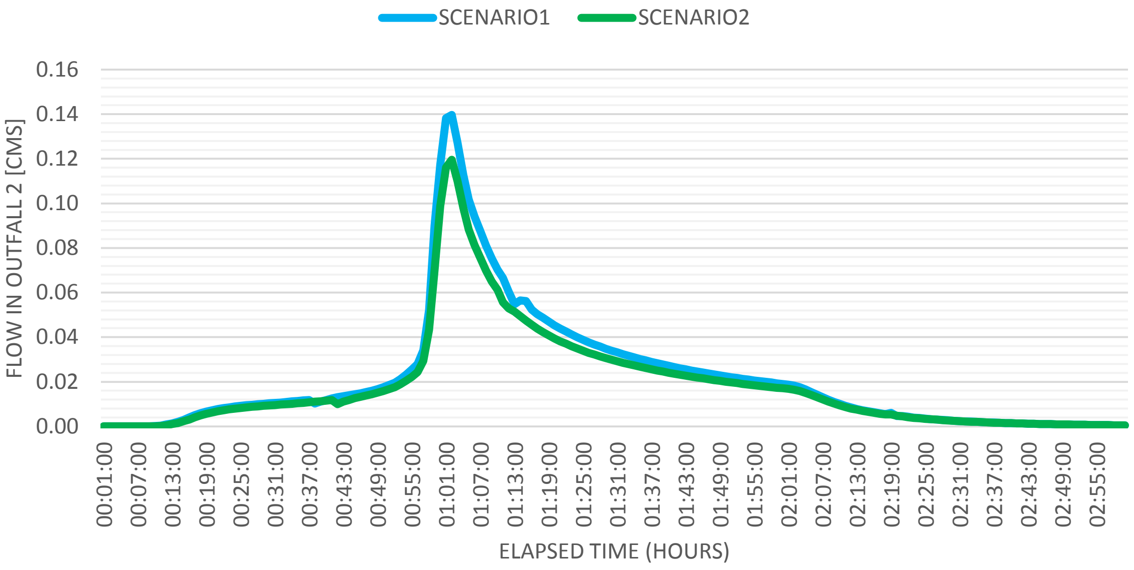


Figure 4.7 - Flow [CMS] in Outfall 2 through the elapsed time for the two scenarios.

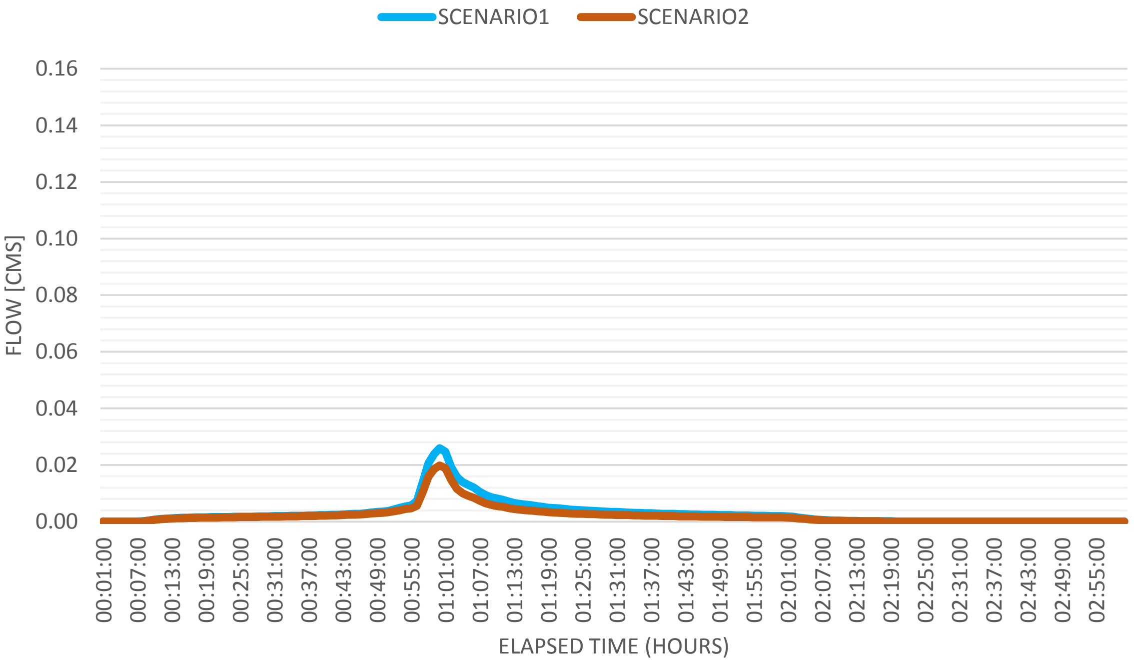


Figure 4.8 - Flow [CMS] in Outfall 3 through the elapsed time for the two scenarios.

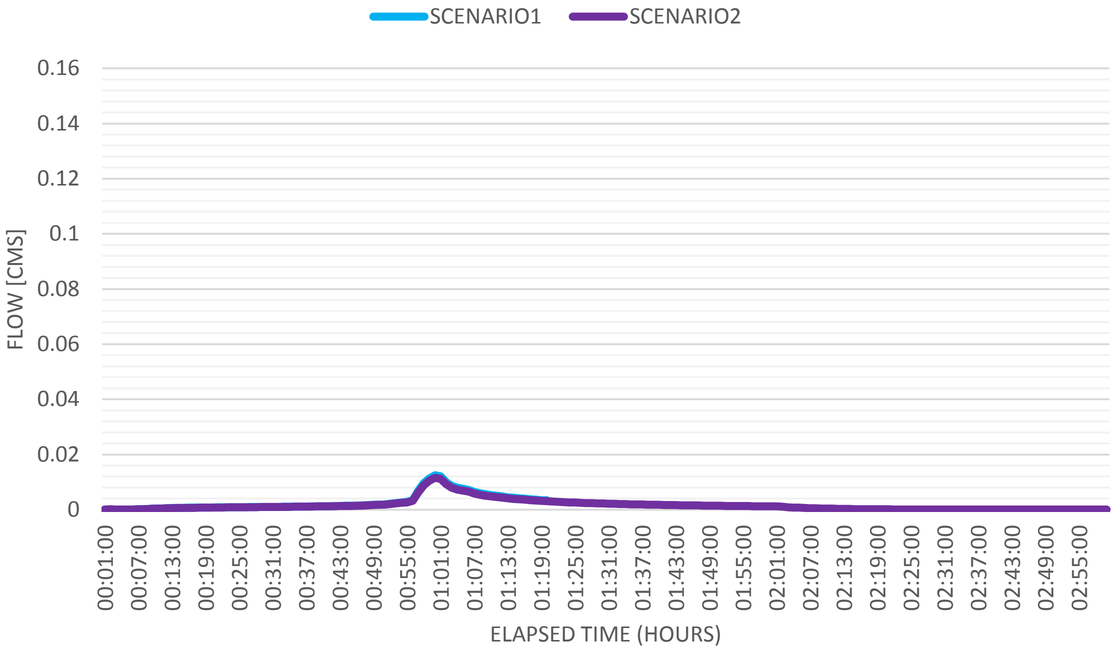


Figure 4.9 - Flow [CMS] in Outfall 4 through the elapsed time for the two scenarios.

Analysing the above figures it can be seen that scenario 2 does contribute to a reduction of the flow, however this contribution is not very high. This is due, as previously mentioned, with the fact that although the subcatchment with green roof has a decrease of 100% in peak runoff and nearly 97% in total runoff the overall area of subcatchments that can be converted into green roofs is not significant, comparing with the overall area of the case study. Table 4.6 shows the percentage of volume reduced in each outfall by introducing the LID tool.

Table 4.6 - Percentage of volume reduced between scenarios for the four outfalls.

	outfall 1	**outfall 2**	**outfall 3**	**outfall 4**
comparing scenario 2 with scenario 1	-8.3%	-12.4%	-24.7%	-8.5%

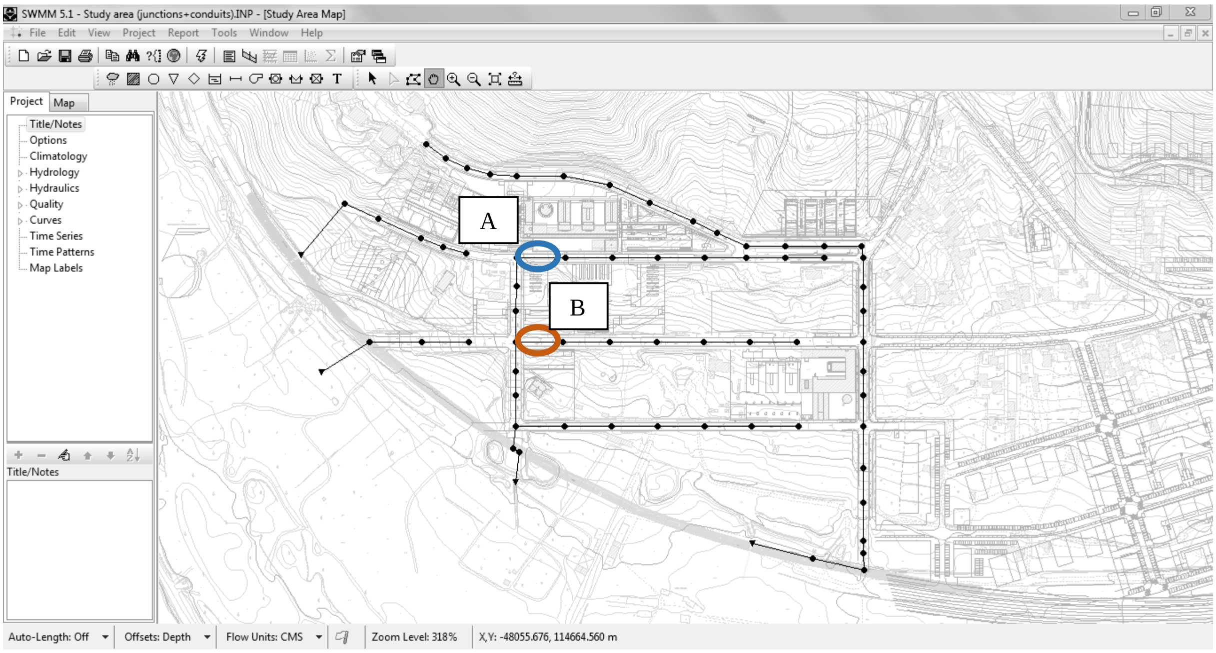
From the table it can be seen that scenario 2 had a reduction of the volume in all of the four outfalls area. The highest decrease was in outfall 3, the area with more green roof percentage, and the second highest decrease was in outfall 2, the largest area but also the area with more green roofs.

It is also important to discuss the difference between the flow of outfall 2 and outfall 1, from the figures. Although they are the largest areas of the case study, outfall 1 has less flow than outfall 2. This is due to the fact that the main part of the area of outfall 1 is forest, which has much more infiltration when comparing with roofs and impervious surfaces that is constituted outfall 2 area.

Concerning the time of max occurrence no difference was verified between scenarios.

4.2.4. Upstream conduits

In order to better assess the contribution of green roofs to the drainage system an analysis to the flow of two conduits was made. Since outfall 3 and 4 have very small areas and also because outfall 1 does not have a lot of green roofs in its area, conduits of outfall 2 were selected (conduit A and B), having in mind the distance to the outfall. These conduits are located according to Figure 4.10 of the drainage system.



Auto-Length: Off
Offsets: Depth
Flow Units: CMS
Zoom Level: 318%
X,Y: -48055.676, 114664.560 m

Figure 4.10 - Still of the SWMM interface with the location of conduits A and B.

The following Figure 4.11 and Figure 4.12 show the flow through the elapsed time in conduit A and B, respectively, for both scenarios.

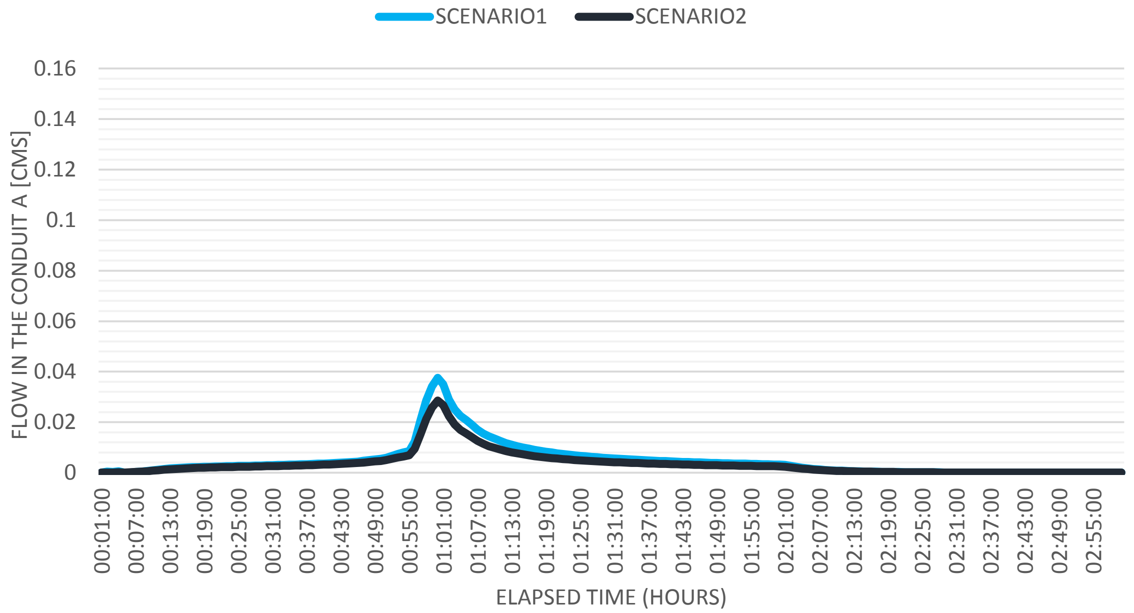


Figure 4.11 - Flow [CMS] in conduit A through the elapsed time for the two scenarios.

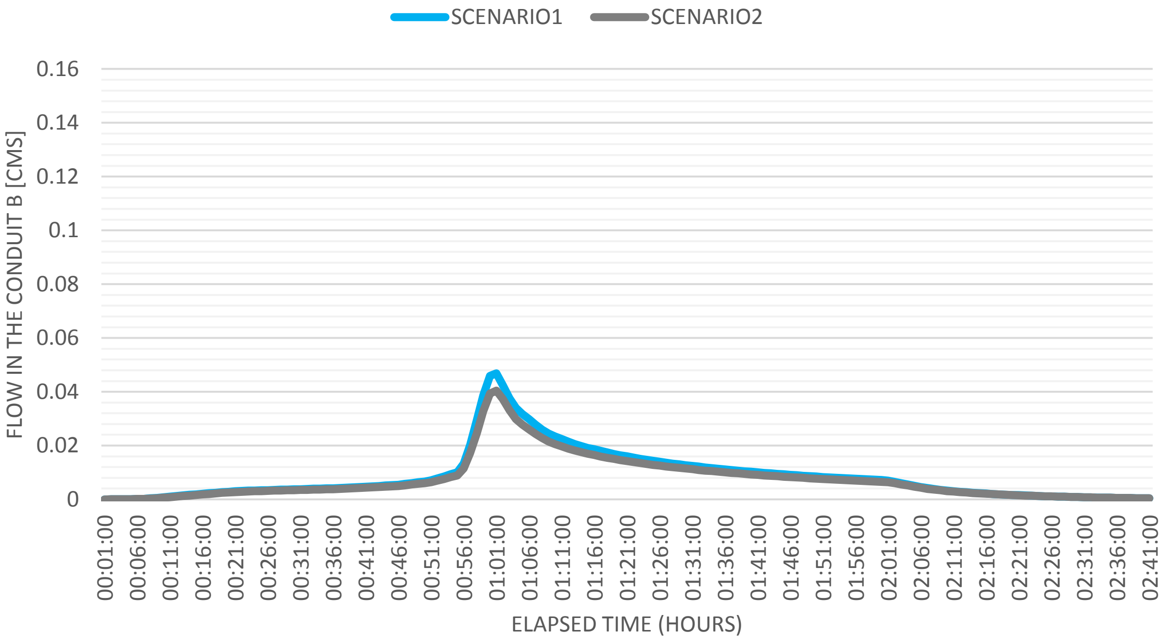


Figure 4.12 - Flow [CMS] in conduit B through the elapsed time for the two scenarios.

Looking at the above figures and the following Table 4.7 we can see that already in the conduits, before the outfall, a reduction was already noticed, higher than the reduction verified in the outfall. This is due to the fact that in the outfall the entire area is contributing whereas in the conduit only part of if, having a brief larger reduction than in the outfall.

Table 4.7 - Percentage of volume reduced between scenarios for conduits A and B.

	A	B
comparing scenario 2 with scenario 1	-23.3	-10.8

4.3. Case study II with a return period of 10 years

The same type of proceedings made for the case study with a return period of 5 years will also be made for this event.

4.3.1. Continuity errors

Table 4.8 shows the continuity errors in the scenarios, in order to assess the quality of the simulation.

Table 4.8 - Continuity error (%) in the scenarios of case study II simulation with a return period of ten years.

		Scenario 1	Scenario 2
Continuity error (%)	**Runoff quantity**	-0.088	-0.073
	Flow Routing	-0.128	-0.093

As can be perceived from the table, the continuity errors obtained are well under 10 percent indicating a simulation with good quality. The same as for the return period of 5 years.

4.3.2. Subcatchments

The following Figure 4.13 shows the subcatchment runoff for the same roofs studied in sub section 5.1.2. (Figure 4.3).

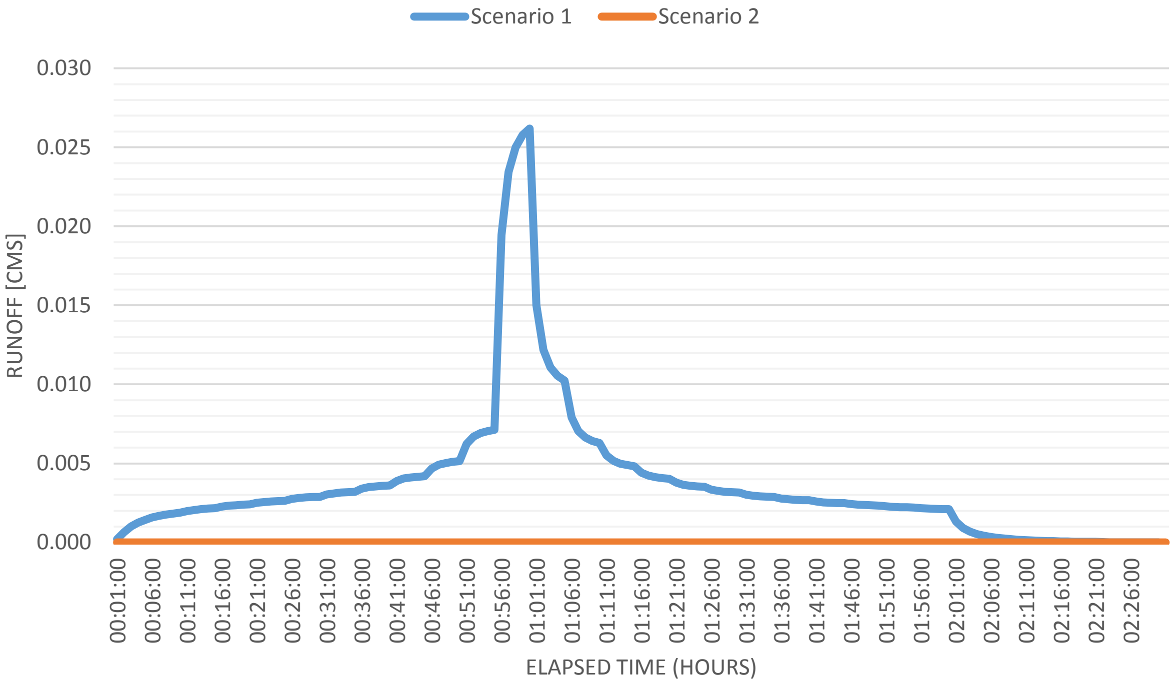


Figure 4.13 - Runoff from subcatchment for the two scenarios with a return period of 10 years.

As verified for the return period of 5 years, both subcatchments have the same behaviour regarding both scenarios, with the exception that now the runoff is higher. From this can conclude that the remaining subcatchments will also behave like the above figure.

Overall analysis

The results shown are very positive, and are just slightly different from the period of return of 5 years. But it is a difference expected since more amounts of water impose a greater effort to the LID control tool.

4.3.3. Outfalls

Having in mind the same information as in 5.1.3., Figure 4.14 to Figure 4.16 show the flow for each outfall through the elapsed time for both scenarios, for a precipitation event with a return period of 10 years.

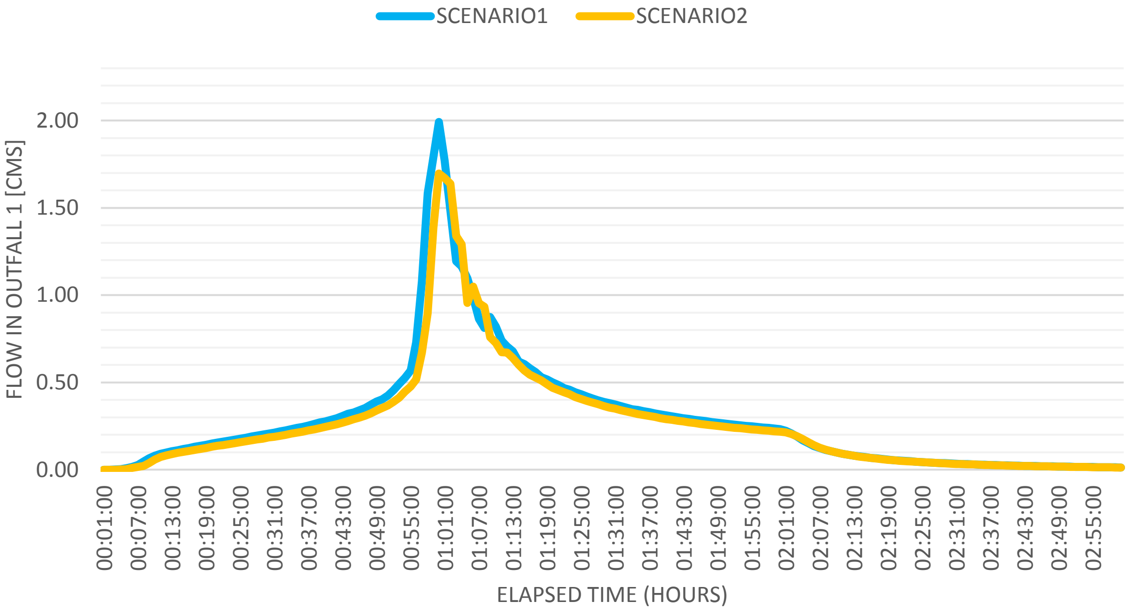


Figure 4.14 - Flow [CMS] in Outfall 1 through the elapsed time for the two scenarios.

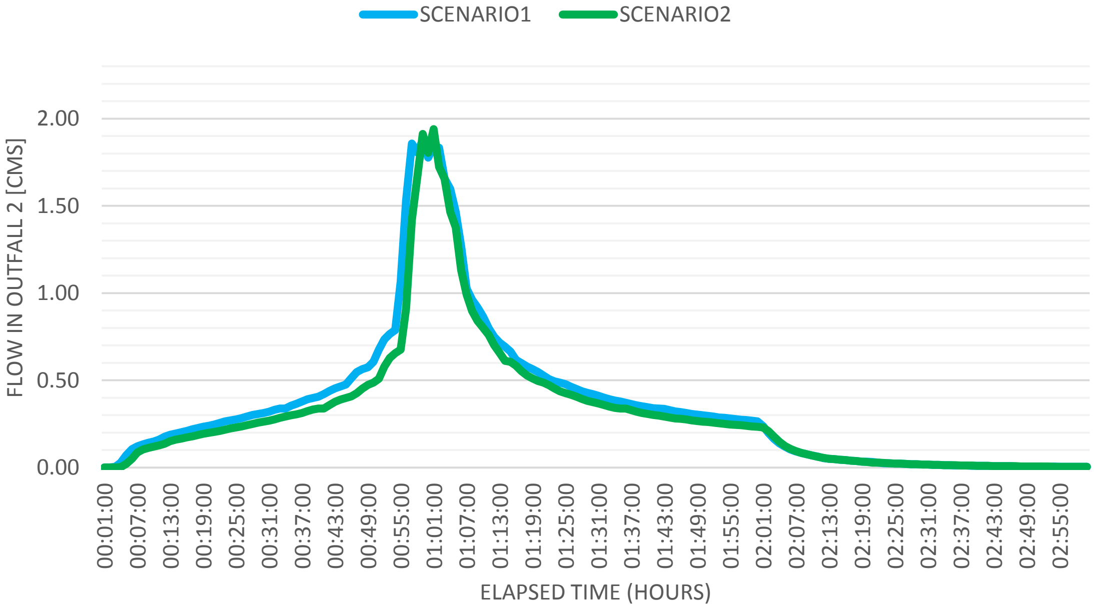


Figure 4.15 - Flow [CMS] in Outfall 2 through the elapsed time for the two scenarios.

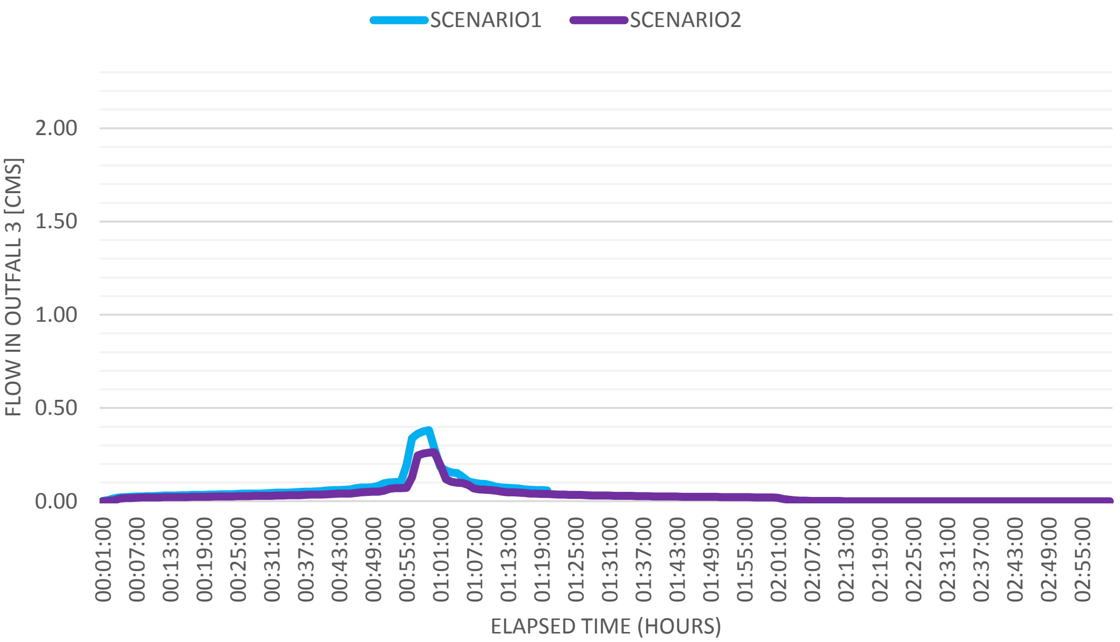


Figure 4.17 - Flow [CMS] in Outfall 3 through the elapsed time for the two scenarios.

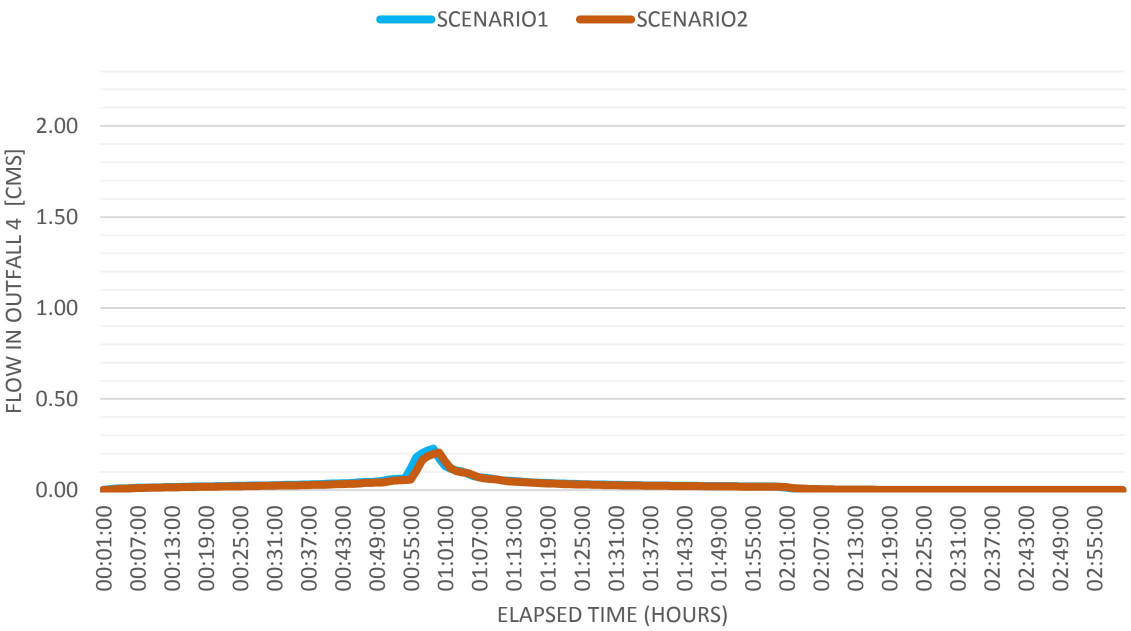


Figure 4.16 - Flow [CMS] in Outfall 4 through the elapsed time for the two scenarios.

From the above figures it can be seen that using the LID control tool also has effect in this precipitation event. The low influence is due to, as referred, the overall area of subcatchments that can be converted into green roofs is not significant, comparing with the overall area of the case study. Table 4.9 shows the percentage of volume reduced in each outfall by introducing the LID tool.

Table 4.9 - Percentage of volume reduced between scenarios for the four outfalls.

	outfall 1	**outfall 2**	**outfall 3**	**outfall 4**
comparing scenario 2 with scenario 1	-8.6%	-11.63%	-31.8%	-9.37%

Again, scenario 2 made a reduction in the volume of all the four outfalls area. The highest decrease was in outfall 3, the area with more green roof percentage, and the second highest decrease was in outfall 2, the largest area but also the area with more green roofs. Concerning the time of max occurrence no difference was verified between scenarios.

4.3.4. Upstream conduits

The conduits studied are the same as in section 5.1.4. Figure 4.18 and Figure 4.19 show the flow through the elapsed time in conduit A and B, respectively, for both scenarios.

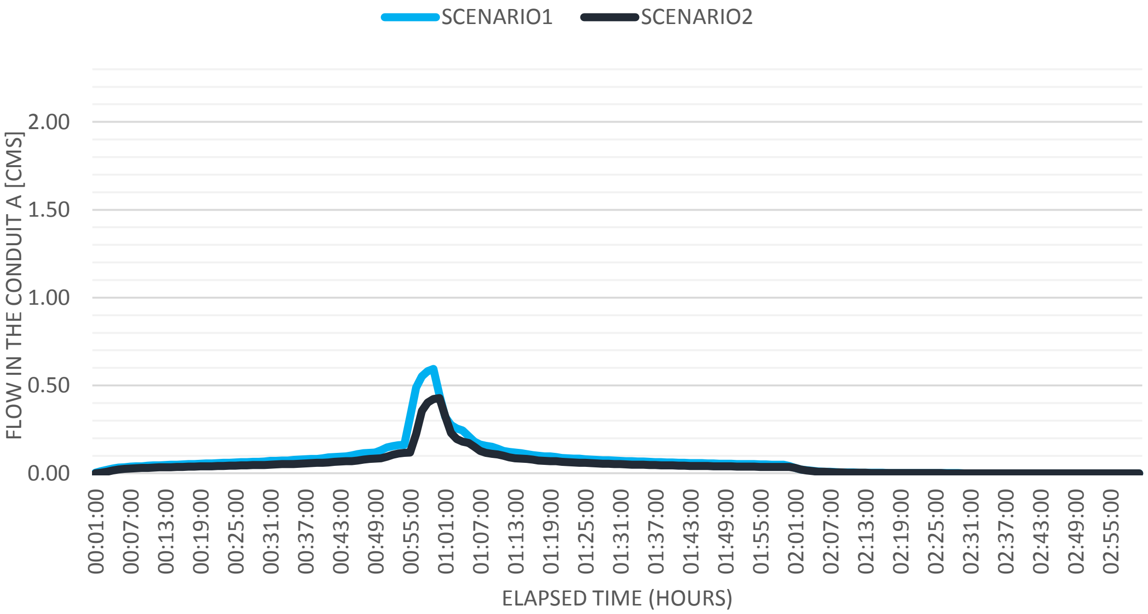


Figure 4.18 - Flow [CMS] in conduit A through the elapsed time for the two scenarios.

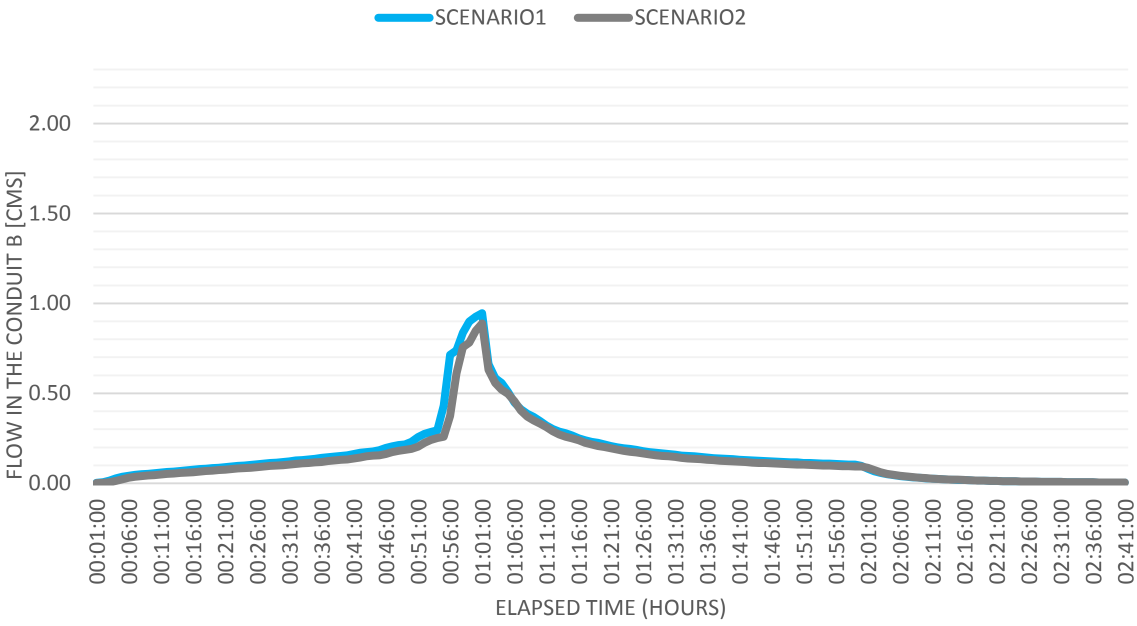


Figure 4.19 - Flow [CMS] in conduit B through the elapsed time for the two scenarios.

Looking at the above figures and the following Table 4.10 we can see that already in the conduits, before the outfall, a reduction was already noticed, although the action of green roofs was already diminished by the other contributing areas.

Table 4.10 - Percentage of volume reduced between scenarios for conduits A and B.

	A	**B**
comparing scenario 2 with scenario 1	-28.1%	-10.9%

In this case, a slight increase of the percentage diminished was verified, being according to the other results of this precipitation event regarding outfalls.

5 CONCLUSIONS AND FUTURE WORK

5.1. Conclusions

In 2014 the urban population was 54% of the total global population and is expected to grow approximately 1.84% per year between 2015 and 2020, 1.63% per year between 2020 and 2025 and 1.44% per year between 2025 and 2030 (WHO@, 2015). As the level of urbanisation increases the characteristics of the original land and the surrounding areas are altered (Davis and McCuen, 2005). In Portugal, by 2011, approximately 43% of the population lived in urban areas (PORDATA@, 2015).

According to the European Environment Agency (EEA@, 2012) the annual precipitation will decrease in southern Europe, however the number of days with high precipitation is projected to increase. For a return period of one year it is expected an increase of 20% in the intensity of precipitation whereas a return period of two years an increase of 30% is estimated.

As forest and open space are replaced by houses, roadways and commercial and industrial areas, combined with climate change, urban areas will deal with the increased risk of flooding (due to drainage system surcharge), bringing many problems for residents. A solution to this problem approached by this study is the Water Sensitive Urban Design (WSUD) philosophy.

WSUD integrates urban planning with the management, protection and conservation of the urban water cycle, ensuring that urban water management is sensitive to natural hydrological and ecological processes (Wong, 2007). It can be said that WSUD is an approach that combines planning and design. The planning is made having in mind the community values and aspirations of urban places whereas the design, concerning storm water runoff, is done regarding the best opportunities and multiple benefit outcomes while managing storm water impacts. Green roofs is one of the technologies used by WSUD.

A green roof is an engineered multi-layered structure which covers a building’s roof with vegetation (Razzaghmanesh, 2014 and Woods Ballard, 2007). Its benefits depend on the green roof characteristics and the weather conditions of its location (Berndtsson, 2010). The construction of green roofs is versatile, from the number of layers, the material and thickness of the layer as well as the roof slope, the roof age and position to the way the system is installed:

complete system, modular system or pre-cultivated blankets (Berardi et al., 2014). Typically the layered system is composed of: waterproofing membrane, root barrier, drainage layer, filter/geotextile layer, growing medium or soil layer and the vegetation layer. It is the type of vegetation layer that names the type of green roof: intensive - landscaped environment with shrubs and trees -, extensive - low growing, maintenance and water needs plants - and simple-intensive - combination of extensive with intensive green roof.

Worldwide green roofs are gaining importance and relevance having more political initiatives to its implementation. For instance law in Tokyo requires that built areas larger than 1 000 m^2 and in public buildings with built areas larger than 250 m^2 green roofs must be installed; in Basel, Switzerland users are repaid 20% of the cost of a green roof; In Toronto, Canada, policies were developed to promote green roofs in buildings with the ratio of 50-70% of the entire building coverage; In the United States of America, some states also developed policies, for instance New York City gives an one year tax credit for green roofs that encompass at least 50% of available roof space (Berardi et al., 2014). More recently France approved a law that requires new commercial buildings to have partially covered roofs with green roofs or solar panels (TheGuardian, 2015).

Green roofs have several benefits, namely regarding: water management, energy consumption, urban heat island, air pollution mitigation, sound absorption and ecological preservation (Berardi et al., 2014). However, this study only focused on the ones concerning water management, specifically storm water management. Acting at-source, green roofs can reduce storm water runoff in the order of 40-100% of the total rainfall (Berardi et al., 2014; Fletcher et al., 2013 and Mohammad et al., 2012) and 60-80% of the peak flow (Bengtsson et al., 2005; VanWoert et al., 2005). Depending on the characteristics of the green roof, the intensity and duration of the rainfall, and climate conditions. The concerns of green roofs are the waterproofing integrity, load induced by the structure, maintenance necessities, resistance, the lack of experts and the initial economic investment.

The Storm Water Management Model (SWMM) is a dynamic hydrology-hydraulic water quality simulation model developed by the United States Environmental Protection Agency (EPA) and is used for planning, analysis and design, mainly in urban areas, of storm water runoff, combined and sanitary sewers and other drainage systems. This software enables to track the quantity and quality runoff made during a simulation period in each pipe and channel of a simulation model (Rossman, 2010). More recently, in March 2014, the SWMM was released with a tool (LID control tool) that allows to model the hydrologic performance of green roofs. The LID control tool has several parameters that can be modified.

This dissertation developed a simulation model concerning green roofs in the facilities of Campus II of the University of Coimbra in order to determine the contribution of this technology to the management of storm water. Two scenarios were studied: (1) the study area characteristics are according to the current state; (2) green roofs are simulated to be introduced by using the LID control tool. A simple application example to understand how the SWMM works and to observe how the different variations to the parameters of the LID control tool would affect the outcomes of the model was also made.

The outcomes from the application example showed that there are certain parameters that influence more the outcomes. After several simulations the berm height showed to be the most promising, concerning the outcomes. The berm height is the height of the confining walls or berms, being the maximum depth to which water can pond above the surface of the unit before overflow (Rossman, 2010). One of the simulations showed a reduction of 100% of the total runoff and peak flow, excellent results to reduce pluvial flooding. The case study developed used the scenario with the best results from the application example.

The outcomes of subcatchments of the case study were the same as for the application example, however, in overall, the percentage of flow reduced was an average 13.5% for a precipitation event with a return period of 5 years, and 15.4% for a precipitation event with a return period of 10 years. The difference between the results for the subcatchments and for the entire system, is due to the fact that the green roof area is only 9.3% of the entire case study area. Thus although a great reduction in the subcatchment, the remaining area attenuates the effect.

Economically speaking, green roof implementation is currently an expensive investment starting in the 55€/m^2. For instance this case study converted 19 904 m^2 into green roof which accounts for at least a total investment of 1 094 725 €. However this value could be less since the roofs already are duly protected which could reduce the price to invest.

5.2. Limitation and future work

In the course of this study some limitations were found. The SWMM control LID tool is a very recent one, not having a lot of data available about simulations, tutorials, as well as results to compare to. Also the green roof model used was built based on theoretical hydrologic mechanisms. There is a need for more scientific research concerning green roofs benefits, since the existing data have a large range of results, which gives uncertainty to the true benefits of this technology.

In future work, the case study should be in a more urbanised area in order to better expose this technology as a solution for pluvial storms. And several other scenarios could be developed whether regarding time events or characteristics of the simulation model (slope, diameter, % imperviousness, among others), as well as different types of vegetation, if there is available data to do so. Also a greater knowledge and understanding of how this new tool of SWMM works should be explored in order to achieve and obtain results in the same greatness as the existing scientific data.

Furthermore, the environmental benefits could be more explored in different works. One of the most interesting to study is the energetic benefits in buildings, economically and environmentally speaking.

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