UNIVERSITAT POLITÈCNICA DE VALÈNCIA

ETS INGENIEROS DE CAMINOS, CANALES Y PUERTOS

TRABAJO DE FIN DE MÁSTER

Study of alternatives for the design of sustainable urban drainage systems (SUDS) at Cathedral Street (Glasgow, United Kingdom)

Presentado por

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EXECUTIVE SUMMARY

This dissertation aims to study the possible application of sustainable drainage systems (SuDS) around Cathedral street.

The objective of this intervention is to minimise the use of conventional sewerage systems in order to prioritise their use in heavy rainfall events. This reduces the volume of water to be treated in the treatment plants, decreasing treatment costs and environmental impacts.

The area of study has been divided into subcatchments to analyse their behaviour without the application of SuDS for two rainfall events, T=10 years and T=200 years. Once analysed, alternatives for the event of T=200 years have been studied.

The study considers the construction of green roofs, permeable pavements, geocellular systems and retention ponds. All of them have been modelled using the software Stormwater Management Model (SWMM) in order to know quantitatively the variations caused by their application in the assumed current drainage system.

A multicriteria analysis has been carried out based on technical, economic and hydraulic criteria to compare the alternatives studied.

Finally, results conclude that the most suitable alternative would be alternative 3 which involves the construction of car parks with geocellular storage systems due to its high impact on the seawage system at an affordable price. It may also be interesting to apply alternative 4 of a retention basin that allows water to infiltrate a large area with a small area of action at a low cost.

RESUMEN

El objetivo de este trabajo de fin de master es estudiar la posible aplicación de sistemas de drenaje urbano sostenible (SuDS) en torno a la calle de la Catedral.

El objetivo de esta intervención es minimizar el uso de los sistemas convencionales de alcantarillado para priorizar su uso en caso de fuertes lluvias. Esto reduce el volumen de agua a tratar en las plantas de tratamiento, disminuyendo los costes de tratamiento y su impacto medioambiental.

El área de estudio se ha dividido en subcuencas para analizar su comportamiento sin la aplicación de SuDS para dos eventos de precipitaciones, T=10 años y T=200 años. Una vez analizados, se han estudiado alternativas para el evento de T=200 años.

En el documento se han considerado la construcción de cubiertas vegetales, pavimentos permeables, sistemas de geoceldas y balsas de retención. Todas las alternativas han sido modeladas utilizando el software Stormwater Management Model (SWMM) para conocer cuantitativamente las variaciones debidas a su aplicación en el supuesto actual sistema de drenaje.

A continuación, se ha realizado un análisis multicriterio basado en criterios técnicos, económicos e hidráulicos para comparar las alternativas estudiadas.

Finalmente, los resultados concluyen que la alternativa más adecuada sería la alternativa 3, que consiste en la construcción de aparcamientos con sistemas de almacenamiento geocelular debido a su alto impacto en la red de alcantarillado a un precio asequible. También puede ser interesante aplicar la alternativa 4 de una balsa de retención que permite que el agua de una gran superficie se infiltre en una actuación pequeña de bajo costo.

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ABREVIATIONS

CHESS-PE	Climate hydrology and ecology research support system potential evapotranspiration
CIRIA	Construction Industry Research and Information Association
FEH	Flood Estimation Handbook
IDF	Intensity, Duration, Frequency
LID	Low Impact Development
SUDS	Sustainable Drainage Systems
SWMM	Storm Water Management Model

1. INTRODUCTION

Urban development processes in cities bring about a series of changes and alterations in natural conditions. Because of the increase of impermeable areas, an increase in runoff flows has been observed. This has resulted in flooding and degradation of water quality due to limited capacity of existing collectors and increased rainfall intensities.

This problem raises the idea of modifying stormwater management from a different perspective that considers environmental, hydrological, economic and social aspects. This management model attempts to imitate the natural water cycle, minimising the negative impact on the environment and encouraging the infiltration and reuse of water.

Sustainable drainage systems (SuDS) are beneficial controlling the quantity and quality of runoff water, but also allowing the creation of natural urban environments that offer a social service and improve the aesthetic quality of the city.

Moreover, this sustainable form of management offers hydrological benefits such as flood prevention, less interference in the natural quality and quantity regimes of the receiving water bodies and the possibility of recharging groundwater aquifers.

Regarding the environmental benefits, SuDS allow the improvement of runoff water quality by reducing the amount of pollutants that reach the receiving environment. In addition, SuDS enrich the biodiversity and reduce the discharges from the treatment plants.

These systems are considered low cost actions because they may require less investment in their construction. They also have a beneficial impact on the economy as they reduce the costs of operating sewage treatment plants and the economic losses due to flood damage.

1.1 Project development and objectives

This project aims at modelling and analysing different sustainable drainage systems applied in different locations of the study area using SWMM software.

The purposes of this study are:

- Establish the hydrological response of Cathedral street catchment area to rainfall events.
- Minimize the use of the conventional drainage network to prioritize its use in case of heavy rain events.
- Implement sustainable drainage measures to minimize surface runoff in key areas.
- Reuse stored water to minimise the impacts and costs of treatment.

To model the current situation, it is necessary to obtain topographical, hydrological and climatological information. This information is selected taking into account CIRIA's (Construction Industry Research and Information Association) considerations in its SuDS Manual (2015).

After discretizing the study area in different subcatchments and providing the necessary information into the model, the current situation has been modelled and its performance has been analysed for two rain events, T=10 years and T=200 years. Later, different SuDS alternatives have been modelled for the T=200 yr. event. With the results obtained it has been possible to know the impact of each measure on hydraulic response of the network when compared with the current situation.

Finally, alternatives have been compared according to their cost and impact on the hydraulics of the system, in order to decide which is the most economically and technically recommended measure.

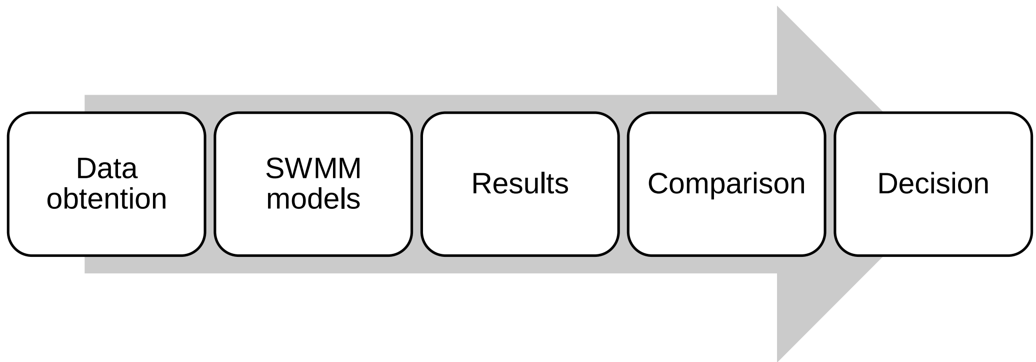

Figure 1. Methodology process

1.2 Sustainable drainage systems

Sustainable Urban Drainage Systems (SuDS) are techniques which aim to reduce runoff from rainwater and retain pollutants dragged in it, allowing new uses for water, while keeping the natural conditions of the places where they are implemented. This enables the recovery of urban areas and offers a pleasant and natural urban landscape.

SuDS are an interconnected system designed to manage, treat and make the best use of stormwater, from where it falls in the form of rain to the point of discharge in the environment.

In SuDS design is common the concept of Suds Management train. This is based on the use of a sequence of components which together control the frequency of runoff, flow rates and runoff volumes while reducing pollution levels to acceptable levels.

As indicated in CIRIA (2015; p.28) there are six different functions of SuDS components:

- **Rainwater harvesting system**: These systems capture water to reuse it for the local environment or in buildings.

- **Pervious surfacing systems**: Permeable surfaces that allow water to penetrate, and also include subsurface storage and treatment. Such systems reduce the amount of water collected by conventional drainage systems.

- **Infiltration systems:** Systems that allow infiltration of runoff water into the ground. They can also allow temporary storage prior to a slow infiltration process.

- **Conveyance systems:** Components that convey flows to temporary storages where they can be treated and controlled.

- **Storage systems**: Allow storage of water discharging it slowly to reduce the peak flows of rainfall events.

- **Treatment systems:** Components that eliminate or allow the degradation of contaminants present in runoff.

There is a wide variety of SuDS components, thus it is easy to adapt them to different study situations. Also these components can fulfil more than one of the functions mentioned above. Some of the existing components are, among others:

- **Green roofs:** Multi-layer systems with vegetation designed to cover roofs and terraces. Their function is to intercept and retain rainwater by reducing the volume of runoff and attenuating peak flows. In addition, they allow the retention of pollutants and act as a thermal insulator in the buildings where it is installed.

Figure 2. Green roof. Source: Susdrain

- **Permeable surfaces:** Surfaces suitable for vehicular and pedestrian traffic circulation that allow water filtration. The lower layers of the section must allow the filtration of the water or its storage for later discharge. This component attenuates the peak flow of runoffs and improves water quality by removing metals, suspended solids, grease and oils.

Figure 3. Permeable pavements. Source Susdrain

- **Infiltration basins:** Depressions in the land covered by vegetation whose purpose is to collect and store runoff. This component also allows sedimentation and filtration of pollutants. The runoff is stored in tanks for subsequent infiltration into the ground.

Figure 4. Infiltration basin. Source: Stormwater Partners

- **Geocellular Systems:** Formation of several plastic modules with high proportion of voids whose function is to create storage areas and infiltration of rainwater at a lower level than the terrain. This component has the capacity to laminate floods.

Figure 5. Geocellular systems. Source: Projectscot

Some benefits of using SuDS are related to the protection and improvement of water quality. These sustainable systems also allow maintaining and restoring the natural regimes of the water cycle, increasing infiltration rates and enhancing the natural recharge of aquifers. SuDS implementation can be used as a flood protection measure as it allows the treatment of flows in highly urbanized areas. In addition, these techniques enrich the biodiversity and appearance of the areas where applied.

Nevertheless, SuDS also present some drawbacks related to the lack of confidence while operating due to past bad experiences and its specialized maintenance needs.

According to CIRIA (2015; p.9) to maximize the benefits of sustainable drainage systems, they must be designed in a way that:

- Evapotranspiration and infiltration should be promoted.
- Runoff should be reduced and stored to imitate its natural volumes and runoff rates.
- Surface water runoff should be considered and reused as a resource.
- Manage rainwater close to where it falls.

2. METHODS AND TOOLS

The SWMM software will be used for modelling the case study and the proposed alternatives in this project.

As noted in the User's Manual (EPA, 2015), the EPA's Storm Water Management Model (SWMM) is a dynamic model to replicate rainfall in punctual or extended periods. This program simulates the quantity and quality of runoff, especially in urban areas.

SWMM reproduces drainage systems using three main modules. First, the runoff module separates the study area into sub-catchments in which a runoff-generating precipitation is applied. Then, the transport module analyses the runoff course through a system of pipes, channels, storage and treatment devices, pumps and regulating elements. Finally, the quality module assesses the evolution of the quantity and quality of the runoff for each subcatchment area and each transport element.

SWMM also has LID controls that model some of the most common SuDS techniques. The software allows to simulate rain gardens, bioretention cells, vegetative swales, infiltration trenches, green roofs, rooftop disconnection, rainwater harvesting and continuous permeable pavement systems. LID controls only model the reduction in runoff mass load resulting from the reduction in runoff flow volume (United States Environmental Protection Agency, 2019).

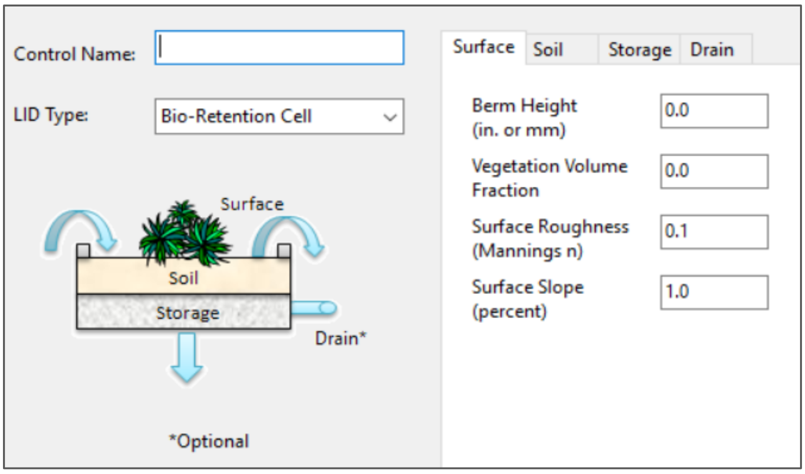

Figure 6. LID Control editor from SWMM

LID controls are represented by a combination of layers whose properties are defined on a per-unit-area basis. Possible layers are the following (EPA, September 2015, p. 78 and 79):

- *Surface Layer*: It represents ground surface receiving direct rainfall and runoff from stream land areas, stores excess inflow in depression storage, and generating surface outflow.
- *Pavement Layer*: It characterises permeable pavement systems surface.
- *Soil Layer*: Engineered soil mixture used in bio-retention cells or, in pavement systems, sand layer that provides bedding and filtration to the pavement layer.
- *Drain system*: This layer conveys water out of storage layer into an outlet pipe or chamber.
- *Drainage Mat Layer*: Material or layer which allows conveyance to any water that drains through the soil layer off in a green roof.

In Table 1 the combination of layers in each LID type is shown.

LID Type	Surface	Pavement	Soil	Storage	Drain	Drainage Mat
Bio-Retention Cell	X		X	Optional	Optional	
Rain garden	X		X			
Green Roof	X		X			X
Permeable Pavement	X	X	Optional	X	Optional	
Infiltration trench	X			X	Optional	
Rain Barrel				X	X	
Roof Disconnection	X				X	
Vegetative Swale	X					

Table 1. Layers used to model LID units

This software needs information to characterize both, the precipitation event and the subcatchments where it is applied.

Rain gauges, enables to characterize the precipitations through the following information:

- Rainfall data in terms of intensity, volume or cumulative volume.
- Recording time interval (hourly, 15 minute, etc.)
- Source of rainfall data: input time series or external file
- Name of rainfall data source

Subcatchments are hydrological units of land whose topography and drainage system route the surface runoff to a single drainage point. These areas are divided into permeable and impermeable subareas.

To characterize them the main parameters needed are: assigned rain gauge, outlet node or sub-catchment, assigned land uses, tributary surface area, imperviousness, slope, characteristic width of overland flow, percentage of impervious area with no depression storage, Manning's n for overland flow and depression storage are needed on both, pervious and impervious areas (EPA, September 2015).

It is also required to provide the following climatological information:

- *Temperature*: These data is used to compute daily evaporation rates. It can be introduced with user-defined time series or through an external climate file with maximum and minimum values.

- *Evaporation*: This phenomenon can occur either in stagnant water on sub-basin surfaces, in groundwater aquifers or in water retained in storage units. Evaporation rates can be defined as a single constant value, a set of monthly mean values, a user-defined time series of values, values calculated from the daily temperatures contained in an external climate file or as daily values read directly from an external climate file (EPA, September 2015).

3. STUDY AREA DESCRIPTION

3.1 Location

The area of study is located in the city of Glasgow, with a population of 621,020 inhabitants, it is the most populated city in Scotland and the third largest in the United Kingdom. Glasgow is located on the banks of the Clyde River in the lowlands of Scotland.

Figure 7. General location of Cathedral street

Cathedral street is located in the university area of Strathclyde University. It is 787 meters long, and it extends from its intersection with North Hanover Street to Castle Street where it is located the cathedral. It is a street with two lanes in each direction and bus stops on both sides.

Regarding the study area, it includes the surroundings whose runoff ends in Cathedral street. Figure 8 shows Cathedral street and its surrounding areas.

Figure 8. Location of the study area. Source: Google Earth

3.2 Topography

EDINA Digimap (The University of Edinburgh, 2019) is a data delivery service from the University of Edinburgh which offers access to a wide range of geospatial information. From its VectorMap Local the topographical information of the area was obtained. It was observed that the study area has two distinct sections. On one side there is an area that tends towards the west. The part of the Cathedral street road that is in this first section has a length of 370 meters and an average slope of 4%. On the other side, the second section tends towards the east with an average gradient of 3.3% and a length of 411 meters.

Through this topographical information two areas whose runoffs flow to Cathedral street are considered. One to the north with a maximum slope of 9.4%. The other one goes to the south with a slope of 8%. Maps related to this information can be found in the Annex 1 of this document.

3.3 Land uses

The area of study has been simplified into three land use typologies: green areas, building areas and paths. The green area is of permeable nature while the others are impervious zones. The distribution of the three typologies within the study area is illustrated in the following figure. The total study area is 151,299 m^2. Through the information obtained from EDINA Digimap, Google Earth and site visits, it has been possible to verify that 26% of the area is of building type, 27% of green type and 47% of path type. For this study is considered that the precipitation falling in buildings contributes to the surface runoff as if it fall on an impermeable surface at ground level.

Figure 9. Land use distribution

3.4 Rainfall data

Precipitation data has been obtained using drainage models from the Flood Estimation Handbook (FEH) (Center for Ecology and Hidrology, 2019), as recommended by CIRIA in the SuDS Manual (2015). As described by Svensson & Jones (2010) the rainfall frequency estimation method of FEH uses the FORGEX method followed by the fitting of a depth-duration-frequency model. FORGEX is an index-flood method that utilises the median AM rainfall as index. Using the Least Squares technique linear segments are adjusted to the AM and then the depth-duration-frequency model is adjusted following a LogGumbel distribution. Circular regions are expanded with a maximum radius of 200km to estimate a particular section of the growth curve. The method uses network maximums and individual gauge series, taking into account the spatial dependence of the data.

FEH provides information about the different rain events through intensity, duration and frequency graphs. Figure 10. Intensity, duration and frequency curves in the study area provides the results obtained where the University of Strathclyde is located.

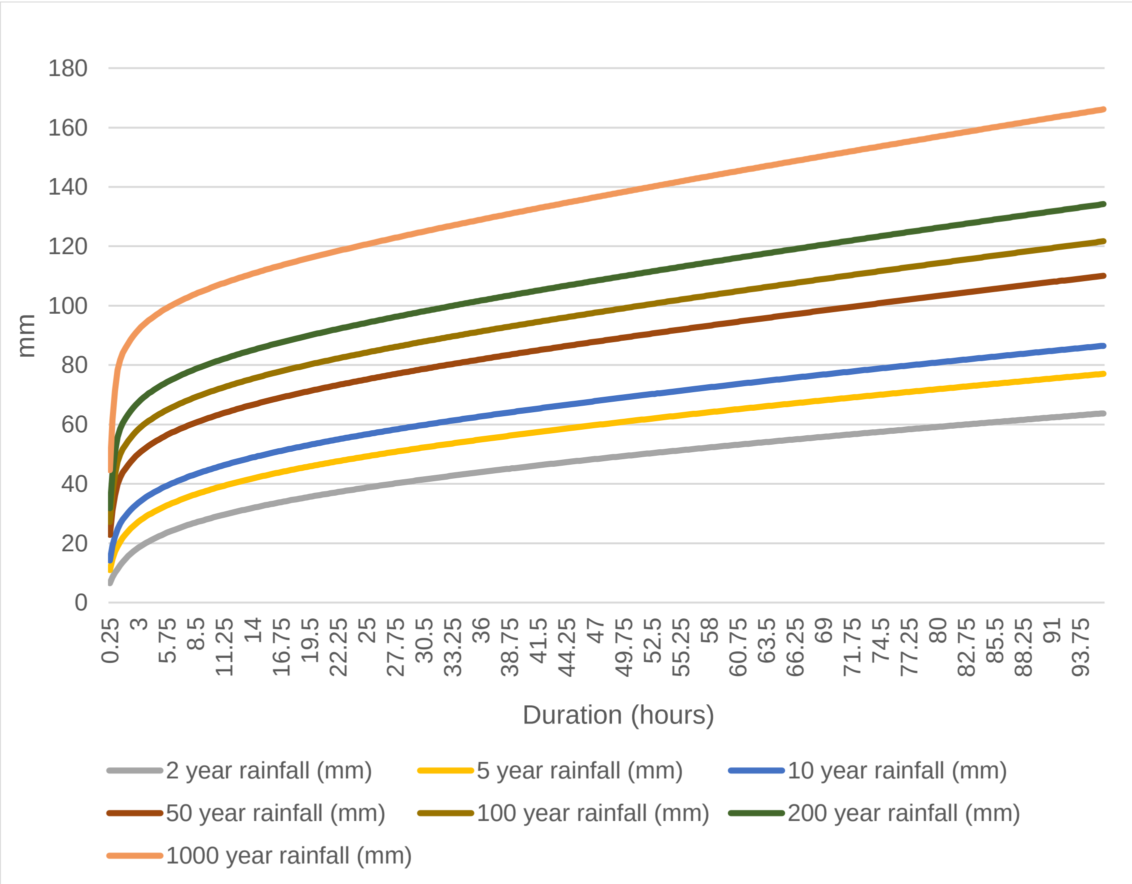

Figure 10. Intensity, duration and frequency curves in the study area

For the design of the different alternatives proposed for Cathedral Street, a design rain event with return period of 200 years has been considered as proposed by CIRIA (2015, p. 510). CIRIA considers the design of normally attenuated storage units to reduce SuDS storage requirements. Since the critical duration of the attenuation storage system is typically less than six hours, CIRIA recommends a design event of 6 hours. In addition, the current situation of the area without SuDS has been analysed for a T=10 years to evaluate the behaviour of the area in a more ordinary situation. With the information obtained from IDF curves of these two return periods, the hyetographs have been obtained through alternate block technique. The 10-years event has an accumulated precipitation of 39.75 millimetres while the 200 years event, has an accumulated precipitation of 74.7 millimetres.

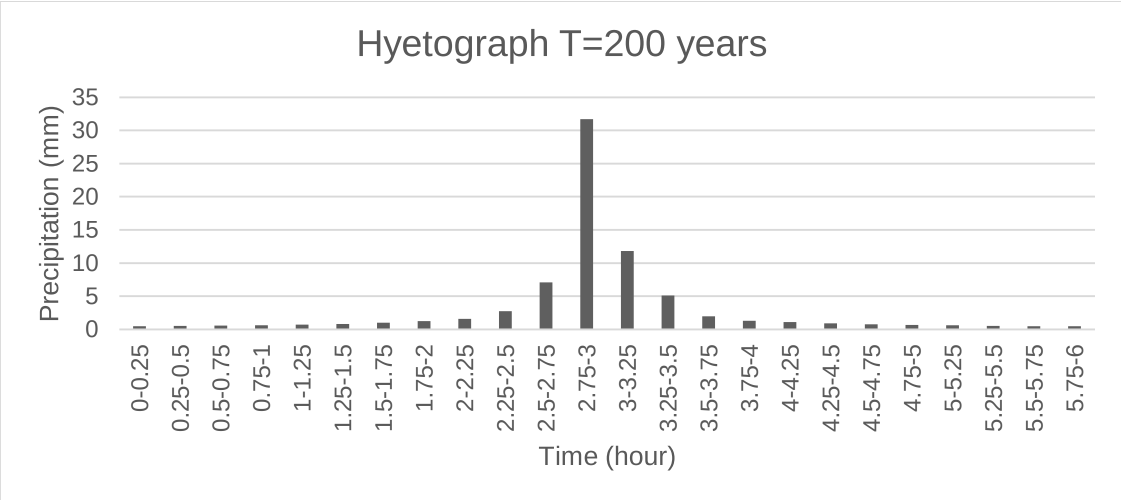

Figure 11. Hyetograph of 200 years return period

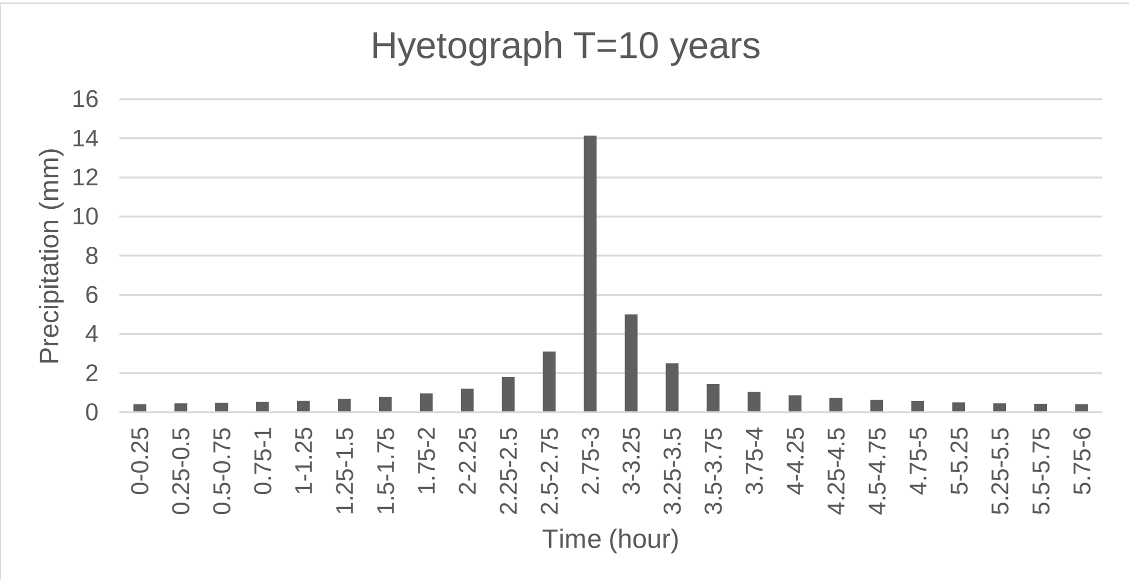

Figure 12 Hyetograph of 10 years return period

3.5 Climatology data

Glasgow Open data offers a rich resource of weather information. Regarding average temperature, it offers information of West Scotland measured from 1910 to 2013 which has been collected using the main weather station based in Bishopton.

For this project, information from 2002 to 2012 has been considered and the average for each season has been obtained. Specifically, to develop the different alternatives, it will be considered an event in spring which represent an average situation.

Season	Average Temperature (°C)
Winter (Dec-Feb)	3.6
Spring (Mar-May)	**7.6**
Summer (June-Aug)	13.5
Autumn (Sept- Nov)	9.04

Table 2. Seasonal average temperature in 2002-2012

Climate hydrology and ecology research support system potential evapotranspiration dataset (1961-2015) (CHESS-PE) provides information on daily potential evapotranspiration using a 1 kilometre resolution grid over Great Britain (Robinson, et al., 2016). Data is based on Penman-Monteith potential evapotranspiration which is obtained assuming a well-watered grass surface and considers air temperature, specific humidity, downward long and short radiation and surface air pressure from the CHESS-met dataset. (Robinson, et al., 2016)

The values obtained from the 2011 spring can be seen below. The data from the 18-05-2011 of a 2.37 mm/day evapotranspiration will be used for this project, which represent an average spring day.

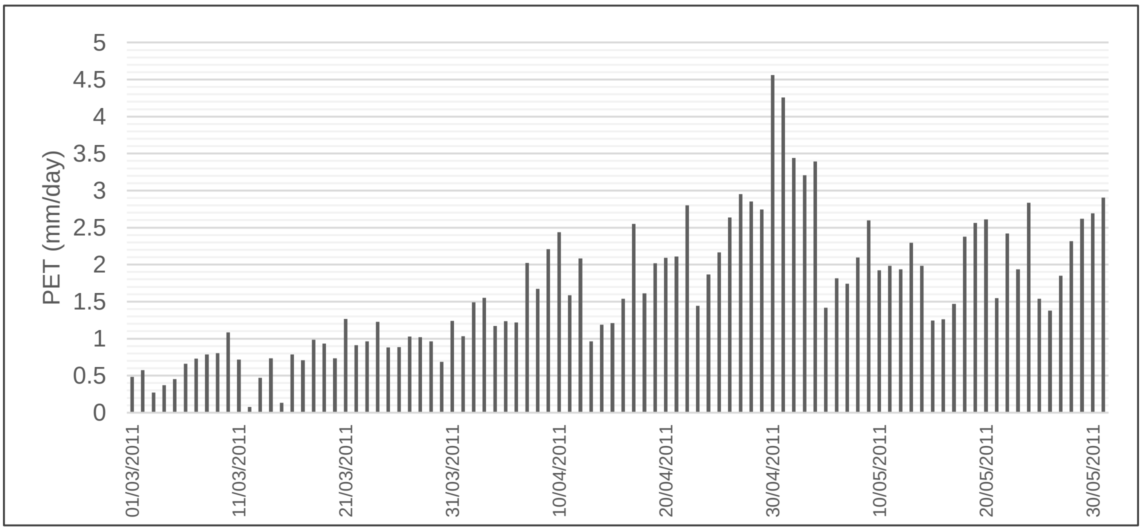

Figure 13. PET for 2011's Spring

4. ACTUAL SITUATION MODEL

Using the topographical, climatological and hydrological information explained in the previous section, the model of the actual situation has been carried out, where it is considered that no SuDS technique has been applied. This first alternative (Alternative 0) has been used as the baseline to analyze other alternatives.

4.1 Area discretization

As a result of the conclusions obtained from the topographical study, it has been decided to divide the study area into two basins. These are differentiated according to whether the runoff flows west or east. The basin whose runoff flows west has been subdivided into three sub-basins named W. The other basin has been discretised into six sub-basins labelled with the letter E. The subcatchments have been selected in a way that land uses and slopes are as much homogeneous as possible. Table 3 shows total area and land uses for each subcatchment.

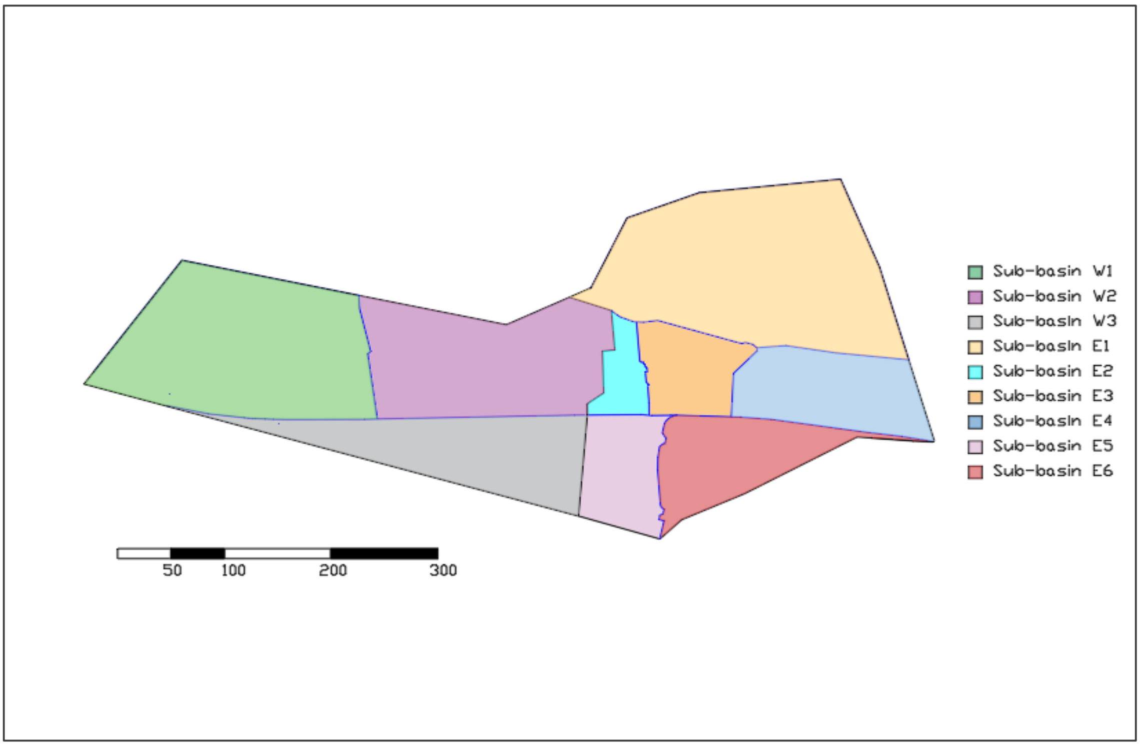

Figure 14. Subcatchments distribution

Subcatchment	Total Area (m^2)	Building area (m^2)	Green area (m^2)	Path area (m^2)
W1	31137	2224	14976	13937
W2	23727	15454	0	8274
W3	14477	5110	294	9072
E1	37220	4901	14495	17825
E2	3578	0	1101	2477
E3	7693	5299	0	2395
E4	12950	826	3747	8377
E5	8341	2850	894	4596
E6	12176	2664	5412	4100

Table 3. Land uses areas for each subcatchment

To perform the model, it is required to know some characteristics of each sub-basin:

- *Subcatchment area* (Area): Area of the subcatchment including any LID controls.
- *Characteristic width* (Width): Characteristic width of the overland flow path for sheet flow runoff.
- *Slope* (%Slope): Average percent slope of the subcatchment.
- *Impervious percentage* (%Imperv): Percent of land area excluding the area of LID controls which is impervious.
- *Impervious area roughness* (N-Imp): Manning's n for overland flow over the impervious portion of the subcatchment.
- *Pervious area roughness* (N-Perv): Manning's n for overland flow over the pervious portion of the subcatchment.
- *Impervious area depression storage* (Dstore-Perv): Depth of depression storage on the impervious portion of the subcatchment.
- *Pervious area depression storage* (DStore-Imp): Depth of depression storage on the pervious portion of the subcatchment.

The percentage of imperviousness has been obtained based on the assumption that land uses of buildings and paths are impervious, therefore:

$$\%Impervious = \frac{Building\ Area + Path\ Area}{Total\ Area}\ x100$$

The impervious area roughness and depression storage parameters have been calculated using a weighted-average. It has been considered that Path's land use was mostly smooth asphalt while Buildings were smooth concrete. The values used for the different Manning's n have been obtained from the software manual (EPA, September 2015). With regard to depression storage it was considered that in both cases the land use was a value of 2 millimetres.

$$Nimperv = \frac{Building\ Area * n\ concrete + Path\ Area * n\ asphalt}{Total\ Impervious\ Area}$$

Also, the parameters for the permeable area were obtained. In this case green area has been classified into areas of grass and wood areas. Grass short and woods light parameters have been obtained from the software manual and can be consulted in table 4.

Surface	n
Smooth asphalt	0.011
Smooth concrete	0.012
Grass	
Short, prairie	0.15
Dense	0.24
Bermuda grass	0.41
Woods	
Light underbrush	0.4
Dense underbrush	0.8

Table 4 Manning’s n- overland flow values. Source: SWMM Manual

Surface	Dstore (inches)
Impervious surfaces	0.05-0.10
Lawns	0.10-0.20
Pasture	0.20
Forest litter	0.30

Table 5 Depression storage values. Source: SWMM Manual

Using the methodology explained above, the following values were obtained to characterize each of the sub-basins.

	Area (hec)	Width (m)	% Slope	% Imperv	N-Imp	N-perv	Dstore-Imp (mm)	Dstore-Perv (mm)
W1	3.11	217.3	11	52	0.0119	0.167	2.00	5.17
W2	2.37	220.3	6.67	100	0.0113	0.00	2.00	0.00
W3	1.45	235.9	7.4	98	0.0116	0.202	2.00	5.52
E1	3.72	253.4	5.5	61	0.0118	0.259	2.00	6.09
E2	0.36	40.4	7.1	69	0.0120	0.150	2.00	5.00
E3	0.77	84.1	7.1	100	0.0113	0.000	2.00	0.00
E4	1.29	162.5	2.5	71	0.0119	0.243	2.00	5.93
E5	0.84	70.2	7.92	89	0.0116	0.188	2.00	5.38
E6	1.22	206.8	3.77	56	0.0116	0.183	2.00	5.33

Table 6. Characteristic parameters of each subcatchment

4.2 Subcatchments connections

As previously mentioned, the topography generates two main flows, towards east and west. For the study of the zone, two final drainage points (outlet points, denoted as Ox) have been established at the end of sub-basins E and W. The first one, O1, is located in the junction of Cathedral street with North Hanover street. The other point, O2, is in the junction of Cathedral street with Castle street. It is worth to note that both points are located just before junctions to eliminate the runoff from neighbouring basins

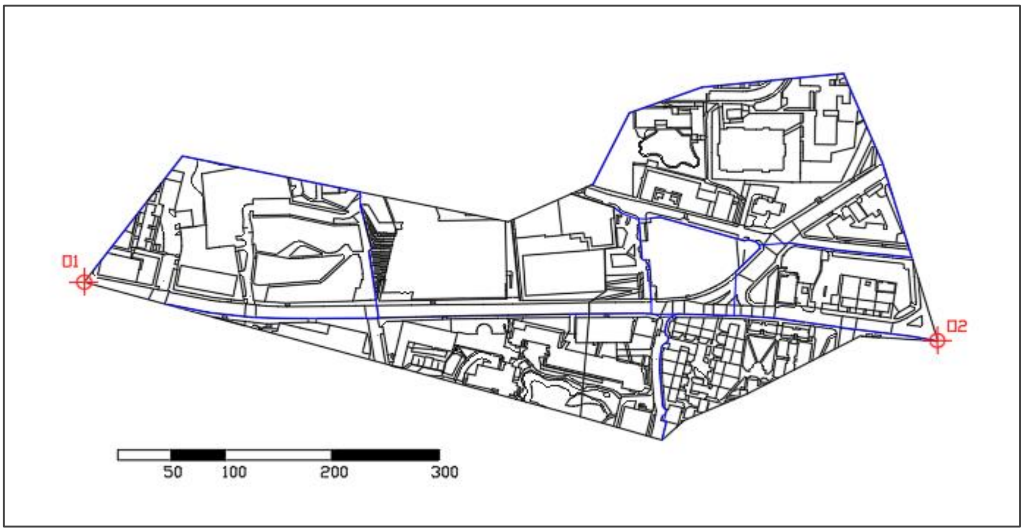

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Figure 15. Drainage points location

In order to convey the runoff generated by the subcatchments to the final drainage points, a sewage network has been assumed. This network is capable of supporting the rainfall event generated by the model but it is close to capacity for T=200. Sewerage pipes of 600 mm, 8000 mm and 1m have been assumed along Cathedral street and Stirling road.

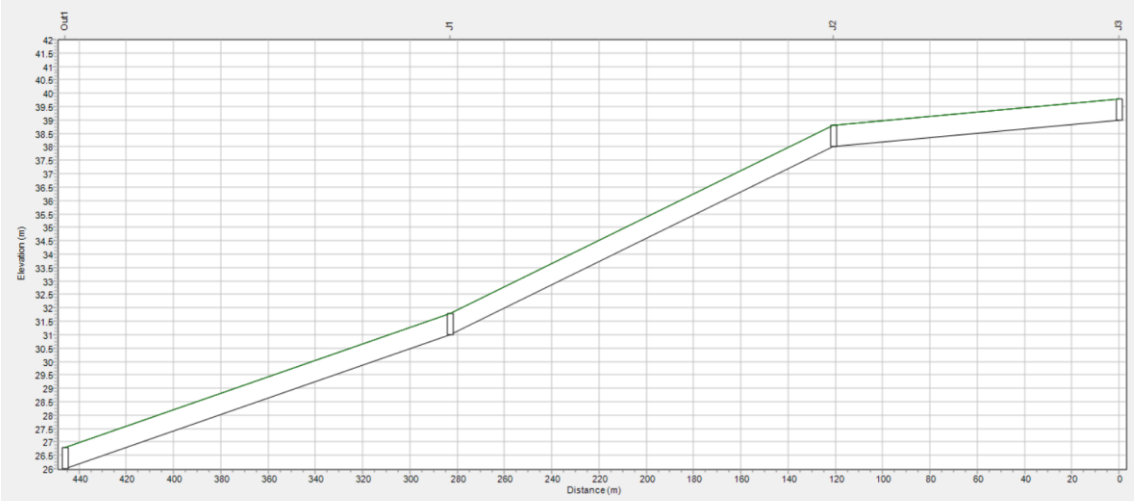

Figure 16. Sewerage system profile assumed for subbasin W

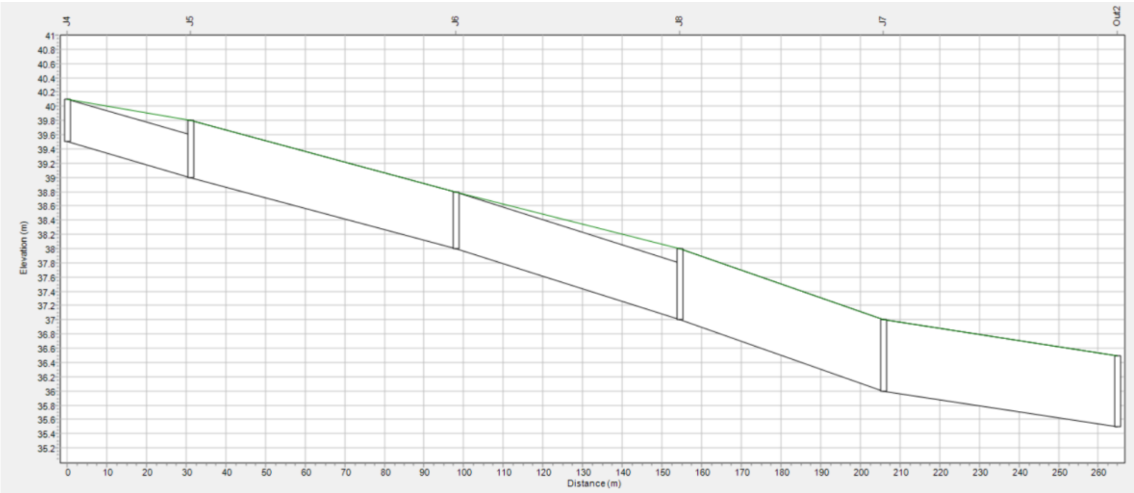

Figure 17. Sewerage system profile assumed for subbasin E

Runoff from the subcatchments reaches the main network through storm water discharge points. Once there, it will be conveyed to the final drainage point. Table 7 provides the distribution of subcatchment for each drainage point. Figure 18 shows where all the conveyor elements of the model are located.

Subcatchment	W1	W2	W3	E1	E2	E3	E4	E5	E6
Junction	J1	J3	J2	J9	J4	J6	J7	J5	J8

Table 7. Drainage points (junctions) for each subcatchment

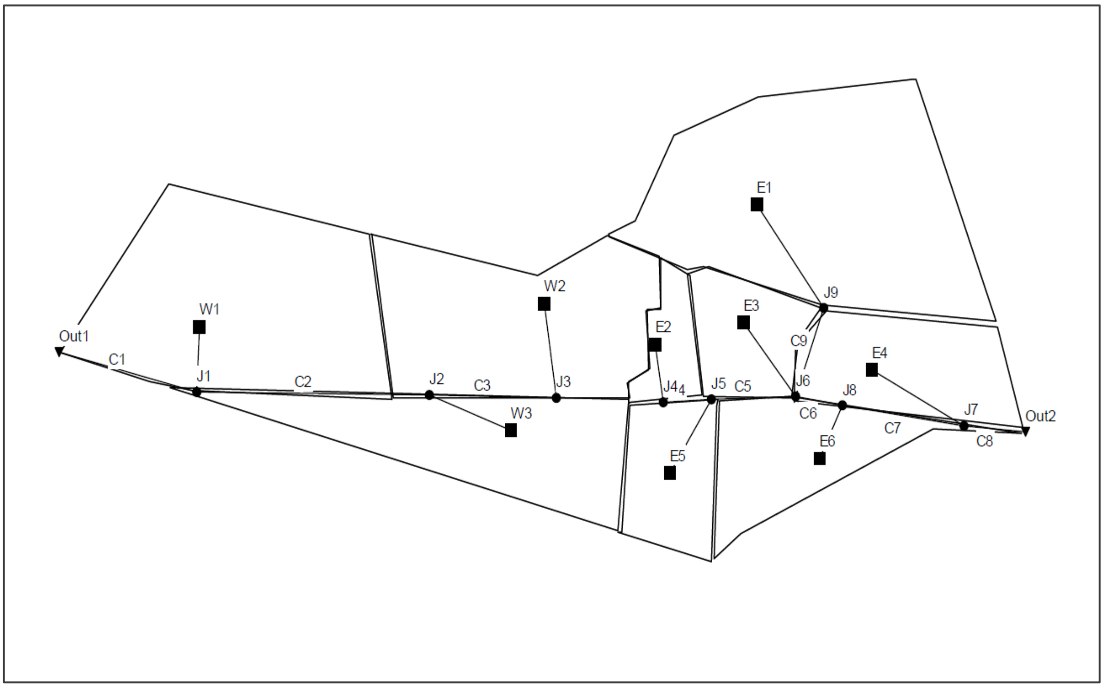

Figure 18. Conveyance elements of the SWMM model

4.3 Design rainfall comparison

The actual situation model has been simulated under two different rainfall events, T=10 years and T=200 years. Runoff quantity continuity results obtained from the SWMM software have been compared and are shown in table 8 to table 11. The results of evaporation, infiltration and storage losses do not vary in the two scenarios.

Runoff Quantity Continuity	Volume hectare (m)	Depth (mm)
Total Precipitation	0.59	39.35
Evaporation Loss	0.01	0.55
Infiltration Loss	0.02	0.99
Surface Runoff	0.53	34.72
Final Storage	0.05	3.31

Table 8. Runoff quantity continuity results for T=10 years

Outfall node	Max Depth	Max. Flow CMS	Peak Hour	Total 10^6ltr
Out 1	0.30	1.04	3:15	2.42
Out 2	0.44	1.15	3:15	2.79

Table 9. Outfall node results for T=10 years

Runoff Quantity Continuity	Volume hectare (m)	Depth (mm)
Total Precipitation	1.12	74.24
Evaporation Loss	0.01	0.56
Infiltration Loss	0.02	0.99
Surface Runoff	1.06	69.71
Final Storage	0.05	3.37

Table 10. Runoff quantity continuity results for T=200 years

Outfall node	Max Depth	Max. Flow CMS	Peak Hour	Total 10^6ltr
Out 1	0.54	2.40	3:15	4.85
Out 2	0.78	2.74	3:15	5.66

Table 11. Outfall node results for T=200 years

Considering the results obtained for each of the sub-basins, which are found in Annex 2, it can be seen that in both situations subcatchments W2, E3 and E5 are the ones that generate the most runoff because these have the greatest imperviousness.

After observing the behaviour of the model under the two scenarios, it was decided to design SuDS alternatives for the event with a return period of 200 years.

5. SuDS Alternatives

Considering the current state of the environment at Strathclyde University, the areas in which there has been major maintenance or have been repaired recently have not been taken into account to apply SuDS techniques. The techniques also attempt to modify the permeability of the areas that generate greater surface runoff.

Therefore, due to its recent construction, no action has been applied in the green zone of the W1 sub-basin nor in the pedestrian zone with green spaces between the library and the gymnasium in the E2 subbasin.

Figure 19. Green zone in subcatchment W1

Figure 20. Pedestrian zone in subcatchment E2

The areas with the highest imperviousness index are affected by buildings. That is why it is considered the construction of green roofs. Large spaces with safe accesses are required for its construction and maintenance. The clearest roofs of all buildings were found in the library and gymnasium buildings in sub-basins E3 and W2.

Figure 21. Roof of the library building

Within the possible actions in the Path land use, the renovation of the cathedral street pavements has been considered due to its current deteriorated state. These construction of permeable pavements would allow the infiltration of precipitation reducing surface runoff.

Figure 22. Actual state of Cathedral street pavements

Due to the deteriorated condition and the large impervious area of the E1 and E4 sub-catchment car parks, it seemed reasonable to consider SuDS techniques. The slopes of the car parks allow runoff to be directed towards permeable areas. It is considered the construction of permeable pavements with a storage layer that allows the reuse of water.

Figure 23. E4 Parking state

Figure 24. E4 Parking actual state

In the university halls zone, subcatchment E6, there is an area where several slopes converge. This is located near the Lord Todd Village Office and is a pedestrian square. The implantation of a filtering or retaining element in the centre of the area would collect the runoff generated by the upper sub-basin areas.

Figure 25. Pedestrian square in E6

Four alternatives have been modelled in SWMM independently, as well as jointly, to verify the implications of their performance in the whole basin.

5.1 Alternative 1. Green roof alternative

5.1.1 Description

The first alternative is based on the installation of green roofs. Green roofs are designed to filter, absorb and retain rainwater that falls directly on the area in which they are placed.

The areas where this type of SuDS will be applied are on part of the roofs of the gymnasium and library buildings. These sites have been taken into account since the areas are large and unobstructed. In addition, they have access for easy and safe maintenance.

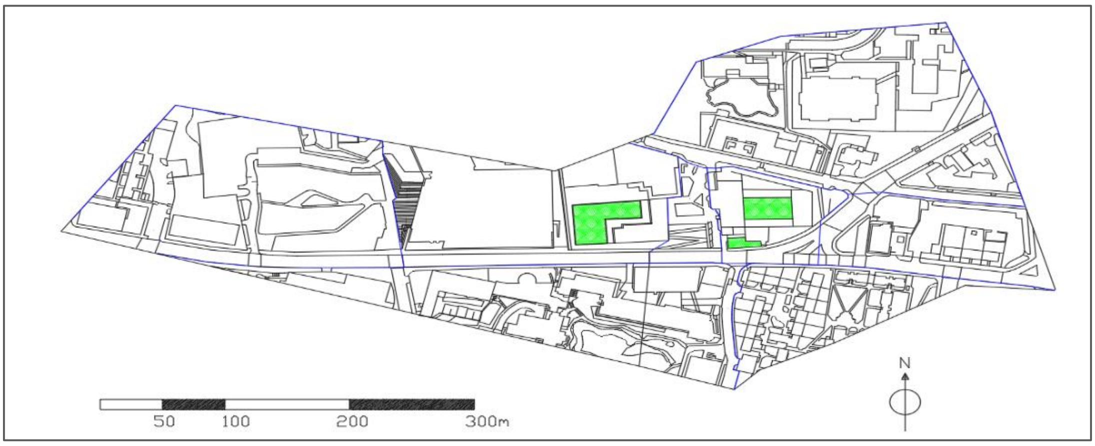

Figure 26. Detail of green roof location

It is proposed to implement extensive roofs. This typology allows low-maintenance species such as mosses, herbs or grasses to be planted. This reduces maintenance costs and the need for a sophisticated irrigation system. Extensive roofs require a thinner layer of soil which reduces the loads on the structural elements of the building.

The extensive roof section consists of several layers. A layer of soil where vegetation is planted, a drainage and storage layer, a layer that prevents rooting and a waterproof layer to prevent humidity in the building.

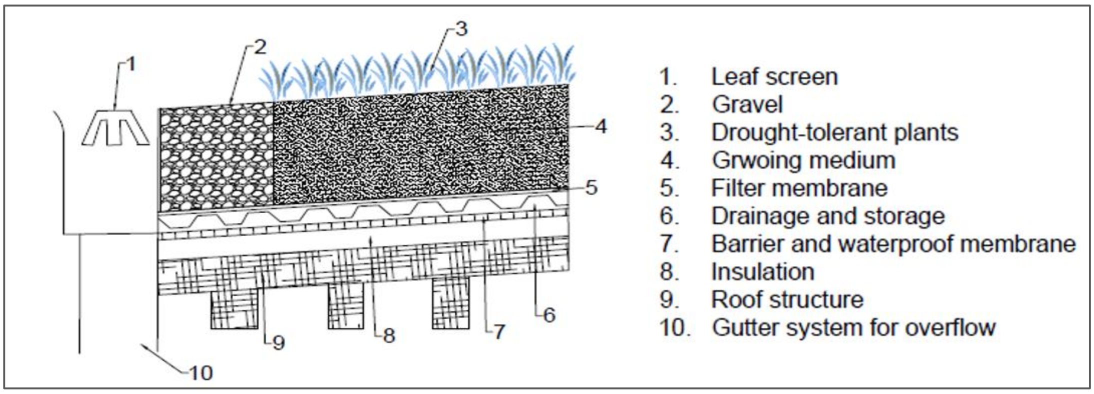

Figure 27. Green roof section

The construction of this type of drainage system is often expensive. Approximate data for construction and maintenance costs as well as lifespan were obtained from the E^2Stormed project (Morales Torres, Perales Momparler, Jefferies, & Andrés Domenech, 2015):

	Cost	Units
Construction	125	£/m^2
Maintenance	13	£/m^2/year
Life span	40	years

Table 12. Construction and maintenance cost and life span of Green roofs

5.1.2 SWMM Model

The model of the current situation has been modified by adding two LID controls on W2 and E3 subcatchments. The installation of green roofs entails the modification of 1,423 m^2 in W2 and 891 m^2 in E3. Therefore, with this alternative, 2,314 m^2 of conventional roofs are modified. Consequently, the percentages of impermeability have been modified to compensate the action of the SuDS, resulting the following characteristics:

	Total Area (hec)	Width (m)	%Slope	%Imperv	N-Imperv	N-perv	Dstore-Imp (mm)	Dstore-Perv (mm)
W2	2.373	220.3	6.67	94.00	0.0114	0.00	2	0.00
E3	0.769	84.1	7.1	88.42	0.0114	0.000	2	0.00

Table 13. Characteristic parameters of W2 and E3 subcatchment on alternative 1

The extensive green roof cross-section has been modelled using a Green Roof Lid Type in SWMM. This LID control has three layers:

-*Surface*: It has been considered that there are no berms and that the surface has a slope of 1% and a Manning's n of 0.15.

- *Soil*: It has been assumed a 150 mm thickness soil

- *Drainage Material*: A 26 mm thick drain has been assumed with a void fraction of 0.5 and a Manning's n of 0.2.

Overflow from vegetated roofs is routed to the same drainage point as in the current situation. The following figure show the LID usage of the model.

5.2 Alternative 2. Permeable pavements alternative

5.2.1 Description

The second alternative is the installation of permeable pavements on the pavements of Cathedral street. This alternative allows rapid rainwater infiltration into the storage layer. This layer allows temporary storage as well as reducing contaminants that are dissolved in the water.

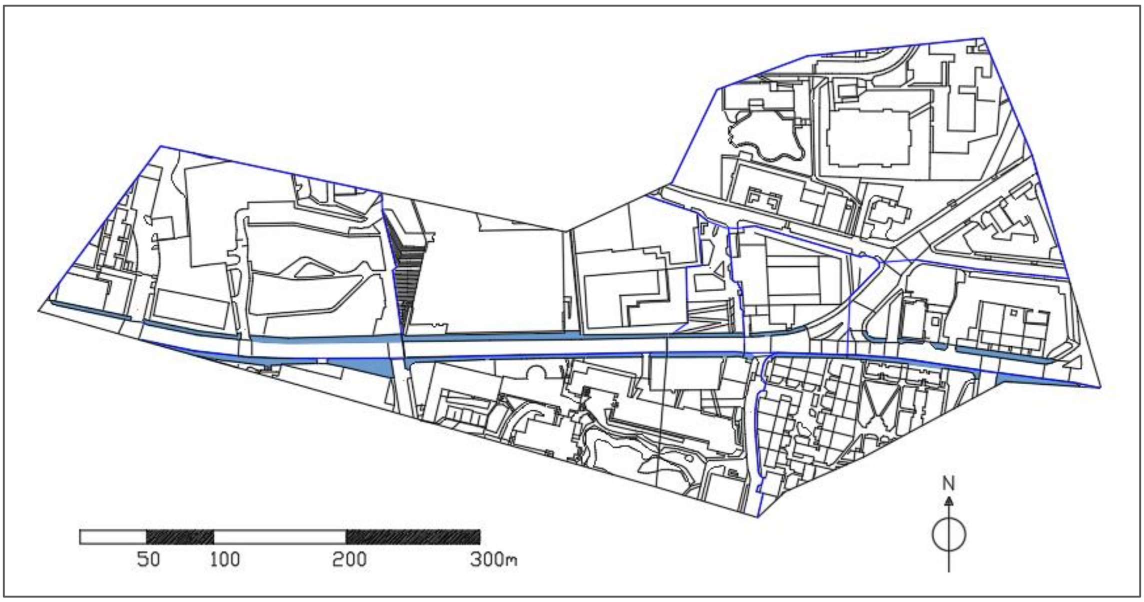

Figure 28. Location of alternative 2

It is proposed to install permeable pavers. This is a structural unit with joints filled made of permeable material, which allows infiltration of storm water runoff. Under this first layer there is a storage layer, that has a drain in its bed which allows drainage of water that has not been infiltrated and takes it to the drainage network.

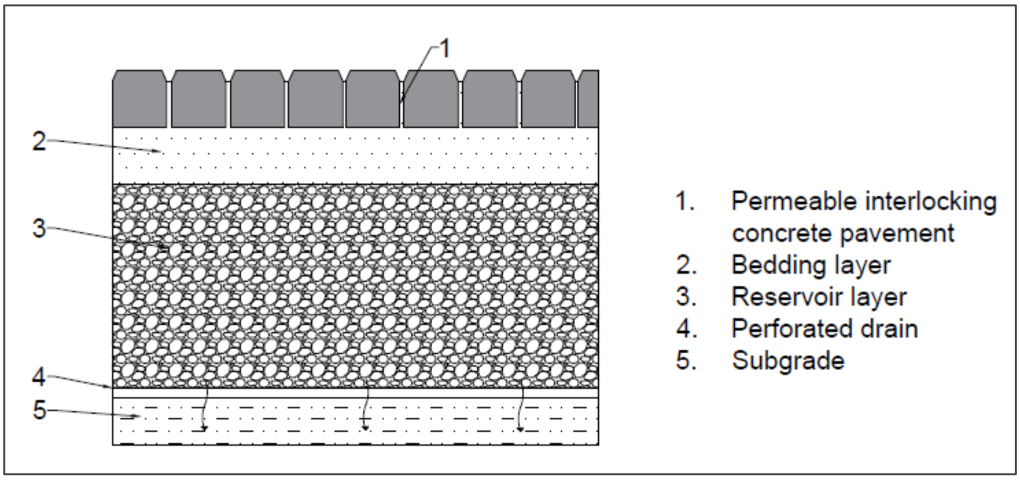

Figure 29. Permeable pavement section

Approximate data for construction and maintenance costs as well as lifespan were obtained from the E[2]Stormed project (Morales Torres, Perales Momparler, Jefferies, & Andrés Domenech, 2015):

	Cost	Units
Construction	52	£/m^2
Maintenance	1	£/m^2/year
Life span	20	years

Table 14. Construction and maintenance cost and life span of permeable pavements

5.2.2 SWMM Model

Five new subcatchments have been created (R1, R2, R3, R4 and R5) to represent the affected areas by the SuDS. They represent the pavement, where SuDS techniques are applied, and the road area whose runoff is infiltrated by the permeable pavement. Table 15 indicates the permeable (pavements) and impermeable (road) area of each Rx sub-basin, its waterproofing percentages and their impervious:pervious ratio.

Subcatch	Zones	m^2	%Imp	Ratio imper:perv
R1	Perm	1866	62.8	1.69
	Imper	3150		
	Total	5016		
R2	Perm	1475	60.0	1.50
	Imper	2209		
	Total	3684		
R3	Perm	387	62.5	1.67
	Imper	645		
	Total	1032		
R4	Perm	322	64.1	1.78
	Imper	574.7		
	Total	896.7		
R5	Perm	1093.875	65.0	1.86
	Imper	2034		
	Total	3127.875		

Table 15. New subcatchment properties

The permeable pavement section has been modelled with a permeable pavement LID type as follows:

- The pavement layer has been decided to be of 120mm with a permeability of 1200 mm/hour indicated by Interpave (Interpave, 2011).
- The storage layer was considered to be 225 mm with a low infiltration of 0.5 mm/hour as the information from the area indicates that infiltration may be either high or low.

- The drainage has been considered to be located in the lower part of the storage layer. Considering a flow exponent of 0.5 it has been requested that the totality of the potentially stored water be drained in the following 24h. Therefore, for a distance of 345 mm the flow coefficient is 1.5.

$$Flow\ coefficient = (2 * Distance\ from\ the\ drain\ to\ the\ surface^{0.5})$$

Subcatchments modeled in the actual situation model have been modified in their parameters to compensate for the loss of the area of the new subcatchments. The new values are shown in table 16.

	Total Area (hec)	Width (m)	%Slope	%Imperv	N-Imperv	N-perv	Dstore-Imp (mm)	Dstore-Perv (mm)
W1	2.708	217.3	11	44.70	0.0118	0.167	2	5.17
W2	2.066	220.3	6.67	100.00	0.0113	0.00	2	0.00
W3	1.290	235.9	7.4	81.00	0.0115	0.198	2	5.48
E1	3.722	253.4	5.5	59.57	0.0118	0.255	2	6.05
E2	0.276	40.4	7.1	60.17	0.0120	0.150	2	5.00
E3	0.700	84.1	7.1	100.00	0.0112	0.000	2	0.00
E4	1.042	162.5	2.5	64.06	0.0119	0.211	2	5.61
E5	0.809	70.2	7.92	93.67	0.0116	0.216	2	5.66
E6	1.157	206.8	3.77	53.24	0.0116	0.183	2	5.33

Table 16. Characteristic parameters of each subcatchment on permeable pavements alternative

Water drained by the RX sub-basins returns to the network by the junctions shown below:

Subcatchment	R1	R2	R3	R4	R5
Junction	Out1	J2	J5	J6	Out 2

Table 17. Junctions of Rx subcatchments

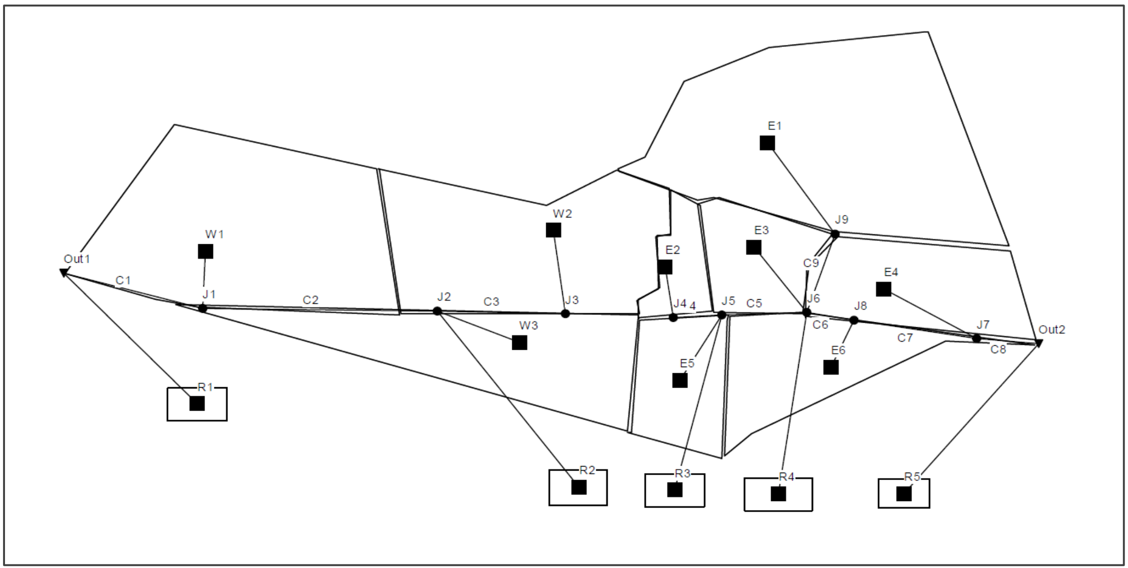

Figure 30.SWMM model for permeable pavement alternative

5.3 Alternative 3. Geocellular systems alternative

5.3.1 Description

The third alternative aims to create storage areas under car parks located in the eastern part of the studied area. The storage structures are proposed to be implemented using geocellular systems. These systems are easier to install and more versatile than stone-filled systems. Geocellular systems permit to achieve higher void ratio levels, which makes them more efficient.

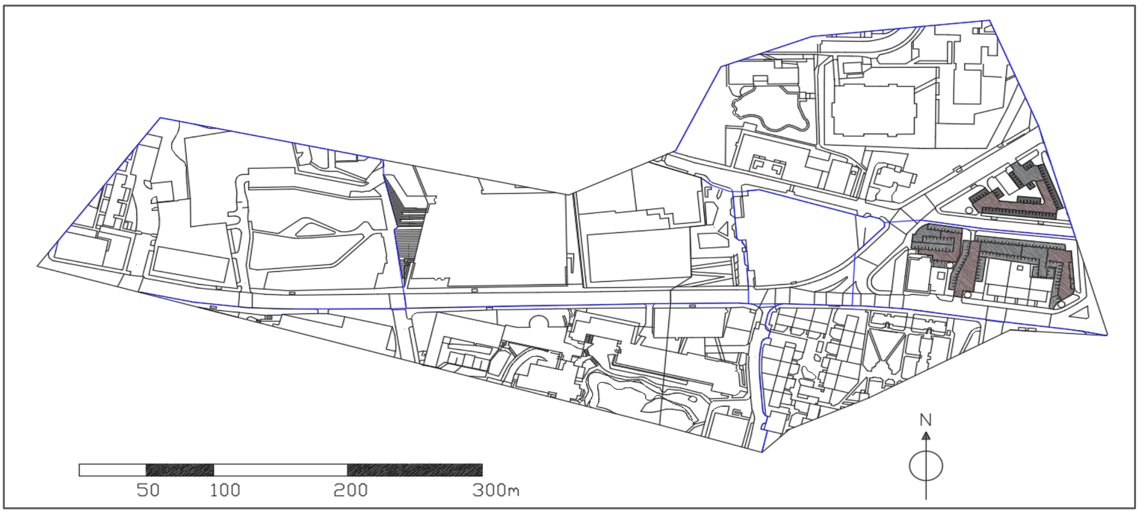

Figure 31. Location of alternative 3

SuDS surface layer has been considered of permeable porous asphalt which allows runoff infiltration. The asphalt is placed over a granular cover layer with a minimum of 0.75 meters that allows the geocells to support the loads of traffic and parking of vehicles (Wavin, 2016). Under there is a layer of permeable geotextile that prevents sedimentation.

The geocellular system is composed of two zones. The first zone has 30 mm cells that allow the infiltrated water to be conveyed to the second zone where the water is stored in modular tanks of 450 mm like those observed in the Atlantis catalogue (2016).

Due to the lack of information on the soil permeability, an impermeable geomembrane at the bottom layer is considered. The stored water will be extracted using a hydraulic pump. The overflow from the storage is connected to the network via a pipe at the top of the storage layer.

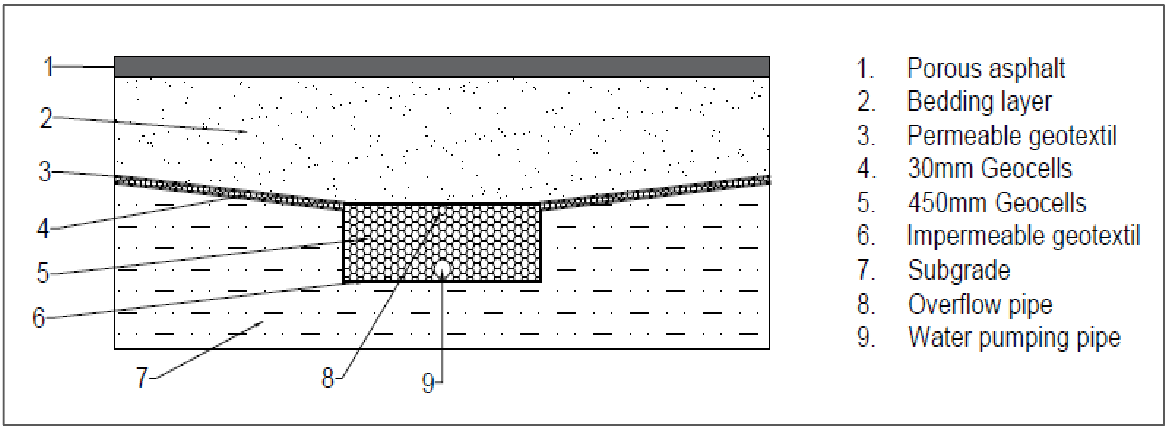

Figure 32. Geocellular alternative cross section

Depending on the part of the section, two costs have been considered to obtain the total cost for this alternative. On one hand, costs of 30mm cell area are similar to cost of permeable pavement, but it is added to the construction cost of £15/m2 for the geotextile and cells. On other hand, the construction and maintenance cost for the 450mm cell area is established from the E^{2}Stormed project (Morales Torres, Perales Momparler, Jefferies, & Andrés Domenech, 2015).

	Cost	Units
Construction cells 450mm	302	£/m^3 stored volume
Maintenance cells 450mm	0.7	£/m^3 stored volume/year
Construction cells 30mm	67	£/m^2
Maintenance cells 30mm	1	£/m^2/year
Life span	20	years

Table 18. Construction and maintenance cost and life span of alternative 3

5.3.2 SWMM Model

Five new subbasins have been created: E1-1GZ, E1-1, E4-1, E4-2A and E4-2B. These subcatchments represent the areas affected by geocellular systems in three car parks.

The car park in the E1 sub-basin is called E1-1 and besides treating the impervious part, it handles the runoff of the E1-1GZ green zone upstream. This may lead to clogging problems due to the possible transport of solid particles from this area, so a system must be installed to prevent it.

Within the E4 sub-basin there are two car parks E4-1 on the left and E4-2 on the right. In the latter, it has been decided to differentiate two parts, E4-2A and E4-2B due to the existence of different slopes. In figure 33 and 34 it is shown the location and nomenclature of the affected areas in the SWMM model.

Figure 33. Localization of new subcatchments for alternative 3

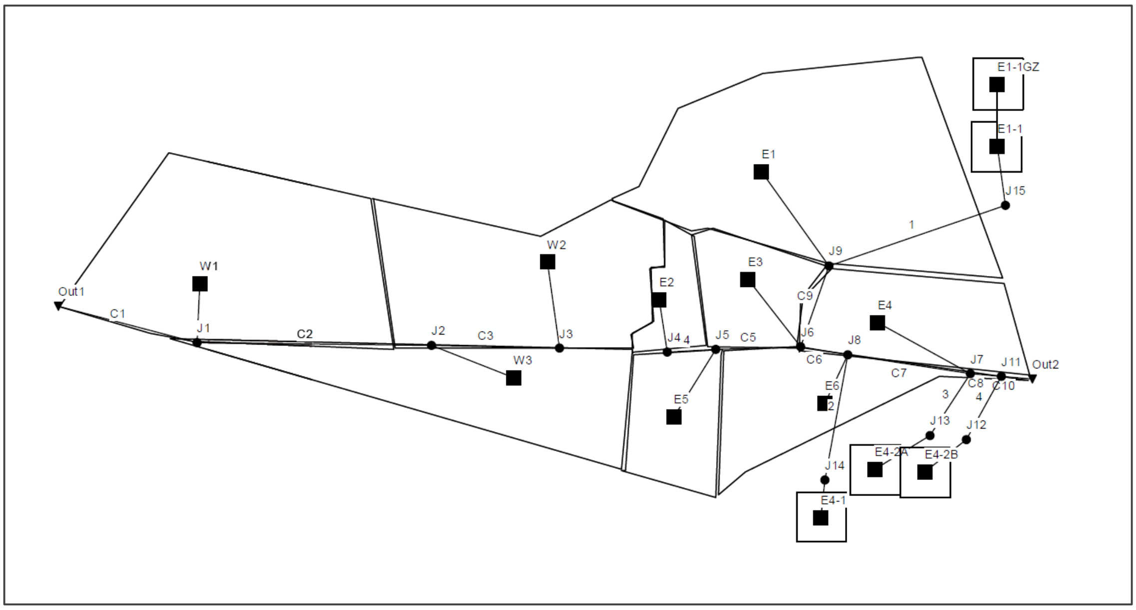

Figure 34. SWMM model for geocellular system alternative

The affected area has been divided in two, an impermeable area and a section in which the SuDS is applied. A maximum ratio of 2:1 between impermeable and permeable areas (impermeable: permeable) was considered as suggested by CIRIA.

Within the permeable zone, there will be, as mentioned above, a zone with 30 mm conductor cells and a 450 mm deposit cell zone. The 30 mm zone is considered to be 2/3 of the permeable zone, while the storage zone is 1/3.

In order to model this situation, the 30 mm cell area has been considered impermeable. This may cause the model to experience a delay in runoff infiltration due to the decrease of the permeable surface area.

In table 19 the area of each new subcatchment and the percentage of impermeability are presented, bearing in mind that only the area with a storage cell section is considered permeable.

Subcath	Zones	m^2	%IMPER
E1-1	Perm	263	85.7
	Imperm + 30mm cells	1575	
	Total	1838	
E4-1	Perm	131	87.2
	Imperm + 30mm cells	889	
	Total	1020	
E4-2A	Perm	154	88.9
	Imperm + 30mm cells	1234	
	Total	1388	
E4-2B	Perm	166	86.9
	Imperm + 30mm cells	1103	
	Total	1269	

Table 19. New subcatchment properties

Water drained by the new sub-basins returns to the network by the new junctions shown below:

Subcatchment	E1-1	E4-1	E4-2A	E4-2B
Junction	J15	J14	J13	J12

Table 20. Junction of new subcatchments

Subcatchment areas E1 and E4 have been modified and are characterized by the following updated parameters.

	Total Area (hec)	Width (m)	%Slope	%Imperv	N-Imperv	N-perv	Dstore-Imp (mm)	Dstore-Perv (mm)
E1	3.422	253.4	5.5	54.04	0.0117	0.264	2	6.14
E4	0.927	162.5	2.5	19.94	0.0116	0.211	2	5.61

Table 21. Characteristic parameters of each subcatchment on alternative 3

The cellular systems section has been modeled with permeable pavement LID control as follows:

- The pavement layer has a thickness of 120 mm with a void ratio of 0.2, and a hydraulic conductivity of 17000 mm/hour (Aggregate industries, 2014).
- A soil layer of 750 mm with a conductivity of 25 mm/hour.
- The storage layer is 450mm thick with a void ratio of 0.90 simulating geocellular systems. Infiltration losses have been avoided by giving a zero value to the seepage rate.
- In the event of filling the capacity of the storage layer, drainage has been modeled with high flow coefficient values to simulate a rapid exit of any excess water volume.

5.4 Alternative 4. Retention basin alternative

5.4.1 Description

The fourth alternative is based on the construction of a retention basin in the area of the university's student halls. This location has been considered due to the existing slopes that are concentrated in a central point, where the construction of the small retention basin is proposed.

Figure 35. Location of alternative 4 affected area.

The objective of this basin is to retain the runoff generated by green areas and part of the two-sided roofs around it. This water will be stored to reuse it in the surrounding green areas irrigation.

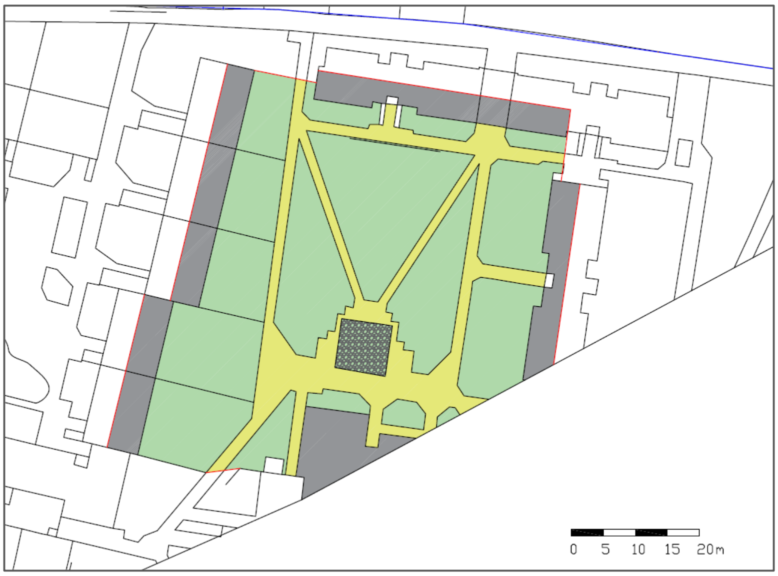

Figure 36. Affected area in alternative 4

This basin has berms that allow greater storage if necessary. The surface can be filled with water creating a small pond but if no further storage is needed, the vegetated surface can be transited. To reuse the volume stored in the system, a hydraulic pump will be placed in the lower part of the cellular storage layer.

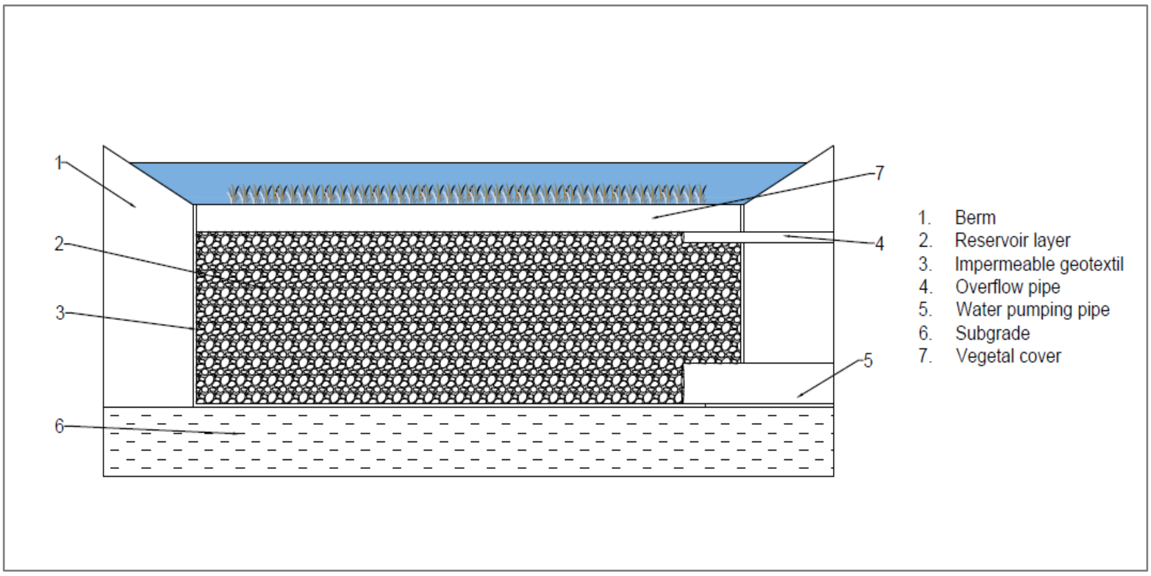

Figure 37. Alternative 4 cross section

Approximate data for construction and maintenance costs as well as lifespan were obtained from the E[2]Stormed project (Morales Torres, Perales Momparler, Jefferies, & Andrés Domenech, 2015). Costs have been obtained from the geocellular section. The costs are a function of the volume stored and therefore depend on the capacity of the storage layer.

	Cost	Units
Construction	305	£/m^3 stored
Maintenance	0.7	£/m^3 stored/year
Life span	30	years

Table 22. Construction and maintenance cost and life span of alternative 4

5.4.2 SWMM Model

The subbasin E6-1 has been created for modelling alternative 4. This subcatchment represents the SuDS area and the upstream subbasin.

Table 23 shows the total areas of each typology and the percentage of imperviousness of the subbasin. The permeable part of the subbasin is the set of green area and the retention basin, while the impermeable part is the total of the roads and half of the buildings. Only half roof has been considered assuming that each part of the roof has a separate downspout.

Subcatch	Zones	m^2	%Imper
E6-1	Perm	2115	39.24
	Imper	1366	
	Total	3482	

Table 23. New subcatchment properties

This new sub-basin has the point of drainage of non-stored water at junction J8, which is the same as subcatchment E6. Because of this incorporation, subbasin E6 has been modified and is characterized by the following parameters.

	Total Area (hec)	Width (m)	%Slope	%Imperv	N-Imperv	N-perv	Dstore-Imp (mm)	Dstore-Perv (mm)
E6	0.869	55.0	3.77	53.00	0.0116	0.203	2	5.53

Table 24. Characteristic parameters altered subcatchment on alternative 4

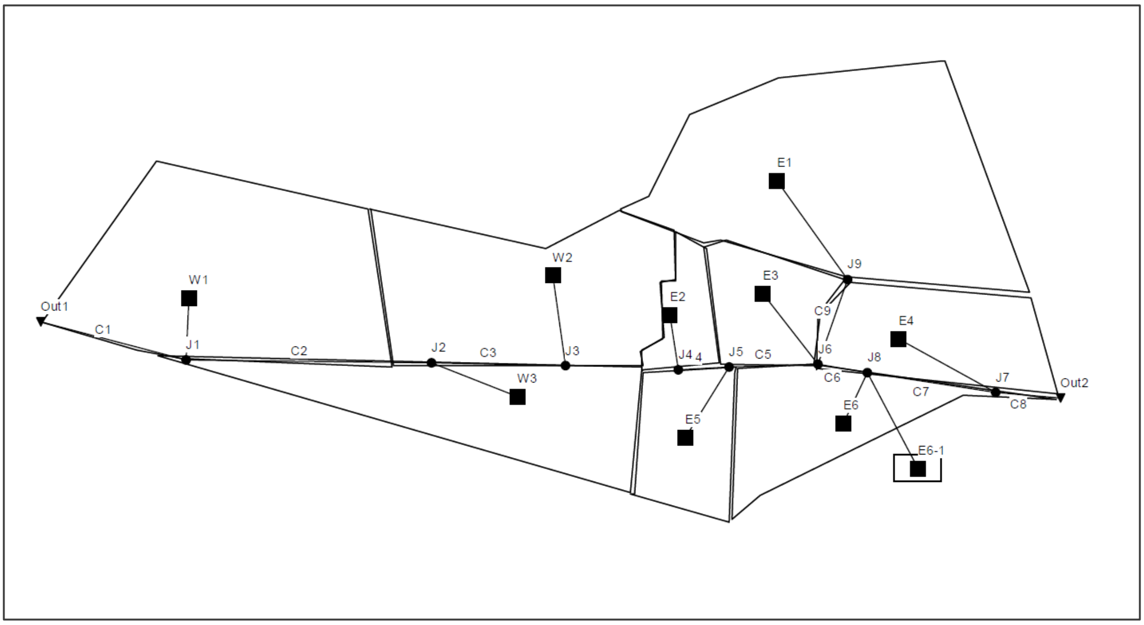

Figure 38. SWMM model for alternative 4

The retention basin section has been modeled with the LID Infiltration trench type of SWMM software. The different layers of the LID control have been characterized as follows:

- A 500 mm berm has been arranged in the Surface layer to allow extra storage.
- The Storage layer has a thickness of 900 mm with a void ratio of 0.9 which represents a geocellular deposit. In order to represent the impermeability of the bottom of the layer the seepage ratio has been considered zero.
- The Drain layer has a drain at a height of 500 mm (at the top of the storage layer) with a flow coefficient of 100 that allows the evacuation of overflows.

5.5 Alternative 5. Combination of previous alternatives.

5.5.1 Description

The fifth alternative combines the above alternatives and aims to analyse the behaviour of the basin by including all actions. Therefore, the affected areas are located in the same locations as in the previous cases. The following figure shows where the different SuDS are located.

Figure 39. Location of alternative 5 SuDS

The cost of this alternative has been assumed to be the total cost of the construction of green roofs, permeable pavements, car parks and the retention basin. In the same way, maintenance costs and annualised costs are also taken into account.

5.5.2 SWMM Model

Subcatchments R1, R2, R3, R4, R5, E1-1, E1-1GZ, E41, E42A, E42B and E6-1, represent the areas affected by SuDS: permeable pavements, car parks and retention basin. These have been created in the same way as indicated in their respective sections.

The characteristics of the subcatchments of the current situation have been changed. Properties of all subcatchments are shown in table 25 .

	Total Area (hec)	Width (m)	%Slope	%Imperv	N-Imperv	N-perv	Dstore-Imp (mm)	Dstore-Perv (mm)
W1	2.708	217.3	11	44.70	0.0118	0.167	2	5.17
W2	2.066	220.3	6.67	93.11	0.0113	0.00	2	0.00
W3	1.290	235.9	7.4	81.00	0.0115	0.198	2	5.48
E1	3.422	253.4	5.5	59.41	0.0118	0.264	2	6.14
E2	0.276	40.4	7.1	60.17	0.0120	0.150	2	5.00
E3	0.700	84.1	7.1	87.26	0.0113	0.000	2	0.00
E4	0.675	162.5	2.5	44.47	0.0117	0.211	2	5.61
E5	0.809	70.2	7.92	93.67	0.0116	0.216	2	5.66
E6	0.792	55.0	3.77	31.70	0.0109	0.183	2	5.33
R1	0.502	12.0	4	62.80	0.0110	0.110	2	0.05
R2	0.368	12.0	3.3	60.00	0.0110	0.110	2	0.05
R3	0.103	12.0	3.3	62.50	0.0110	0.110	2	0.05
R4	0.090	12.0	3.3	64.10	0.0110	0.110	2	0.05
R5	0.313	12.0	3.3	65.00	0.0110	0.110	2	0.05
E1-1	0.184	63.0	5.5	85.70	0.0117	0.100	2	7.00
E1-1GZ	0.116	63.0	2	0.00	0.0100	0.100	2	7.50
E41	0.102	31.0	2.5	87.20	0.0116	0.211	2	5.61
E42A	0.139	42.0	2.2	88.90	0.0116	0.211	2	5.61
E42B	0.127	40.0	2.2	86.90	0.0116	0.211	2	5.61
E6-1	0.348	73.0	3.77	41.08	0.0115	0.237	2	5.87

Table 25. Characteristics of subcatchments in alternative 5

The connections of the SuDS to the sewage network have been made in the same way as in the individual cases. These can be observed in the figure 40.

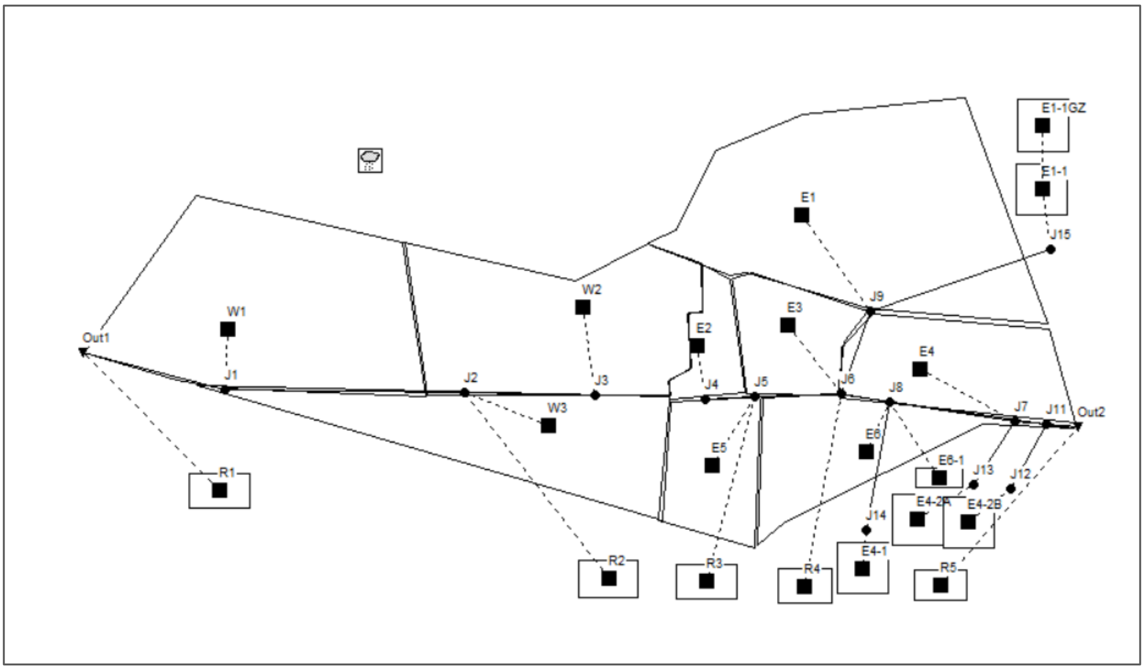

Figure 40. SWMM model for alternative 5

6. RESULTS

6.1 Cost results

The construction and maintenance costs of each of the alternatives are shown below according to the unit costs indicated in the previous sections. In addition, the annualised cost has been obtained, which has been calculated using the following formula taking into account a discount rate of 3%.

$$C_a = C_{maint} + \frac{C_{imp}}{(1+r)} * \frac{r*(1+r)^n}{(1+r)^n - 1}$$

Where:

Ca: annualized cost of the measure (pounds/year)

Cmaint: Maintenance cost (pounds/year)

r: discount (%)

n: lifespan (years)

It has been considered that the maintenance cost of the current situation is 0 £/year because it is assumed that in the case of implementing the other alternatives, this cost still exists for the maintenance of the conventional drainage system.

COSTS	A0	A1	A2	A3	A4	A5
Construction (£)	0	289,250	267,482	184,030	17,568	758,573
Maintenance (£/year)	0*	30,082	5,144	1,632	36	36,894
Annualized (£/year)	0*	247,020	205,755	139,654	11,895	604,324

Table 26 Costs summary for each alternative

6.2 Hydraulic results

The studied alternatives have been tested with a rain event of a return period of 200 years with a duration of 6 hours. Following are the results obtained in the SuDS, the behaviour of the peak flow and the volume in the drainage points.

6.2.1 LID Control actuation

The proposed alternatives have affected the behaviour of the main basins by increasing infiltration, evaporation or storage. Below are the contributions of each of the LID Controls according to their area.

Alte	Subcat	LID control	Total Inflow mm	Evap Loss mm	Infil Loss mm	Surface Outflow mm	Drain Outflow mm	Initial Storage mm	Final Storage mm
A1	W2	ExtensiveGR	74.24	0.53	0	66.45	0	15	22.23
	E3	ExtensiveGR	74.24	0.53	0	66.31	0	15	22.37
A2	R1	PermPav	193.85	0.56	2.88	25.95	82.25	0	83.59
	R2	PermPav	180.13	0.56	2.88	15.42	80.95	0	81.77
	R3	PermPav	193.16	0.56	2.88	27.78	82.60	0	80.93
	R4	PermPav	202.42	0.56	2.88	35.51	83.41	0	81.57
	R5	PermPav	206.72	0.56	2.88	37.50	83.46	0	83.70
A3	E1-1	Parking5%	774.43	0.56	0	311.13	0	0	461.13
	E4-2A	Parking2%	646.93	0.56	0	186.62	0	0	458.38
	E4-1	Parking2%	557.56	0.56	0	101.50	0	0	454.34
	E4-2B	Parking5%	547.76	0.56	0	92.34	0	0	453.78
A4	E6-1	RetentionBasin	3651.58	0.30	0	2669.63	0	0	993.77

Table 27. LID Control Results

6.2.2 Peak flow analysis

The proposed alternatives are aimed to reduce peak flows volume and to laminate the event over time. With regard to the two main drainage points, a comparison has been made between the current case and the different proposed interventions. For this purpose, the maximum observed value, the maximum flow and the time in which this occurs were considered.

Alternative	Node	Maximum depth m	Peak flow time	Max depth variation respect A0 %
A0	Out 1	0.54	3:15	-
	Out 2	0.78	3:15	-
A1	Out 1	0.54	3:16	0
	Out 2	0.78	3:16	0
A2	Out 1	0.49	3:15	-9.26
	Out 2	0.74	3:15	-5.13
A3	Out 1	0.54	3:15	0
	Out 2	0.71	3:15	-8.97
A4	Out 1	0.54	3:15	0
	Out 2	0.76	3:15	-2.56
A5	Out 1	0.49	3:15	-9.26
	Out 2	0.67	3:15	-14.1

Table 28. Peak flow results in each alternative

Alternative	Node	Maximum Flow CMS	Peak flow time	Max flow variation respect A0 %
A0	Out 1	2.397	3:15	-
	Out 2	2.740	3:15	-
A1	Out 1	2.391	3:15	-0.25
	Out 2	2.738	3:15	-0.07
A2	Out 1	2.114	3:15	-11.81
	Out 2	2.581	3:15	-5.80
A3	Out 1	2.397	3:15	0
	Out 2	2.455	3:15	-10.40
A4	Out 1	2.397	3:15	0
	Out 2	2.679	3:15	-2.23
A5	Out 1	2.102	3:15	-12.31
	Out 2	2.285	3:15	-16.61

Table 29. Peak flow volume results in each alternative

Depth variation along the rainfall event in both nodes has also been analysed.

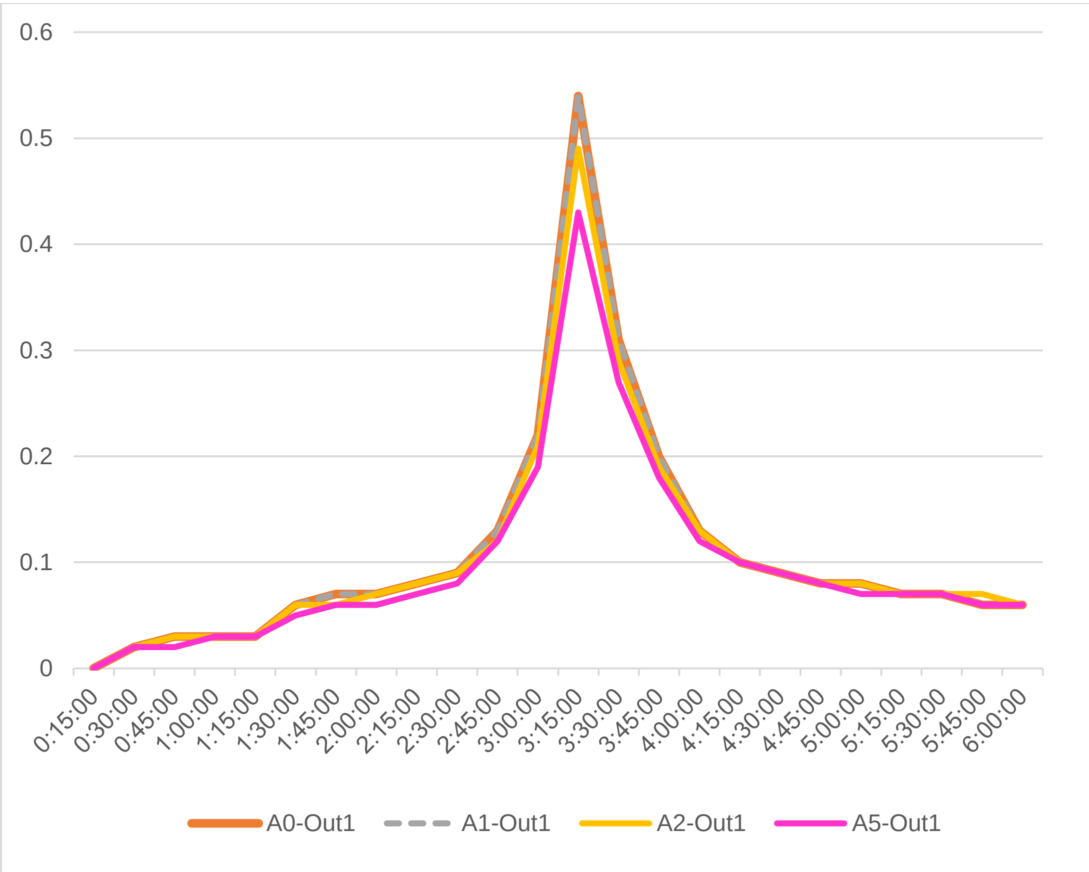

Figure 41. Depth along time in node Out 1

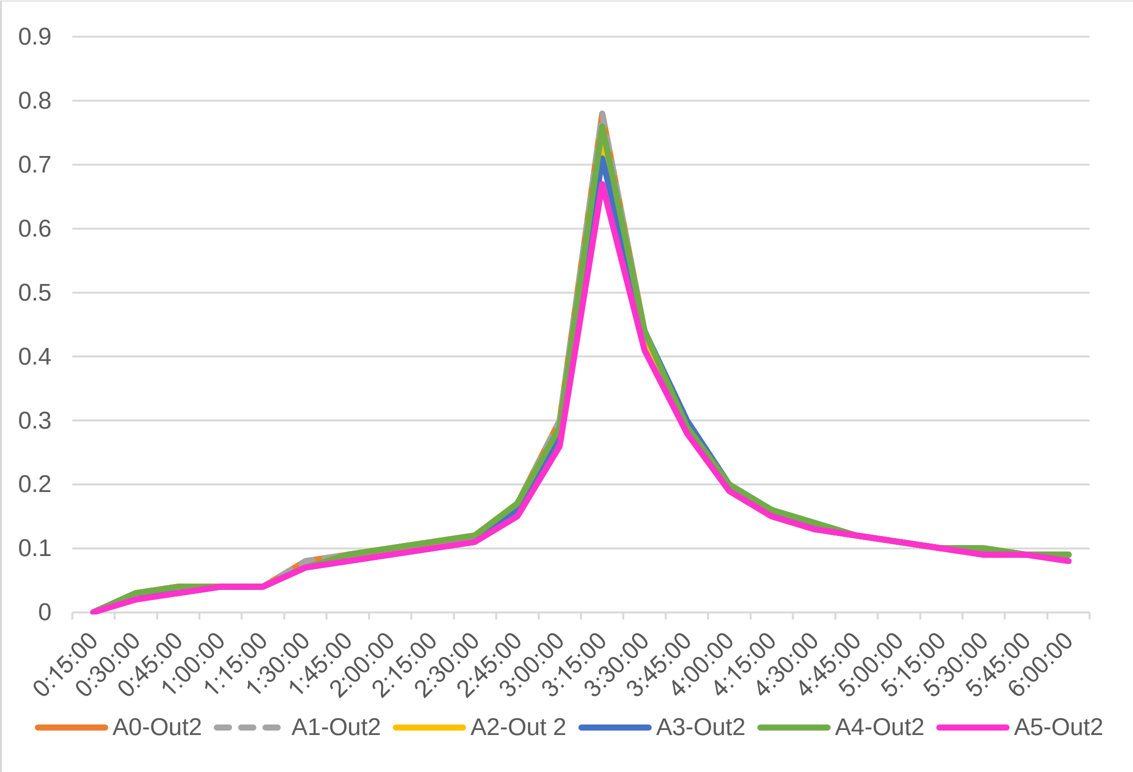

Figure 42. Depth along time in node Out 2

Since the studied basins have a much larger area than the treated one, it is difficult to identify the hydraulic implication of the alternatives. Therefore, it is analysed the variation of different nodes along the drainage network that represent the performance of the SuDS with respect to a smaller area. Alternative 5 has not been considered in the analysis of J4 and J9 as it produces the same results in the studied nodes.

The following graph shows the variation of node J4. This is only affected in the case of alternative 2. As it is found in the upper part of the basin, the variations are higher because it only collects water from sub-basin E2.

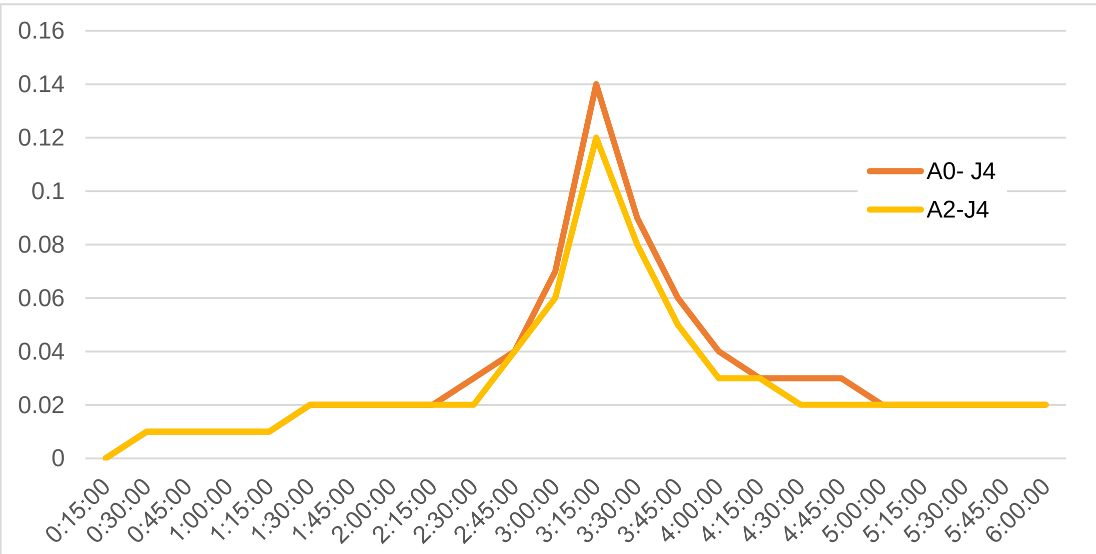

Figure 43. J4 variation in alternative 2

Another node that presents notable variations is the J9, for the same reason as the previous one. In this case, node J9 is only altered in alternative 3 and represents the variation in the inflow of sub-basin E1.

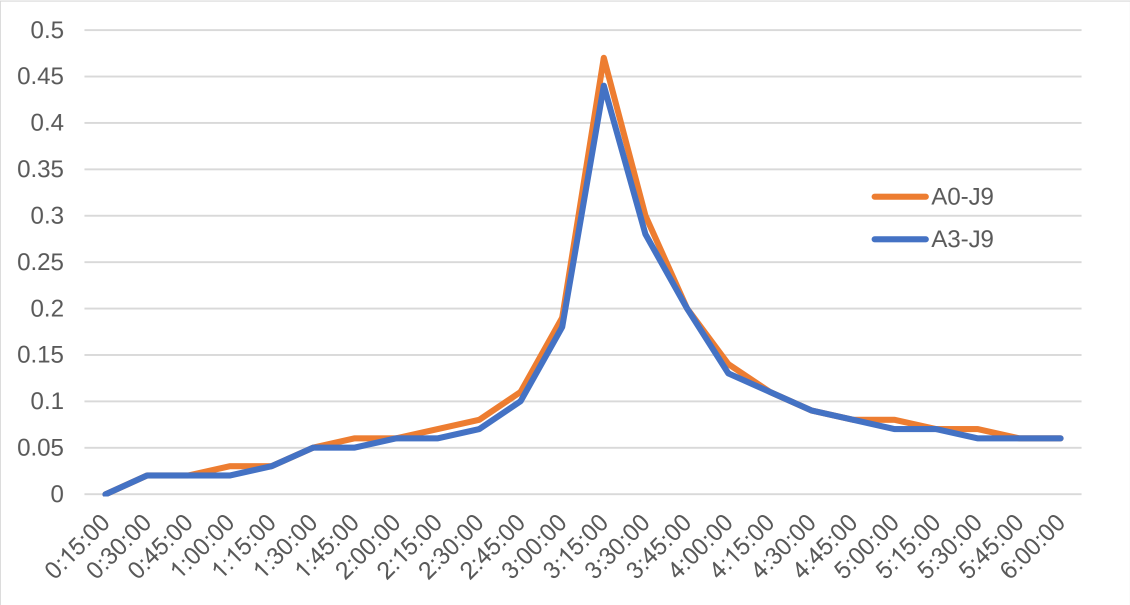

Figure 44. J9 variation in alternative 3

The variation in node J8, which is located in the middle of the sub-basin, has also been studied. It can be observed that the variations are lower because the flow depends on a larger area.

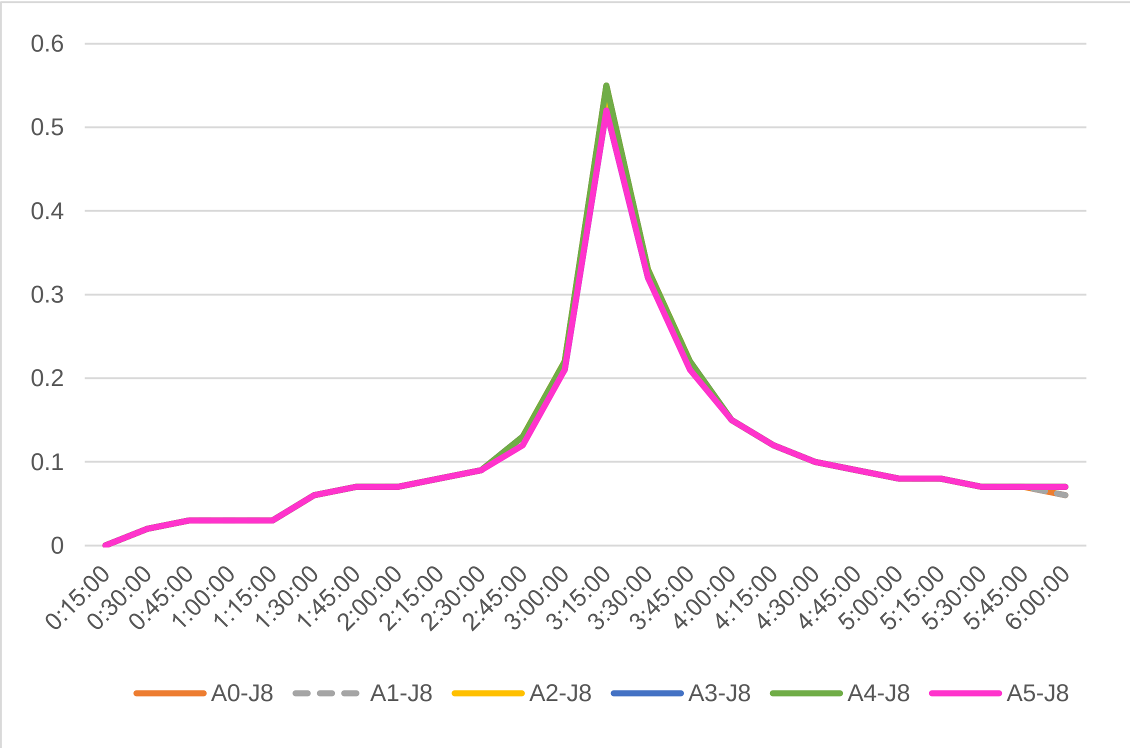

Figure 45. J8 variation in different alternatives

6.2.3 Volume analysis

Total inflow volume at each drainage point has also been observed and compared with the results of the current situation to determine the reduction caused by the alternatives studied.

Alternative	Node	Total Inflow Volume 10^6 ltr	Inflow variation respect A0 %
A0	Out 1	4.85	-
	Out 2	5.66	-
A1	Out 1	4.83	-0.25
	Out 2	5.65	-0.12
A2	Out 1	4.57	-5.8
	Out 2	5.50	-2.67
A3	Out 1	4.85	0
	Out 2	5.27	-6.98
A4	Out 1	4.85	0
	Out 2	5.58	-1.34
A5	Out 1	4.55	-6.21
	Out 2	4.94	-12.57

Table 30. Total inflow results in each alternative

7. ALTERNATIVES COMPARISON

The alternatives have been compared with the use of a cost/variation ratio. This ratio represents the cost of a 1% decrease in total volume. To calculate it the annualised cost has been divided by the variation of the volume of flow in the peak in each alternative. table 31 shows the results obtained.

Alternative	Node	Cost £/year	Total Volume Variation %	Ratio £/year%
A0	Out 1	0	-	-
	Out 2	0	-	-
A1	Out 1	151,905	-0.25	607,620
	Out 2	95,114	-0.12	792,617
A2	Out 1	133,640	-5.8	23,041
	Out 2	72,115	-2.67	27,009
A3	Out 1	-	0.00	-
	Out 2	139,654	-6.98	20,008
A4	Out 1	-	0.00	-
	Out 2	11,895	-1.34	8,877
A5	Out 1	285,545	-6.21	45,981
	Out 2	318,778	-12.57	25,360

Table 31. % Variation cost in each alternative

From the results obtained and the calculated ratios for each subbasin, the following could be concluded:

Green roof (A1) is the most expensive alternative. It generates little or no variation with the current situation in the compared aspects. This is mainly due to the size of the study area compared to the SuDS affected area.

Construction of permeable pavements (A2) generates great variations in both drainage points in terms of peak flow volume and depth variation. This alternative has a better behaviour in the control of peak flows than in the reduction of the use of conventional systems. It also has a cost per % of variation from the highest of the alternatives studied.

Geocellular storage systems (A3) present significant variations in drainage point Out 2 with respect to peak flow and the total volume that enters the conventional sewage network at a medium price.

Retention basin construction (A4) allows to obtain a variation in drainage point 2 similar to the one observed in alternative 2 with a lower cost. In addition, because it allows storage, this alternative has an important role in reducing the volume treated by the drainage network.

Finally, alternative 5, which combines all the SuDS techniques previously proposed, has shown that the set obtains better results.

8. CONCLUSIONS

This project enables to know, after having executed the current situation model with SWMM, how the area of study responds to the rainfall events applied. Having a look on the different sustainable drainage systems, it can be concluded that the geocellular storage systems adapts better than any other of the systems purposed, to the objectives of this study. The system outstands because it minimizes the use of the conventional drainage network, while at the same time permits storing water which can be reused. Thus, the impact and costs derived from sewage treatment plants can be reduced. Apart from that, alternative 3 also offers good results and a clear competitive advantage in terms of price when compared to the others.

Retention basin implementation can also be considered. Even though the affected area is relatively small, the results appreciated in the drainage system meet the objectives proposed as well. This alternative might be applied jointly to the geocellular storage system, since it would improve these results.

Some of the limitations found to study the drainage systems is the lack of runoff information generated to calibrate and validate the model. Hence, although a SuDS comparison can be produced, these results are not completely reliable. Additionally, a better knowledge of the drainage land capacity would have allowed the researcher to purpose a wider variety of alternatives.

Considering aspects of the present research, further investigation should allocate the focus on greater subcatchment discretisation and more detailed specification in terms of the solutions to apply. Another aspect to take into consideration for further studies is that other types of rainfall events are needed to have a better understanding of the sustainable drainage system. This would result in analysing the behaviour of SuDS techniques during a regular rainfall.

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ANNEX 1: DRAWINGS

Drawing 1. Topography

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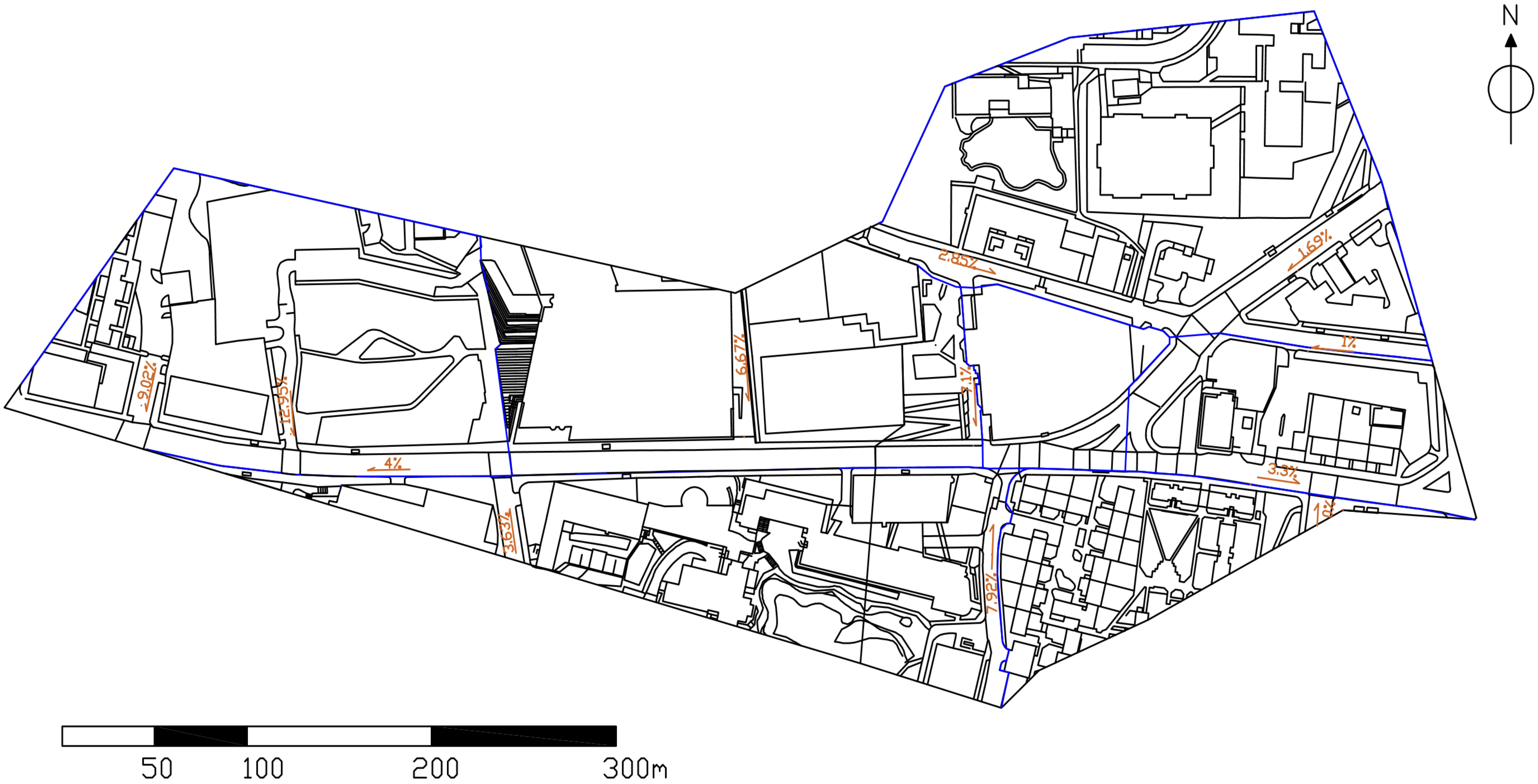

Drawing 2. Road inclination

ANNEX 2: RESULTS

1. T=10 Rainfall event results

Subcat	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Imperv Runoff mm	Perv Runoff mm	Total Runoff mm	Total Runoff 10^6	Peak Runoff ltr	Runoff Coeff CMS
W1	39.35	0	0.55	1.67	19.32	14.03	33.35	1.04	0.44	0.847
W2	39.35	0	0.56	0	37.14	0	37.14	0.88	0.37	0.944
W3	39.35	0	0.56	0.59	30.94	5.03	35.97	0.52	0.23	0.914
E1	39.35	0	0.55	1.4	22.13	11.11	33.24	1.24	0.49	0.845
E2	39.35	0	0.55	1.07	25.77	9.2	34.97	0.13	0.06	0.889
E3	39.35	0	0.56	0	37.18	0	37.18	0.29	0.12	0.945
E4	39.35	0	0.55	1	26.41	8.21	34.62	0.45	0.19	0.88
E5	39.35	0	0.56	0.21	34.86	1.82	36.68	0.31	0.13	0.932
E6	39.35	0	0.55	1.54	20.69	13.01	33.71	0.41	0.18	0.857

2. T=200 Rainfall event results

Subcat	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Imperv Runoff mm	Perv Runoff mm	Total Runoff mm	Total Runoff 10^6	Peak Runoff ltr	Runoff Coeff CMS
W1	74.24	0	0.55	1.67	37.47	30.83	68.31	2.13	1.06	0.920
W2	74.24	0	0.56	0	72.19	0	72.19	1.71	0.84	0.972
W3	74.24	0	0.56	0.59	59.96	10.97	70.93	1.03	0.51	0.955
E1	74.24	0	0.55	1.41	43.01	25.19	68.2	2.54	1.2	0.919
E2	74.24	0	0.55	1.07	49.98	19.98	69.96	0.25	0.13	0.942
E3	74.24	0	0.56	0	72.2	0	72.2	0.56	0.27	0.973
E4	74.24	0	0.55	1.01	51.31	18.32	69.63	0.9	0.45	0.938
E5	74.24	0	0.56	0.21	67.76	3.97	71.73	0.6	0.29	0.966
E6	74.24	0	0.55	1.55	40.1	28.57	68.66	0.84	0.42	0.925