2019

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Jack, R.

Jack, R. (2019) 'The feasibility of reducing storm water runoff using green roofs', The Plymouth Student Scientist, 12(1), p. 207-246.

The Plymouth Student Scientist
University of Plymouth

*The Plymouth Student Scientist, 2019, **12**, (1), 207-246*

The feasibility of reducing storm water runoff using green roofs

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Abstract
Green roofs are where a roof of a building is partially covered with vegetation which acts as a means of providing flow control by attenuation, storage and losses due to evapotranspiration. A green roof consists of several-layered materials to achieve the desired vegetative cover and drainage characteristics. Through using InfoWorks Integrated Catchment Modelling (ICM) and the software's integrated Sustainable Urban Drainage (SUD) control editor, simulations were run using Time Series Rainfall (TSR) rainfall over a long continuous period of 10 years. The effects green roofs have on reducing the runoff from roofs and the attenuation of the flow to the sewer system within Plymouth city centre could then be analysed. The most reliable outcomes from the year of 2004 was analysed to present comprehensive results. The main findings of this study provided evidence that green roofs are very beneficial and have the potential to reduce the runoff by up to 15% via evapotranspiration and attenuating flows reaching the sewer system. The type of green roof installed has also been shown to have a significant impact on the retention rate with intensive green roofs being 1.9 times more effective than extensive roofs.

Introduction

Due to climate change and an ever-increasing population and urban development there is a rising strain on the older combined sewer networks. This may lead to numerous problems such as increased flooding of sewage caused by the surcharging of the sewer system or more frequent spills occurring at Combined Sewer Overflows (CSO's) within the network. These spills into the receiving watercourse only tend to occur during increased rainfall when the combined sewers have reached capacity. This may be harmful to the environment and in some cases to people's health.

Water companies are having to find ways to mitigate the influence of the growth in population and climate change to reduce the effect of surcharge within the sewer systems. Methods such as storage tanks and oversized sewers are traditionally used to reduce flooding and CSO spills. However, there is a limitation on the available space for these methods and over the past decades more environmentally friendly and sustainable approaches such as retention basins, swales and green roofs are being considered. Unfortunately, there are limited studies on this method and they are thought to be more expensive therefore, are not implemented on a large scale within the UK.

This investigation examines the benefits green roofs may have if implemented at a city-wide scale within Plymouth and whether the same approach can be used within areas or cities with a different sewer, topographical and building layout.
Through the study of existing green roof policies across the world, such as the one implemented by the city of Toronto, Canada, and correspondence with UK manufacturers of green roofs a realistic approach to modelling green roofs was evaluated within a pre-existing InfoWorks ICM model.

This project has been supported by the urban drainage modelling team, within Arcadis, Plymouth City Council (PCC) and South West Water (SWW). Arcadis is a leading global design and consultancy firm and contributed their expertise and use of the InfoWorks ICM software to aid in this project. SWW is a water company that provides services to Devon and Cornwall, they have given their permission to use their model of the Plymouth city centre in InfoWorks ICM produced by Arcadis. InfoWorks ICM is an integrated modelling platform and with the data provided by SWW and surveys the model could be created. Through correspondence with the PCC any planned developments were used to help build on the scenarios used for this research.

Aims and Objectives

The aim of this project was to investigate whether the use of green roofs could aid in reducing the runoff into the combined sewer system and the overall benefits this would have to the system. The study area chosen was Plymouth city centre due to it being local and it has and idealistic sewer, topographical and building layout. Corresponding with the PCC and using their strategic master plan, planned development or refurbishments were identified over the next twenty years. This detailed plan enabled a realistic approach to the installation of green roofs. Wherever there was a redevelopment area an intensive green roof was proposed and where an area is refurbished an extensive green roof has been recommended.

Through using a verified model of the Plymouth city centre that Arcadis provided with the permission of SWW these different methods of green roofs were incorporated into the model. Four scenarios were determined as follows: Base model (updating the population to meet 2035 figures), Extensive green roofs (updated population and any planned refurbishment have an extensive green roof installed onto it), Intensive green roofs (updated population and any planned redevelopment have an intensive green roof installed onto it) and Extensive and Intensive green roofs (updated population and all green roofs installed at the appropriate locations).

Results consisting of total outflow volume from each green roof, graphs showing the outflow trend throughout the year, flow through the two outfalls at the end of the network, a breakdown showing the effect of green roofs and remaining roof area has on the runoff and the effect of certain green roofs will be extracted from the InfoWorks ICM model. They were then analysed to examine the effects green roofs had on the outflow from the building the green roofs are installed on, the total volume from the network, runoff from the roof and flow and volume within conduits immediately downstream.

Literature Review

Green roof standards

Green roofs are commonly made up of five layers: drainage material, filter layer, growing medium and vegetation (Czemiel Berndtsson, 2010; Bianchini & Hewage, 2012a). Wang *et al.* (2017) stated that common green roofs also have a waterproof and root resistant membrane layer. The substrate (growing medium) within green roofs are most commonly a single layer of a mixture of organic and inorganic matter. However, green roofs can also have a dual substrate layer consisting of an upper organic nutrition layer and a lower inorganic absorption layer.
The root resistant layer is the first layer on the building and there are two types, physical or chemical. The main purpose of this layer is to provide a waterproof membrane to the existing roof. It is also used to protect the building from plant roots.(Bianchini & Hewage, 2012a). The purpose of the drainage layer is to provide free space to allow any excess water to freely move off the roof. This also aids in reducing the weight of the green roof so increasing the structural integrity. The filter layer is in place to prevent the particles from the upper layers from draining with water runoff (Czemiel Berndtsson, 2010). The main purpose of the water retention layer is to help maintain the moisture in the growing medium to aid growth of the vegetation.

Green roofs can be classified as extensive, semi-intensive or intensive. Whether a green roof is extensive or intensive depends on the depth of the growing medium, vegetation type, construction material, management and allocated usage (Berardi, GhaffarianHoseini, 2014). Extensive green roofs are the most suitable for retrofitting as they are well suited to roofs with low load bearing capacity. They have a lower cost than the semi-intensive or intensive green roofs as there is a shallower substrate layer with fewer nutrients but is suitable for less demanding plants. Semi-intensive green roofs require more maintenance and are heavier than an extensive green roof. They cost more due to a deeper substrate layer and allows for a larger variety of plants and vegetation. Bushes, trees and ponds are all possible on an intensive green roof. This requires a lot more maintenance and this puts a lot of strain on the building's roof. The intensive green roof is more suitable for new builds as the building can be designed to take the extra load. (IGRA, 2017).

Green roof run off

Many studies have been carried out investigating the runoff retention ability of green roofs. Zhang *et al.* (2015) studied rainwater runoff at a site in Yubei district, Chongqing, China. This area had a subtropical monsoon climate with an annual rainfall of approximately 1200mm. They found that the green roof had an average retention volume, of a 1m^2 area by 150mm deep vegetation layer, of 11.61mm and an average retention rate of 77.2%. However the higher temperatures can lead to a higher rate of evapotranspiration therefore, there is an increase capacity of green roofs in hotter climates. Zhang *et al.*, (2015) concluded that the substrate depth is an important factor affecting the retention capacity of green roofs. Gregoire & Clausen, (2011) carried out a study on a green roof with 102mm deep substrate on a public plaza at the University of Connecticut (USA). The green roof retained 51.4% of the precipitation Stovin, (2010) carried out research alongside the "Sheffield centre for green roof research". They studied an 80mm deep substrate green roof at the University of Sheffield (UK). The study found that the average retention volume is 34% and the average peak reduction was 56.9%. Each of these studies looked at different substrate depths which support Zhang *et al.*, (2015) conclusions, however, all three green roofs studies were carried out in different countries and other factors may have influenced the retention capacity such as the climate that the green roof is installed in that will effect evapotranspiration rates.

Viola, *et al.* (2017), through using 12 extensive green roof platforms at the Michigan State University, demonstrated that the retention values of green roofs decreased as the slope of the green roof increased, with an average retention of 80%. Gette *et al.* (2007) came to the same general conclusion with the difference being most significant for slopes between 2-15%.
Lee *et al.* (2015) concluded increasing antecedent dry days improves the water retention capacity of the green roofs during smaller magnitude rainfall events whilst carrying out an investigation in Seoul, Korea. Wang *et al.* (2017) surmised that rainfall characteristics (rainfall depth, duration and intensity) and green roof design (type and depth of substrate layer, age of the green roof and drainage and vegetation) were also key factors that influenced the rainfall retention capacity of green roofs.

Maintenance of green roofs

Green roofs can be subjected to numerous problems such as getting waterlogged through poor outlet placement, burnt due to lack of irrigation or ruined due to instillation by other traders. It is suggested by green roof experts (sky garden, 2017) that extensive sedum roofs require biannual visits to clear any weed infestation and drainage outlets and inspection chambers are cleared of vegetation. It is also recommended that once during early spring, fertiliser should be applied. Wildflower roofs generally require less maintenance. A visit once or twice a year is required to cut and remove season growth and to clear the drainage outlets and inspection chambers.

During the early establishment stage of green roofs access to a water point will be necessary. Extensive green roofs will need more care taken to them and will need to be watered during prolonged periods of drought. Intensive green roofs do not need as much maintenance as the deeper the substrate the more moisture it can hold during dry periods.

Other benefits of green roof

As well as rainwater retention, green roofs have many other benefits including reduced air and noise pollution, increased habitat and biodiversity, increased roof lifespan, reduction of energy demand for heating and cooling, provision of recreational and agricultural spaces and mitigation of the urban heat island effect. (Whittinghill *et al.*, 2014; Bianchini & Hewage, 2012a; Viola *et al*., 2017). Urban areas usually have higher levels of toxins in the air. Green roofs can contribute to reduce air pollution by: controlling the temperature variations of a building therefore reducing the demand for heating and air conditioning so reducing the amount of energy required and CO_2 emitted from power plants, and plants use CO_2 for photosynthesis (Bianchini & Hewage, 2012a). Through studying a dry deposition model, Yang *et al*. (2008) showed that green roofs removed 85kg/ha/yr of air pollutants in Toronto.

Through shading the roof top layer green roofs can protect the building from the direct influence of solar radiation therefore, reducing the indoor temperature. Berardi, GhaffarianHoseini (2014) and Niachou *et al.* (2001) conducted a study in Greece looking at the thermal effects a green roof had on a building. They found that green roofs reduced the energy required to cool the building between 2% and 48%. In the colder climates green roofs also aid in keeping the indoor temperature warm as the green roofs add insulation. However the thermal performance of the green roof depends on the amount of water held in the substrate layer. Therefore, green roofs in a damp cold climate ,such as the UK, will add little benefit to the thermal performance of the roof. Although there is evidence that the green roof will benefit the building it is installed as it has been found in some studies that green roofs have a negative effect on the insulation of neighbouring roofs (Berardi, GhaffarianHoseini, 2014).

The urban heat island effect occurs due to the dark colors of the buildings absorbing energy from the sun. This effect can be mitigated by installing green roofs as the plant matter on the roof will absorb the solar energy and release vapours which aids in controlling the temperature (Bianchini & Hewage, 2012a). Albedo is a measure of how reflective a surface is. It is given as a value between 0 and 1 or a precentage value, the higher the value the more reflective the surface. The albedo of green roofs range from 0.7 to 0.85 and this is greater than traditional materials used for making roofs (Berardi, GhaffarianHoseini, 2014). Through modelling green roofs within the New York Metropolitan region, Rosenzweig *et al.* (2006) established that a 50% extensive green roof coverage would reduce the city’s average temperature by 0.1-0.8°C. However within New York the buildings tend to be situated closer together which may be a key factor in these findings and further research would need to be done to identify whether green roofs have the ability to reduce average temperatures. Rain water harvesting can also be done in conjunction with a green roof to provide water to houses for uses such as toilet water. However there are a couple of issues: the volume of water that can be harvested is dramatically reduced and organic material within the substrate can potentially filter through with the rain water causing discolouration.

Finally there have been some studies into green roofs aiding in health. A study carried out in Texas demonstrated that patients recovering from post surgery recovered quicker with less chance of relapse if they could look out onto a green space. There have also been studies into how green spaces affect mental health such as stress, it is thought that having acess to a green space can reduce stress (Living roofs, 2015). However these studies are theoretical and to provide supportive evidence of green roofs to help aid in the health of people further more comprehensive studies will need to be carried out.

Run off from roofs
Rainwater flowing off conventional roofs has been shown to pick up pollutants from rooftops including heavy metals (Lye, 2009); atmospheric depositions, such as SO_2, NO_x and particles (Speak et al., 2012); and organic substances, such as leaves, dead insects, and bird waste (Wang *et al.*, 2017). Although green roofs will reduce these pollutants reaching the sewer system they are thought to increase the concentration of certain nutrients in the runoff. Zhang *et al.* (2015) found that the average pH of the runoff was higher from the asphalt roof than the green roof. However, Zhang *et al.* (2015) and Wang *et al*. (2017) found that the green roof substrate appears to leach certain pollutants, particularly nitrogen and phosphorus, believed to be from the organic matter in the soil, the decaying vegetation and any fertilisers used on the green roof. Therefore it is important to construct the green roofs from suitable materials to avoid deterioration of runoff water quality (Zhang *et al.*, 2015). Wang *et al*. (2017) suggest that there is the possibility that the vegetation may capture air pollutants that may eventually leach into the roof runoff. This is just a theory at the moment and therefore should be looked into before deterring the build of a green roof.

Traditional methods of storage
Construction work, such as storage tanks or upsizing sewers are used to increase sewer capacity. The provision of storage is the most commonly used method of solving flooding problems within the UK. Purposefully built storage is usually on-line or off-line attenuation tanks (May *et al*., 1998). However, due to climate change and densification in urban areas these are only short-term solutions and there is limited space to keep upgrading the sewer system. To increase sewer capacity, it is common to replace or enhance a stretch of sewer close to the flooding location. This can include installing a sewer that provides a higher flow capacity or it could be constructing a length of bypass sewer (May *et al*., 1998). However there are significant risks that this approach may induce such as flooding further downstream and therefore is not a sustainable solution.

A CSO tank is built to store the excess water when a large rainfall event occurs before overflowing into a receiving body of water (CSO, 2014). The infrequent spills at a CSO may be polluting the receiving watercourse and harming the environment around it. As the effects of climate change and densification increases the frequency of spills may also increase, this is a very unsustainable approach to combating the flooding issue. Storm water attenuation tanks are usually buried under open land on the site. They are made up of a tank where the outlet restricts the flow. Enlarged pipes can also act as storage. They have a smaller throttle pipe downstream that causes backfill under larger flows therefore increasing the risk of flooding further upstream (CSO, 2014).

Building standards

Green roofs require appropriate levels of sunlight, moisture, drainage, aeration to the plants root system and nutrients. The structural design of the green roof must comply with the Eurocodes BS EN 1990:2001 and the roof drainage designs should comply with BS EN 12056-3:2000, (Allnut *et al.*, 2011). There also needs to be access to the green roof particularly for installation and maintenance. When designing an intensive green roof, access for recreational use also needs to be considered to follow standards of safety and security as regulated by Building Regulations.

Policies

A few cities across the world have appreciated the effect green roofs may have on reducing the storm water runoff. In 2004 the City of Chicago worked alongside private developers to help reduce storm water runoff by adding SUDs to buildings, including green roofs. (Martinez, 2012). In 2009 Toronto city council put a bylaw in place that required that green roofs are constructed in new, commercial, residential and industrial developments. In 2015 the French government also approved a law that all new buildings in commercial zones must be partially covered by green roofs or solar panels (Semaan & Pearce, 2016).

Although Singapore do not have any legislations or policies in place for green roofs, the city has agreed to reach 50 hectares of skyrise greenery area by 2030. They aim to achieve this by providing financial subsidies and incentive schemes (Semaan & Pearce, 2016).

There are currently no standards or installation policies for green roof in the UK as they are still relatively new within the UK and there is a lack of data and information. However, in 2011 'The GRO Green Roof Code' was developed by a range of organisations involved with UK green roofs and this document sets out the best practice for UK green roofs. Green roofs are being considered in some local planning policies in Sheffield and London (Red Rose Forest, 2014).

Cost analysis

Green roofs cost more than conventional roofs to install as they require more materials and labour, however, there are multiple cost saving benefits throughout its lifespan such as, reduced energy costs and extended roof life (Sky gardens, 2006). The natural thermal insulation helps cool or heat the building therefore, reducing the energy required. The expected life span of a green roof is between 40 to 55 years (Bianchini & Hewage, 2012b), whereas the average expected life span of an asphalt roof is 15-30 years.

Existing attenuation policies

Plymouth and South West Devon joint local plan is a vital planning process which looks ahead to 2034. It aims to establish a strategic framework for sustainable growth and the management of change. Within the framework in policy DEV37 it is stated that development should minimise surface water runoff and ensure that it does not increase flood risks elsewhere (Plymouth city council, 2017). Plymouth city centre is also a critical drainage area, due to the topographical layout and the fact that it is heavily urbanised making it prone to flash flooding due to substantial rainfall events. Due to the combined drainage systems and high tides restricting the discharge of surface water from low lying land there are additional critical drainage problems such as flooding and water quality problems. Therefore, new surface water sewers should not be connected to the combined sewer system. To comply to the EA guidelines all new developments must safely manage on site surface water up to a 1 in 100-year storm plus climate change conditions.

Additional water storage areas would need to be provided to contribute to a reduction in flooding downstream. The way that most developers now combat the need for additional storage areas is by adding a water storage tank beneath the building however, due to the limited space within the centre it may be harder to build suitable tanks that are required to aid in attenuating the flows. It is thought that green roofs may be used in conjunction with a storage tank to reduce this issue therefore a smaller storage tank would be needed combatting these limitations.

Methodology

About the study area

Most of the sewer systems across the UK including Plymouth were built during Victorian times. However due to World War II the majority of Plymouths sewers, including the tunnel system, were damaged and had to be rebuilt post war during the late 1940’s, early 1950’s. At that time sewage and storm water runoff was all combined within the same system. The sewer system in the centre of Plymouth is a gravity combined system therefore rainfall influences flooding. The sewage from the centre is treated at Plymouth Central Sewage Treatment Works (STW) during high levels of rainfall some of the sewage may be spilt to the environment via CSO’s. Plymouth is an ideal location for this study as the city centre sewer system all drains into the Plymouth tunnel which then drains via gravity into a shaft 40m deep therefore the impact the green roofs have on the sewer capacity can be identified easily. The sewage is then pumped vertically up the 40m shaft to Plymouth Central STW. The need for pumping is extremely expensive and reducing storm flow into the system will help reduce this cost. When the STW does overflow Ultraviolet (UV) is used to neutralise organisms before discharging to the environment. This is also a very costly process and reducing storm flow into the system will aid in the reduction of spills so reducing the cost of the UV.

About the model

The pre-existing model was provided by Arcadis, which had been built and expanded on during numerous schemes, it has recently been verified. The model was built using the ‘WaPUG Code of Practice for the Hydraulic Modelling of Urban Drainage Systems’ written by CIWEM, 2002 and following the SWW Wastewater Network Modelling Specification, 1st edition. The model used for this study is a type II ‘drainage area planning model’. A type II model is used to give an overview of a specific drainage area and includes all ancillaries, (WaPUG, 2002). The sewer data required within the model is the details of the sewer network and connectivity, pipe sizes, ground levels, pipe levels and pipe roughness. Most of this data can be obtained from records held on Geographical Information System (GIS). Surveys, such as manhole surveys, ancillary surveys and Impermeable Area Surveys (IAS) were also carried out for certain areas where more detail was required. For verification purposes, rainfall data from a short-term flow survey was used in combination with flow data.

Modelling SUDS

The green roofs were modelled within InfoWorks ICM using the inbuilt SUDS control editor. The design of the control is made on a per unit area basis so that it can be placed in any sized sub catchment. The SUDS parameters contain fields for the vertical layers that comprise a SUDS control. As mentioned previously green roofs are typically made up of five layers. In terms of hydraulic properties, the drainage material and filter layer has little or no influence on the runoff from the green roof and therefore is not considered within the model. The green roofs SUDS control includes a surface layer, soil layer and drainage mat. The surface layer corresponds to the ground surface which receives direct rainfall, the soil layer represents the engineered soil mixture used to support vegetative growth and the drainage mat represents the mat that lays between the soil and the roof structure, it conveys any water that drains through the soil layer off the roof. The hydrological performance of the green roof SUDS feature can be modelled by calculating the mass balance equations.

Scenario development

There was potential to look at the effects of climate change or population growth. For this project, population growth was considered and the effect of climate was accounted for by adding 10% of rainfall to the existing rainfall following standard industry practice. Using PCC strategic masterplan any development plans were used to estimate the increase in residential, student, office and retail population.

A verified baseline model of the present day was provided by Arcadis. A projected baseline model was run with 2035 population estimations (shown in Table 1) to allow a comparison of the effects of the green roof, as the increase in foul flow caused by population growth would reduce the effect of the green roof. As mentioned in section 0 extensive green roofs are most suitable for retrofitting as they are more suited for roofs with low load bearing capacity whereas intensive roofs are more suitable for redevelopment as the roof can be designed to bear the weight of the green roof (IGRA, 2017). Therefore, in the model, using the PCC strategic masterplan scenarios were developed the results of this model was used for the comparison against three other models as detailed below:

1.0: All predicted refurbishment projects have an extensive green roof installed.
2.0: All predicted redevelopment projects have an intensive green roof installed
3.0: All predicted refurbishment and redevelopment projects have extensive and intensive installed respectively.

Population development

The residential density of Plymouth city centre is taken as 0-20 people per hectare within the PCC strategic masterplan document, a residential population of 1000 is given. By 2035 a population of 3000-4000 is anticipated due to the redevelopment. A population of 4000 was used as the worst-case scenario.

The project focus area was broken down into proposed development and refurbishment this focus area was replicated in the model as shown in Figure 1 which was extracted from the model. Sub catchment 39 was not used in analysis as since the PCC document has been released the bus station had already been built within that area therefore no green roofs would be implemented. Retail, office and residential areas were used to calculate different populations shown in Table 1. A breakdown of the different types of population were required because residential population uses a different wastewater profile than office and retail. Therefore, to create a more realistic approach these population were inputted separately. These areas have been used to calculate relevant population growth for each area.

Table 1: Population calculations

Area of Development	**Retail Area m2**	**Office Area m2**	**Residential area m2**	**Residential units**	**Additional residential population**	**Office l/day**	**Retail l/day**	**Office P.E.**	**Retail P.E.**
Colin Campbell court & Western approach	5,379	-	23,745	303	700	-	73196	-	595
Cornwall street east	15,877	-	6,980	92	202	-	63508	-	516
Royal parade west	3,670	-	8,356	110	242	-	14680	-	119
New George street west	15,490	-	2,301	30	66	-	61960	-	504
Mayflower street west	4,950	14,614	11,088	136	299	109605	-	891	-
Mayflower street east	1,079	34,132	-	-	-	255990	4316	2081	35
Morley court	-	-	-	-	381	-	-	-	-
Cornwall street west	-	-	-	-	0	-	-	-	-
Cornwall street south	-	-	-	-	381	-	-	-	-
Royal parade east	-	-	-	-	0	-	-	-	-

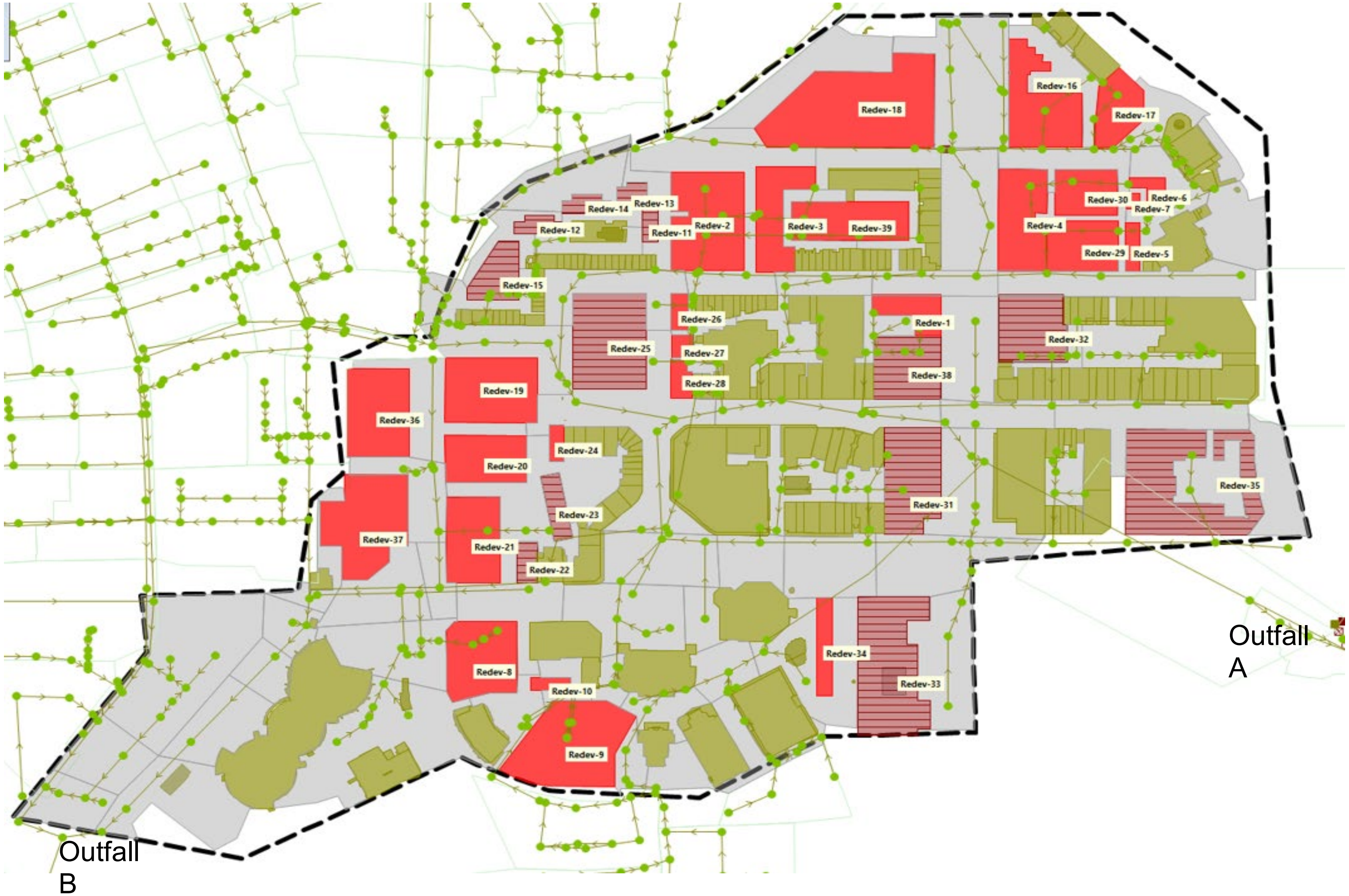

Figure 1: Position of each sub-catchment within the model
(Map developed and reproduced with kind permission from Arcadis (InfoWorks ICM))

Scenarios

Table 2: Scenarios inputted into the model

	2020 Baseline	**2035 Baseline**	**2035 aspired refurb (Extensive green roofs)**	**2035 aspired redevelopment (Intensive green roofs)**	**2035 aspired everything (Intensive and extensive)**
Overall population	2308	9630	9630	9630	9630
Residential population	1000	4000	4000	4000	4000
Retail Population	1308	2003	2003	2003	2003
Office population		3626	3626	3626	3626
Development (Location)	No Development	No Development	Morley Court, Plymouth city market, New George street west, Cornwall street south, Royal parade west & east, Civic centre	Mayflower street west & east, Cornwall street west & east, Western approach car park, Colin Campbell court, Notte street	
Max area green roofed (m^2)	0	0	18700	37900	
Why	Verify the model	Show effects of pop increase	Effect of extensive	Effect of intensive	Best Case

Table 3: Modelling data for each type of green roof

Type of green roof	**Intensive (Wildflower blanket)**	**Extensive (Sedum blanket)**
Soil type	Sedum substrate – low nutrient, free draining root zone	Sedum substrate – low nutrient, free draining root zone
Thickness of soil	100mm	50mm
Vegetated (Yes/No)	Yes – Planting mix (30-40 species) – Depth 25mm	Yes – Sedum blanket (8-12 sedum species)
Soil porosity	0.60	0.60
Field capacity	0.35	0.35
Wilting point	0.10	0.10
Conductivity (mm/min)	0.60	0.60 (36mm/hr)
Conductivity slope	10	10
Suction head (mm)	75	75
Drainage layer thickness	20mm	20mm
Drainage layer type	Recycled PE rigid load tolerant drainage and retention board	Rigid HDPE drainage board
Mat void fraction	0.30	0.30
Mat roughness (Mannings n)	0.02	0.02

Green roof parameters
Modelling the green roofs within InfoWorks.ICM
To model the green roofs the key sourcing parameters are:

- Soil type
- Thickness of soil
- Vegetated (yes/no)
- Soil porosity
- Field capacity
- Wilting point
- Conductivity (mm/min)
- Conductivity slope
- Suction head (mm)
- Drainage layer thickness
- Drainage layer type
- Mat void fraction
- Mat roughness (mannings n)

Through email correspondence with Sky Garden (D Wordley 2018, personal communication, 06 February), a leading supplier and installer of green roofs nationwide, the typical layout of an intensive and extensive green roof has been deduced. Any missing parameters were obtained from manuals written by Green Roof Direct and a range for each parameter was given by the Environmental Protection Agency (EPA), when using this range, the central value was taken.
Due to the soil used in the growth media being an engineered mixture of aggregate, sand and organic matter it is very different from naturally occurring soils and there is limited information on the standard soil properties. The soil produced is a light-weight product with high porosity and water holding capacity. However, there is limited data for suction head values for an engineered mixture of aggregate therefore, the ranges for the suction head were defaulted to those typical of loam and sandy loam soils.

Due to the need for access up to the green roof for maintenance and certain objects on the roof such as air conditioning units it has been assumed that less than 100% of the roof will be greened. Therefore, to deduce an appropriate percentage of the roof to be greened, Google Earth was used to surmise an average of 58% of each roof could be greened. This was used in the simulations as the green roofs.

Additional parameters
The model was run using TSR which is past rainfall provided by the Met Office. In the scope Flood Estimation Handbook (FEH) rainfall was suggested to be used however, this would not have shown the effect of recurring rainfall. Therefore, will not show the effect of the green roof already being saturated during additional rainfall. Yearly rainfall was run across all seasons to show the full effects of the green roofs as in winter there is usually constant rainfall with lower peaks, therefore the green roof is expected to handle the smaller peaks better. However, the green roof will have been saturated from previous rainfall so would be able to hold less water. Whereas during the summer there is less rain however the rainfall that does occur tends to be short and flashy with higher peaks. The yearly rainfall data used was from the closest rain gauge possible at Torpoint during the years of 2004 to 2013.

Results
To analyse the effects green roofs, have on the total outflow of each building into the sewer system of the Plymouth city centre simulations were run using TSR. The year of 2004 was chosen for further analysis as this year gave the most stable results for all scenarios therefore, aiding in the most reliable analysis. The effect during the year of 2004 is shown in Table 4 and Table 5.

Table 4: Overall effect of the green roofs on the outflow per roof

Sub catchment ID	Extensive/Intensive green roof	Area (ha)	Total outflow green roof (m^3)	Total outflow no green roof (m^3)	Difference in the Total outflow (m^3)	Percentage decrease (%)
Redev-1	Intensive	0.138	7855.63	7740.12	115.51	1.5
Redev-2	Intensive	0.482	6534.53	6136.96	397.57	6.1
Redev-3	Intensive	0.262	4504.55	4287.31	217.24	4.8
Redev-4	Intensive	0.331	15380.32	15106.44	273.88	1.8
Redev-5	Intensive	0.050	2954.40	2912.34	42.06	1.4
Redev-6	Intensive	0.048	2260.58	2220.21	40.37	1.8
Redev-7	Intensive	0.015	2110.95	2098.34	12.61	0.6
Redev-8	Intensive	0.351	2782.80	2492.52	290.28	10.4
Redev-9	Intensive	0.558	2927.15	2467.43	459.72	15.7
Redev-10	Intensive	0.035	678.13	648.69	29.44	4.3
Redev-11	Extensive	0.036	4530.51	4505.51	25	0.6
Redev-12	Extensive	0.052	5145.07	5108.96	36.11	0.7
Redev-13	Extensive	0.049	4589.45	4555.43	34.02	0.7
Redev-14	Extensive	0.055	5158.67	5120.48	38.19	0.7
Redev-15	Extensive	0.154	5968.06	5861.97	106.09	1.8
Redev-16	Intensive	0.366	68089.89	67787.31	302.58	0.4
Redev-17	Intensive	0.195	32654.91	32492.57	162.34	0.5
Redev-18	Intensive	0.854	60390.54	59689.15	701.39	1.2
Redev-19	Intensive	0.406	13650.87	13315.52	335.35	2.5
Redev-20	Intensive	0.261	8440.49	8224.07	216.42	2.6
Redev-21	Intensive	0.310	11102.69	10846.04	256.65	2.3
Redev-22	Extensive	0.057	5931.53	5891.95	39.58	0.7

Table 5 (Continued): Overall effect of the green roofs on the outflow per roof

Sub catchment ID	Extensive/Intensive green roof	Area (ha)	Total outflow green roof (m^3)	Total outflow no green roof (m^3)	Difference in the Total outflow (m^3)	Percentage decrease (%)
Redev-23	Extensive	0.087	6946.07	6885.66	60.41	0.9
Redev-24	Intensive	0.034	6284.34	6255.75	28.59	0.5
Redev-25	Extensive	0.477	8951.08	8627.57	323.51	3.6
Redev-26	Intensive	0.043	6991.83	6955.66	36.17	0.5
Redev-27	Intensive	0.035	6413.54	6384.10	29.44	0.5
Redev-28	Intensive	0.051	6621.59	6578.70	42.89	0.6
Redev-29	Intensive	0.242	17426.31	17225.51	200.8	1.2
Redev-30	Intensive	0.195	5664.42	5502.08	162.34	2.9
Redev-31	Extensive	0.393	20603.26	20336.21	267.05	1.3
Redev-32	Extensive	0.307	19249.19	19040.03	209.16	1.1
Redev-33	Extensive	0.584	4102.89	3707.58	395.31	9.6
Redev-34	Intensive	0.104	859.95	772.53	87.42	10.2
Redev-35	Extensive	0.677	23986.41	23528.77	457.64	1.9
Redev-36	Intensive	0.376	4476.30	4165.53	310.77	6.9
Redev-37	Intensive	0.475	4244.62	3852.78	391.84	9.2
Redev-38	Extensive	0.289	23107.15	22910.12	197.03	0.9

Table 6: Average percentage decrease per type of green roof

Type of green roof	Average percentage decrease (%)
Extensive	1.88
Intensive	3.62

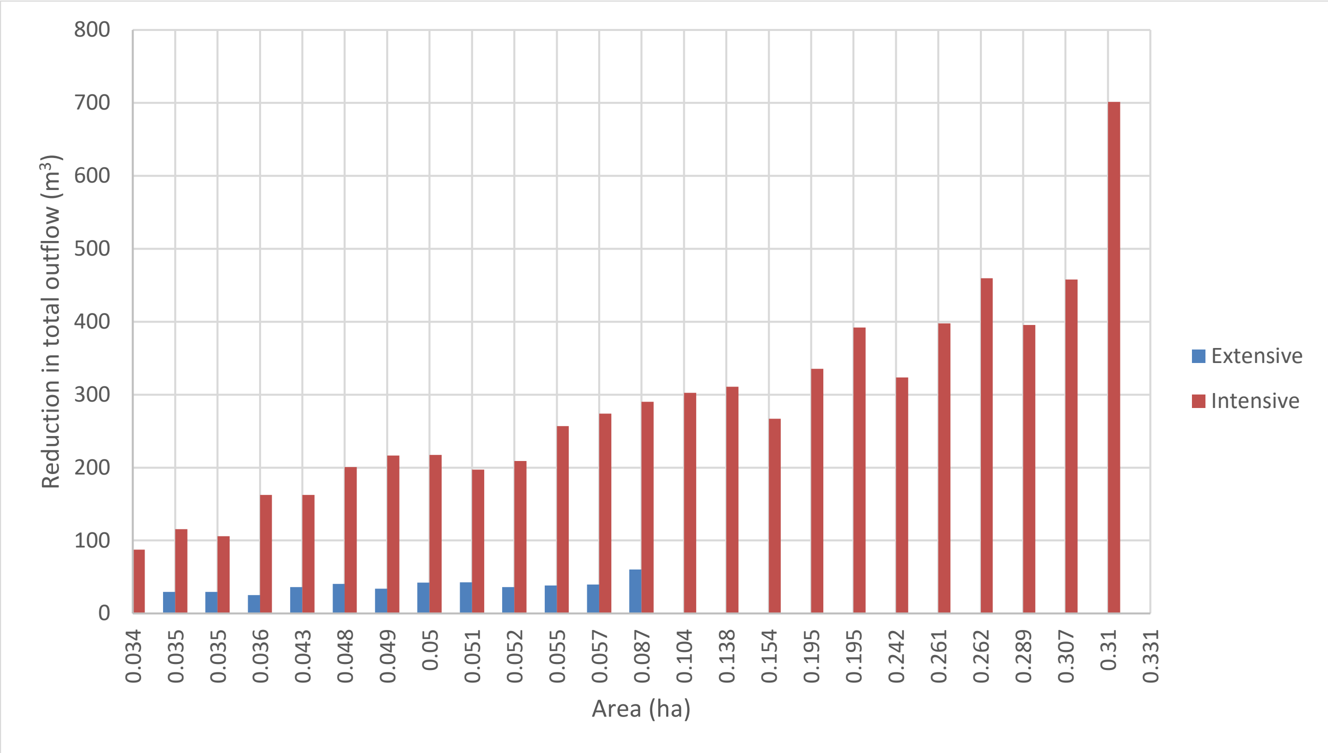

Figure 2: Area of green roof against reduction in outflow

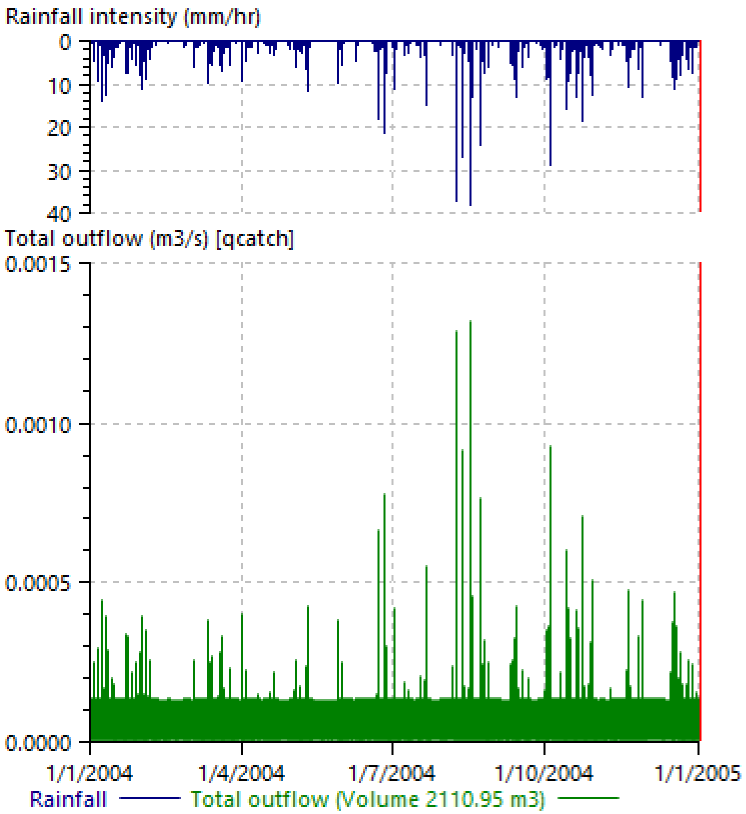

Figure 3 - Redev-7 outflow with no green roof installed

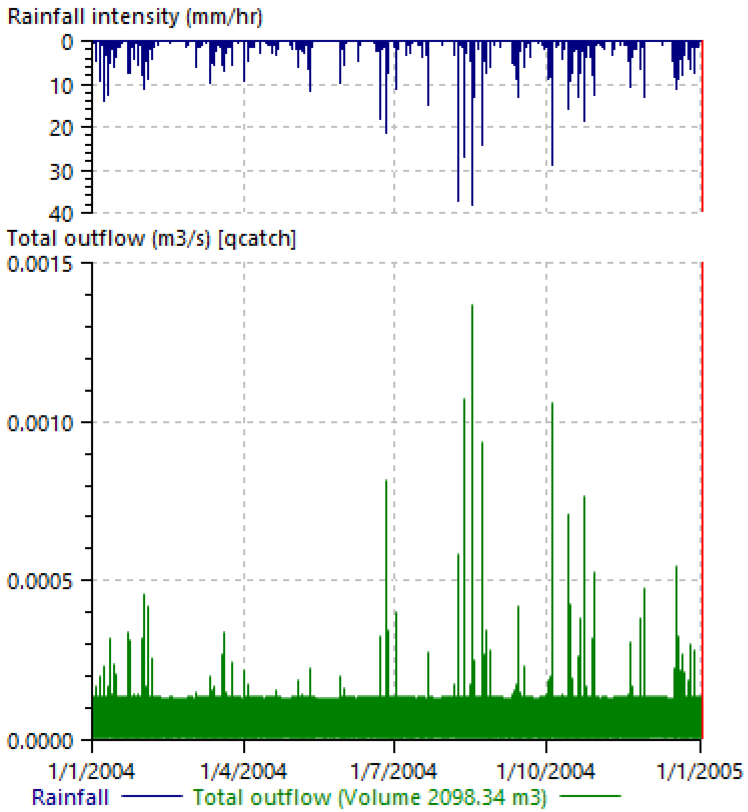

Figure 4 - Redev-7 outflow with an intensive green roof installed

Figure 3 and Figure 4 show the effects an intensive green roof has on the total ouflow of the building it is installed on. Figure 3 shows the total outflow without a green roof installed and Figure 4 shows the total outflow with a green roof installed. Subcatchment Redev-7 has been chosen as it is the smallest intensive green roof area within the study area.

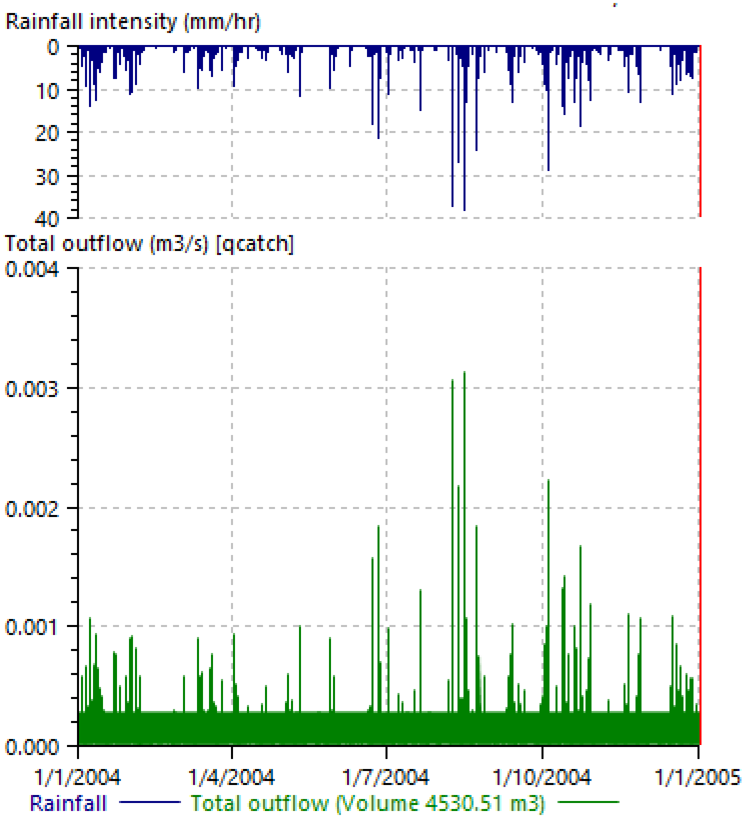

Figure 5: Redev-11 outflow with no green roof installed

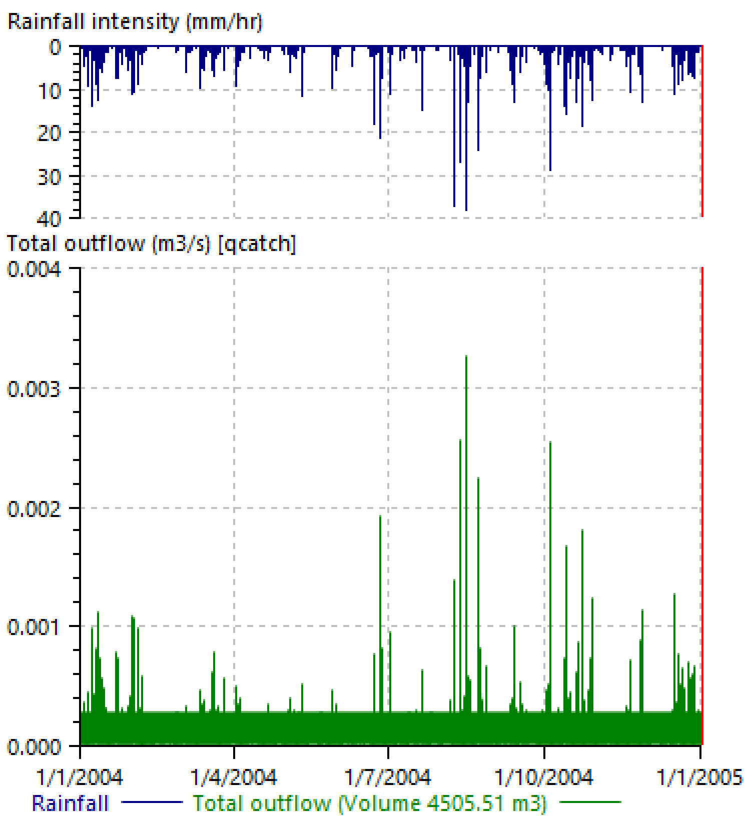

Figure 6: Redev-11 outflow with an extensive green roof installed

Figure 5 and Figure 6 show the effects an extensive green roof has on the total outflow of the building it is installed on. Figure 5 shows the total outflow without a green roof installed and Figure 6 shows the total outflow with a green roof installed. Subcatchment Redev-11 has been chosen as it is the smallest extensive green roof area within the study area.

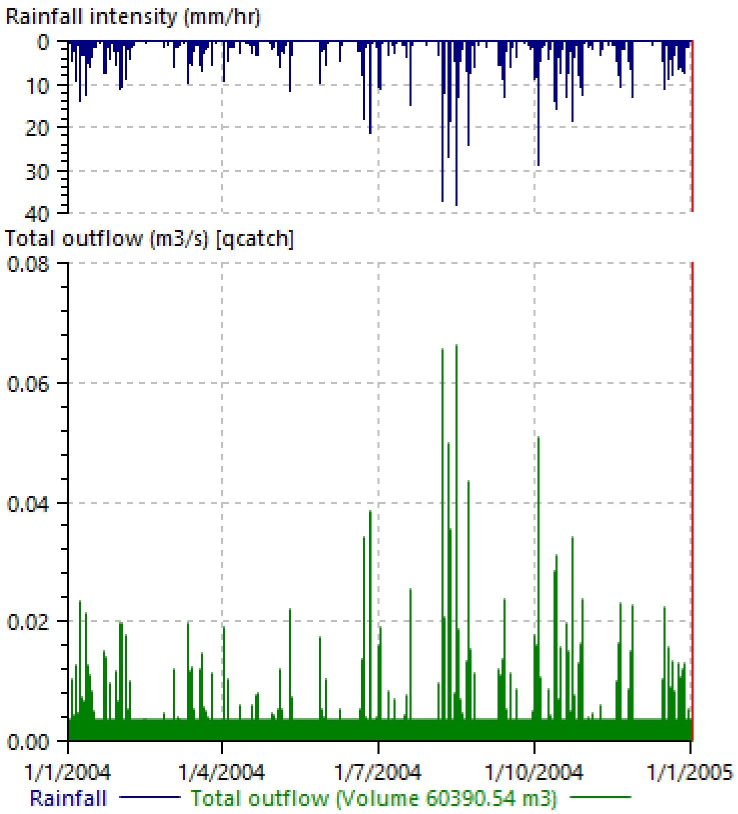

Figure 7: Redev-18 outflow with no green roof installed

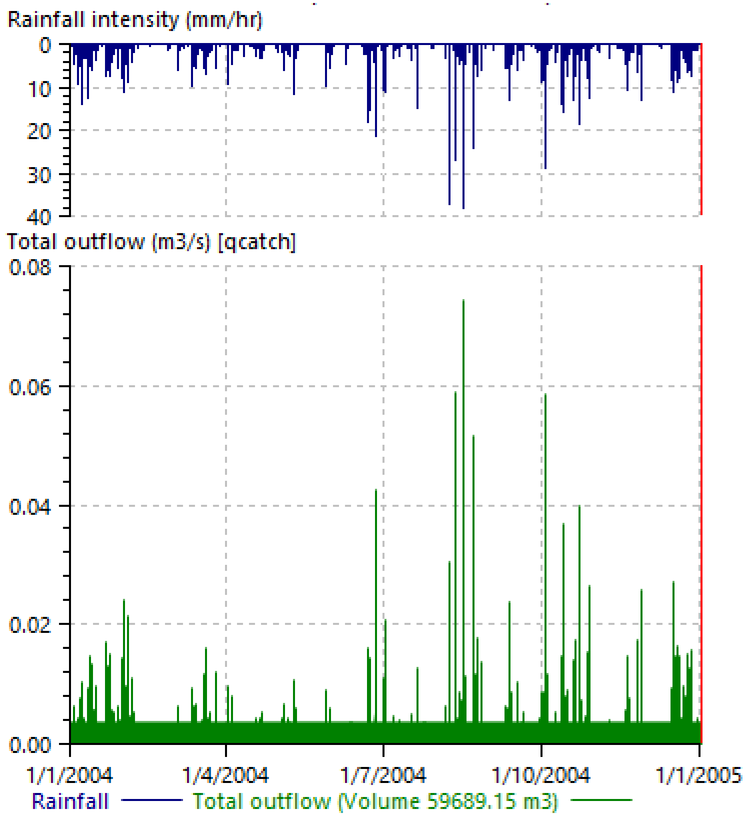

Figure 8: Redev-18 outflow with an intensive green roof installed

Figure 7 and Figure 8 shows the effect an intensive green roof has on the total outflow of the building it is installed on. Figure 7 shows the total outflow without a green roof installed and Figure 8 shows the total outflow with a green roof installed. Subcatchment Redev-18 has been chosen as it is the largest intensive green roof area within the study area.

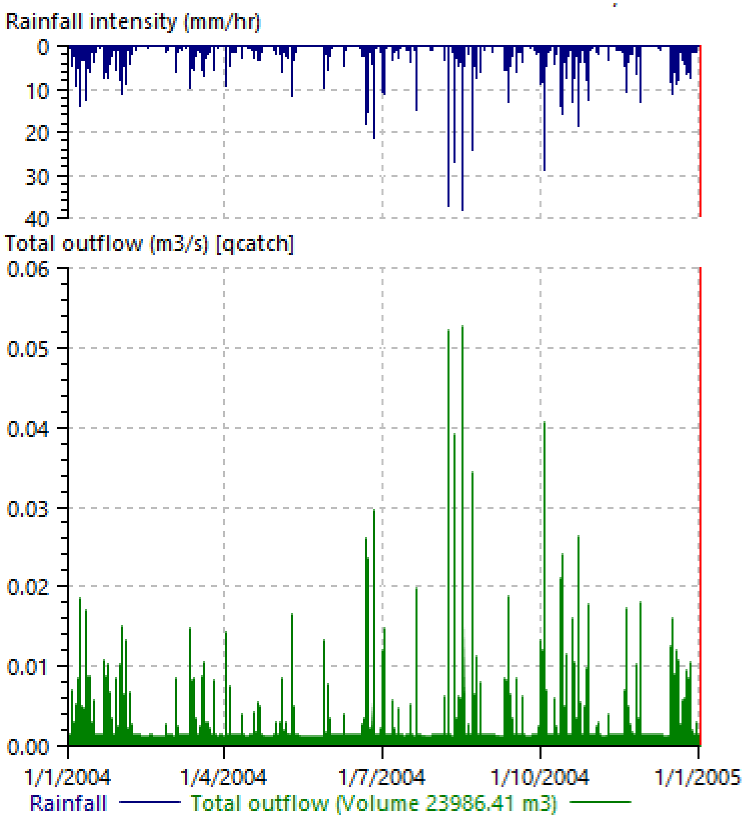

Figure 9: Redev-35 outflow with no green roof installed

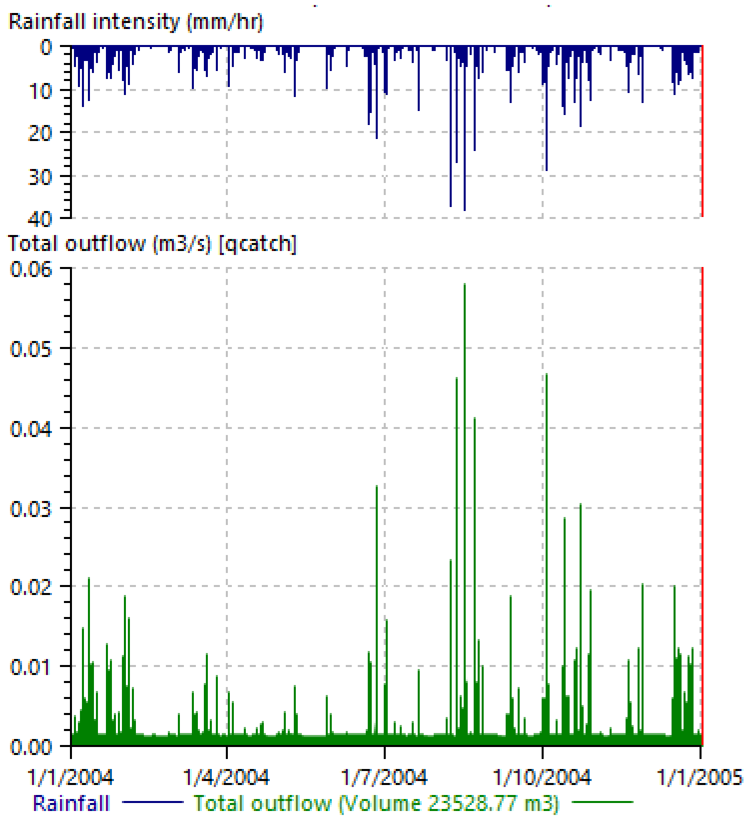

Figure 10: Redev-35 outflow with an extensive green roof installed

Figure 9 and Figure 10 shows the effect an extensive green roof has on the total outflow of the building it is installed on. Figure 9 shows the total outflow without a green roof installed and Figure 10 shows the total outflow with a green roof installed. Subcatchment Redev-35 has been chosen as it is the largest extensive green roof area within the study area.

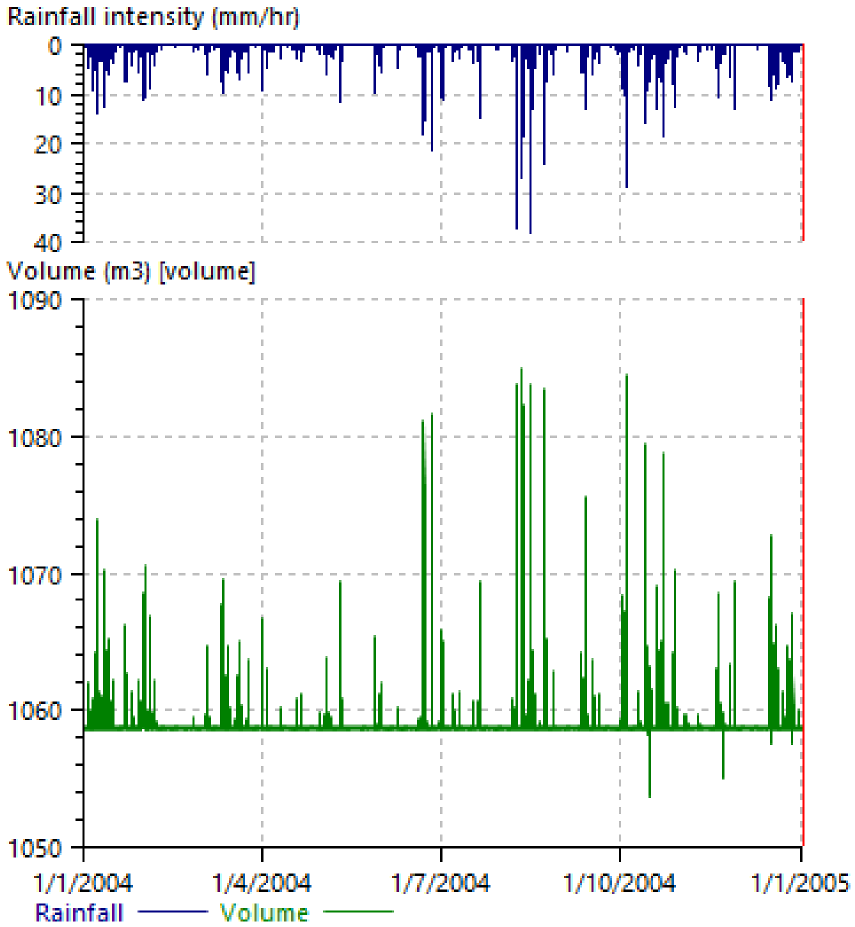

Figure 11: Outfall volume with no green roofs installed

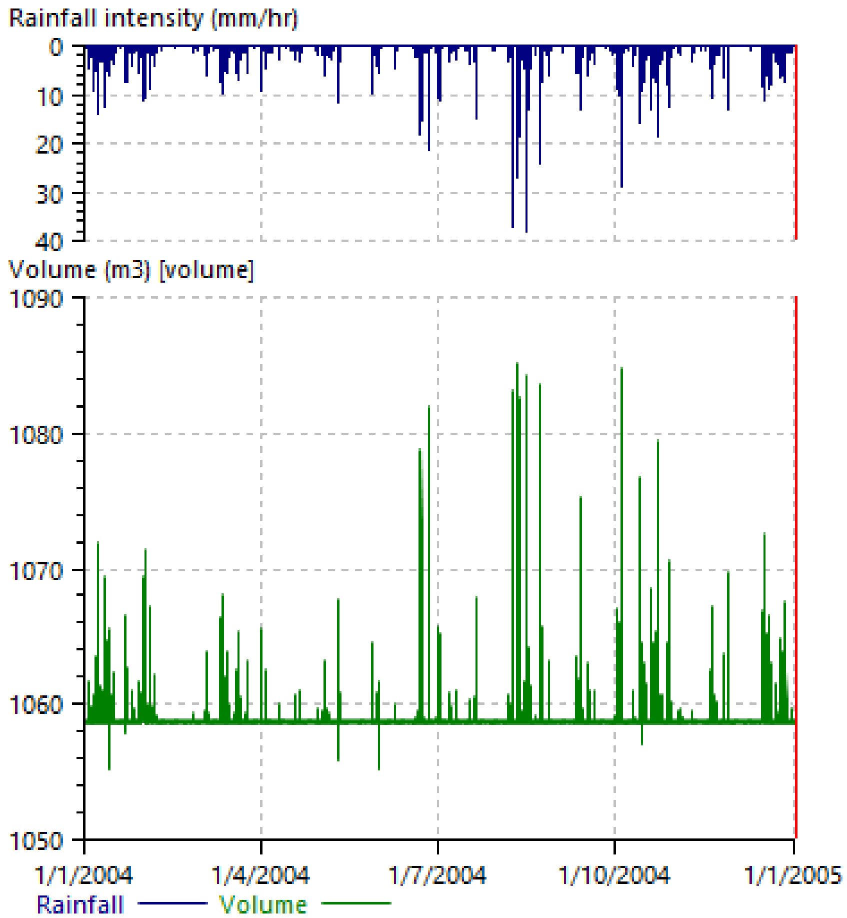

Figure 12: Outfall volume with green roofs installed

Figure 11 and Figure 12 show the volume within outfall A with no green roofs installed and with green roofs installed respectively

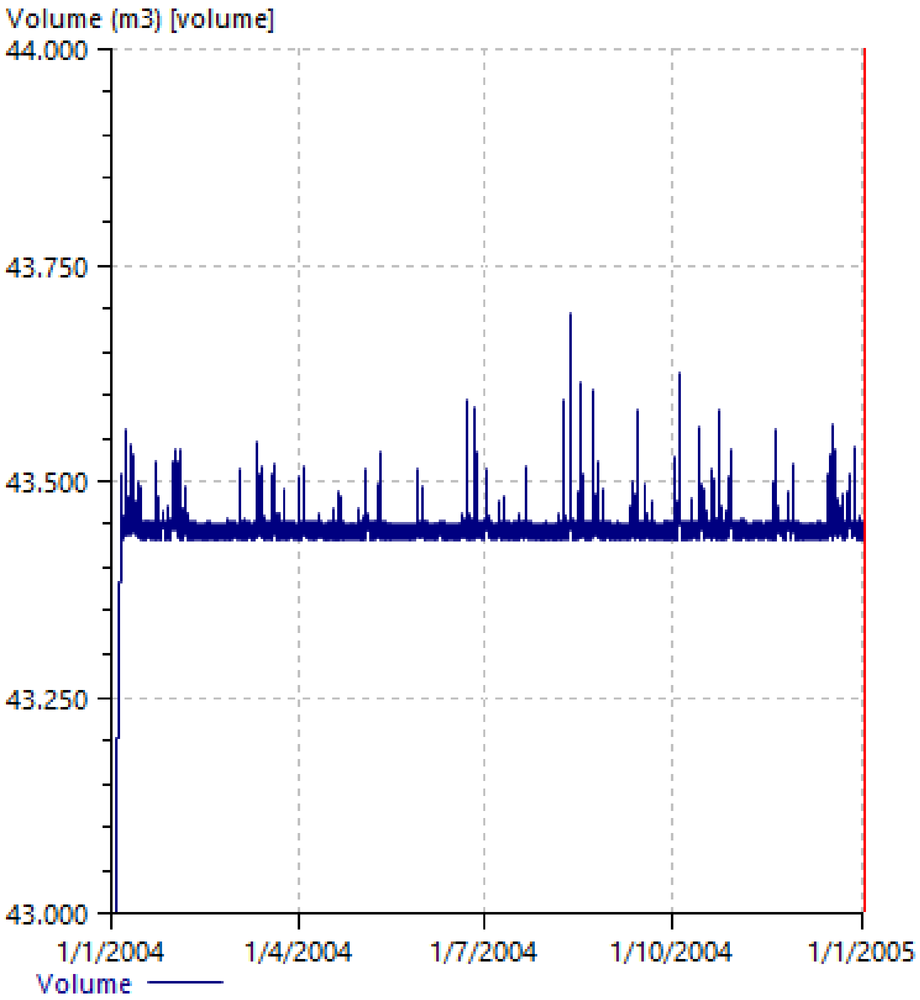

Figure 13: Outfall volume without green roofs installed

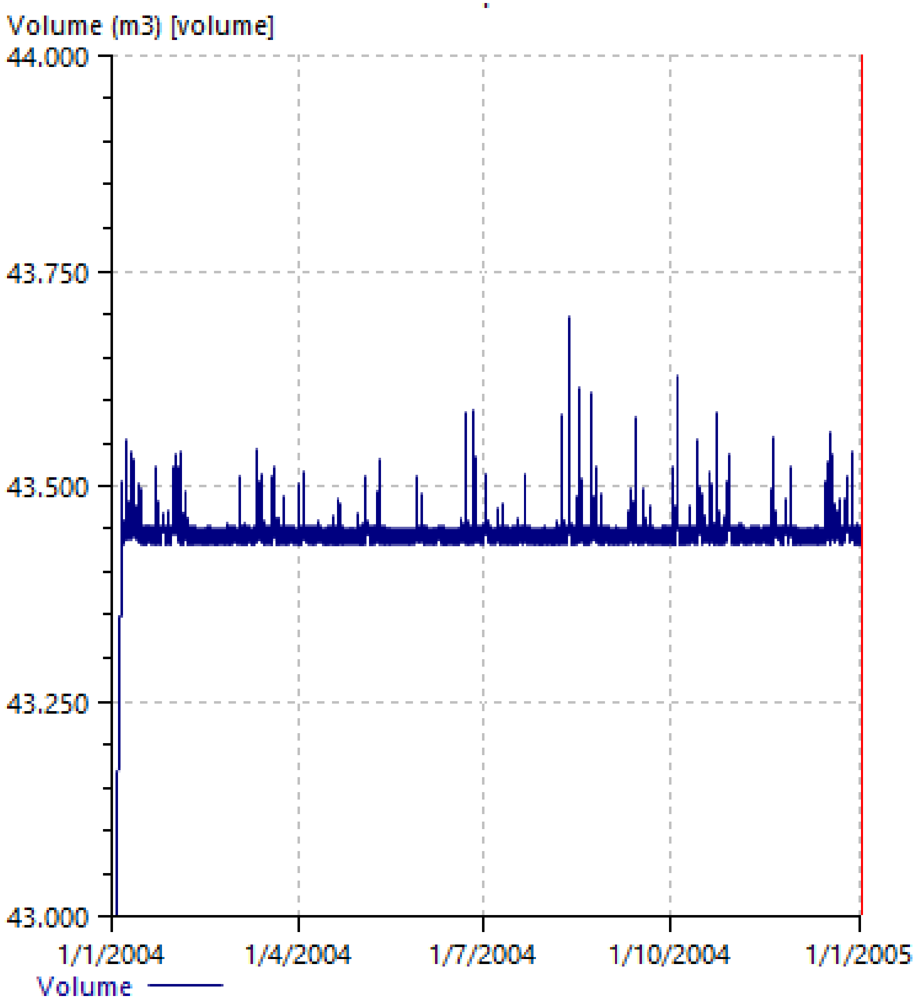

Figure 14: Outfall volume with green roofs installed

Figure 13 and Figure 14 show the volume within outfall B without and with green roofs installed respectively. Figure 15, Figure 16 and Figure 17 shows the breakdown effect of an intensive green roof on subcatchment 18. Figure 15 shows the runoff from the remainder of the roof when the green roof is installed. Figure 16 shows the runoff from the intensive green roof installed. Figure 17 shows the runoff from the roof before the green roof is installed

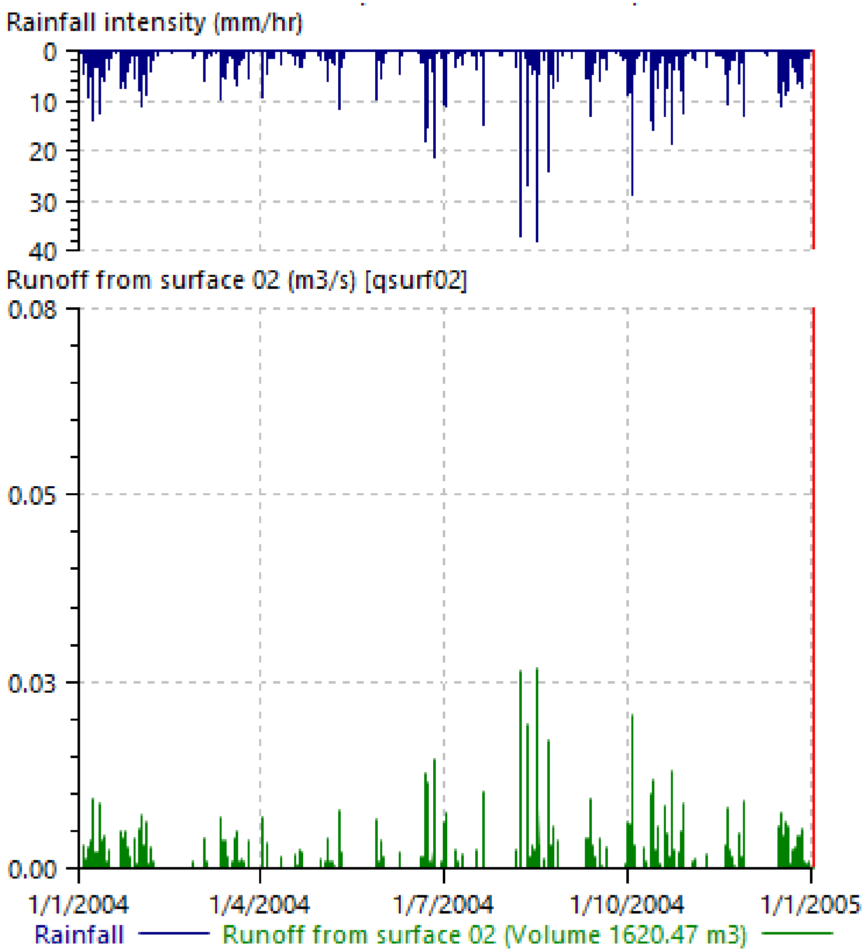

Figure 15: Runoff from the remainder of the roof with intensive green roof (Redev-18) installed

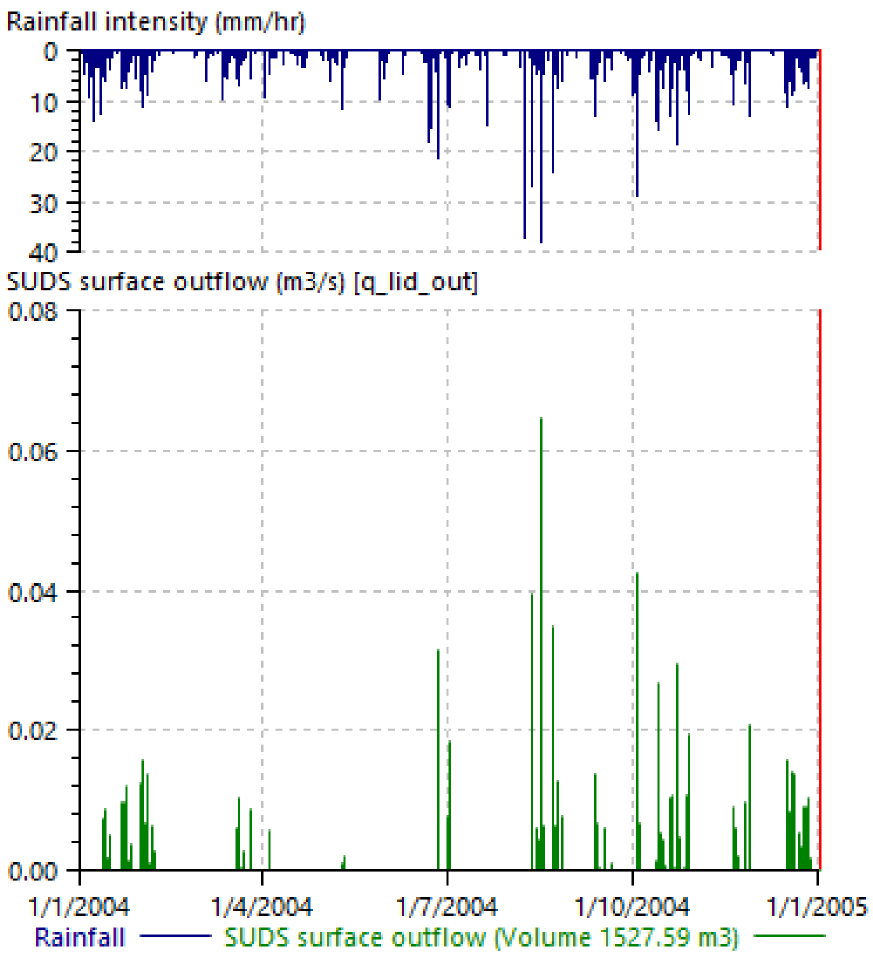

Figure 16: Runoff from the intensive green roof (Redev-18) installed

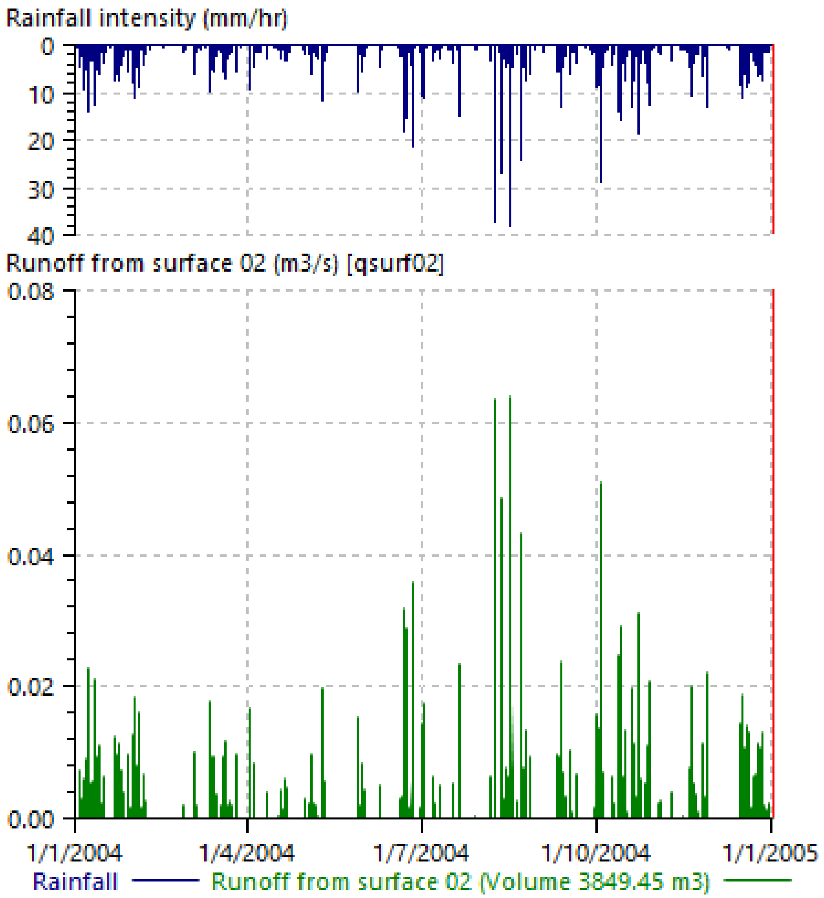

Figure 17: Runoff from the roof without an intensive green roof (Redev-18) installed

Figure 18, Figure 19 and Figure 20 show the breakdown effect of an extensive green roof on subcatchment 35. Figure 18 shows the runoff from the remainder of the roof when the green roof is installed. Figure 19 shows the runoff from the extensive green roof installed. Figure 20 shows the runoff from the roof before the green roof is installed.

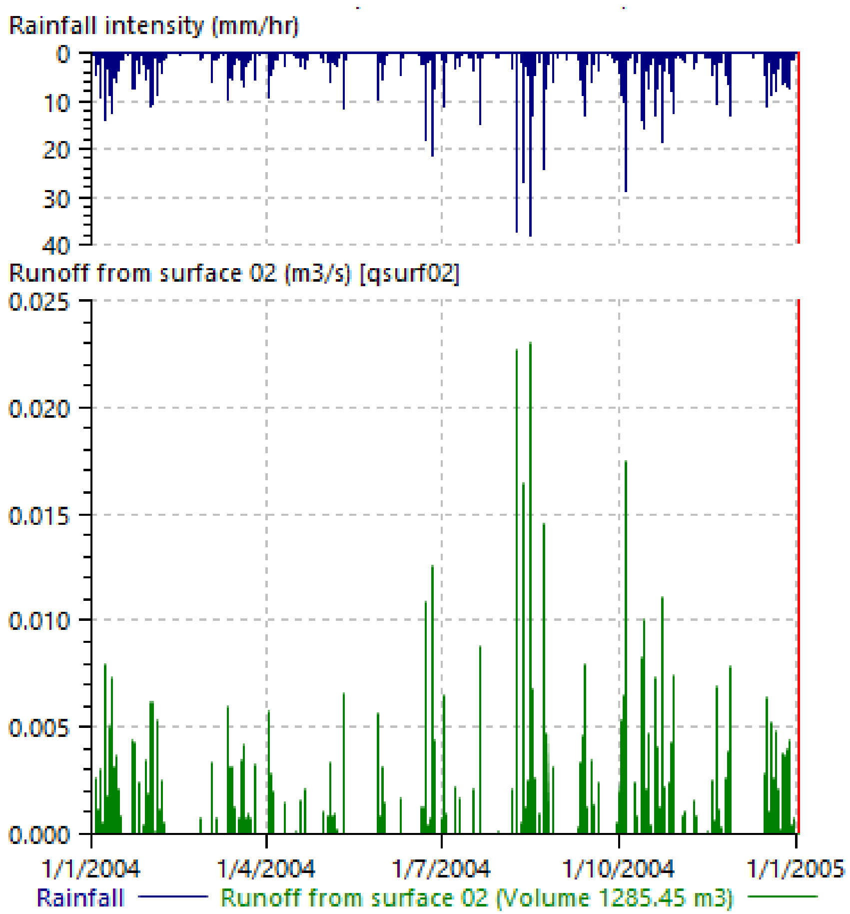

Figure 18: Runoff from the remainder of the roof with extensive green roof (Redev-35) installed

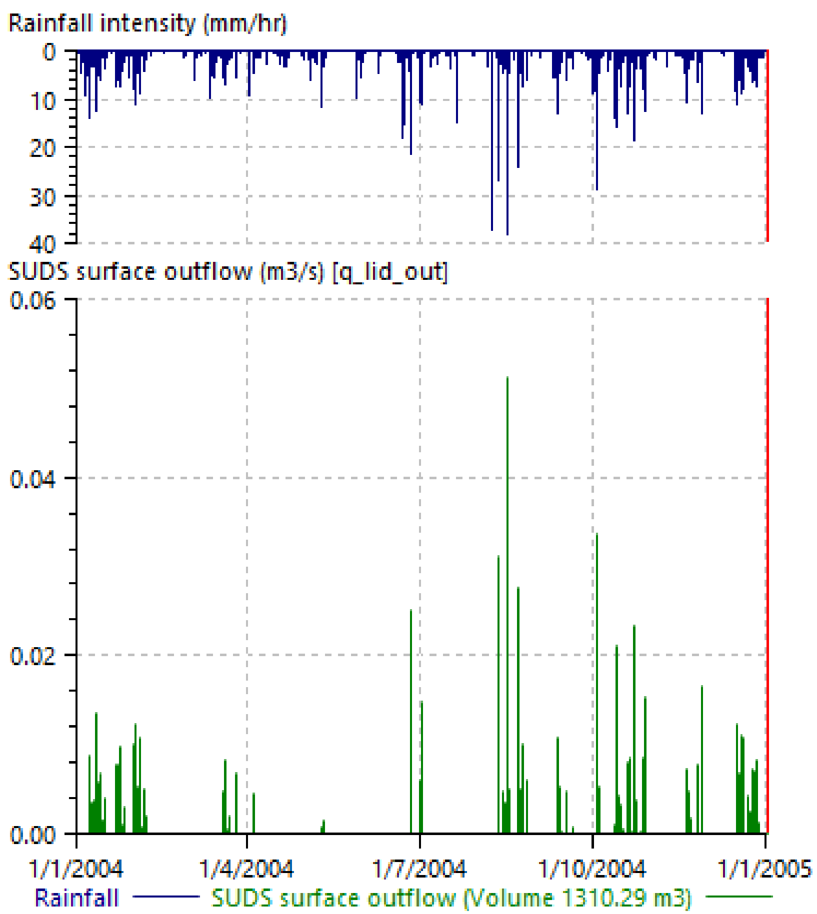

Figure 19: Runoff from the extensive green roof installed (Redev-35)

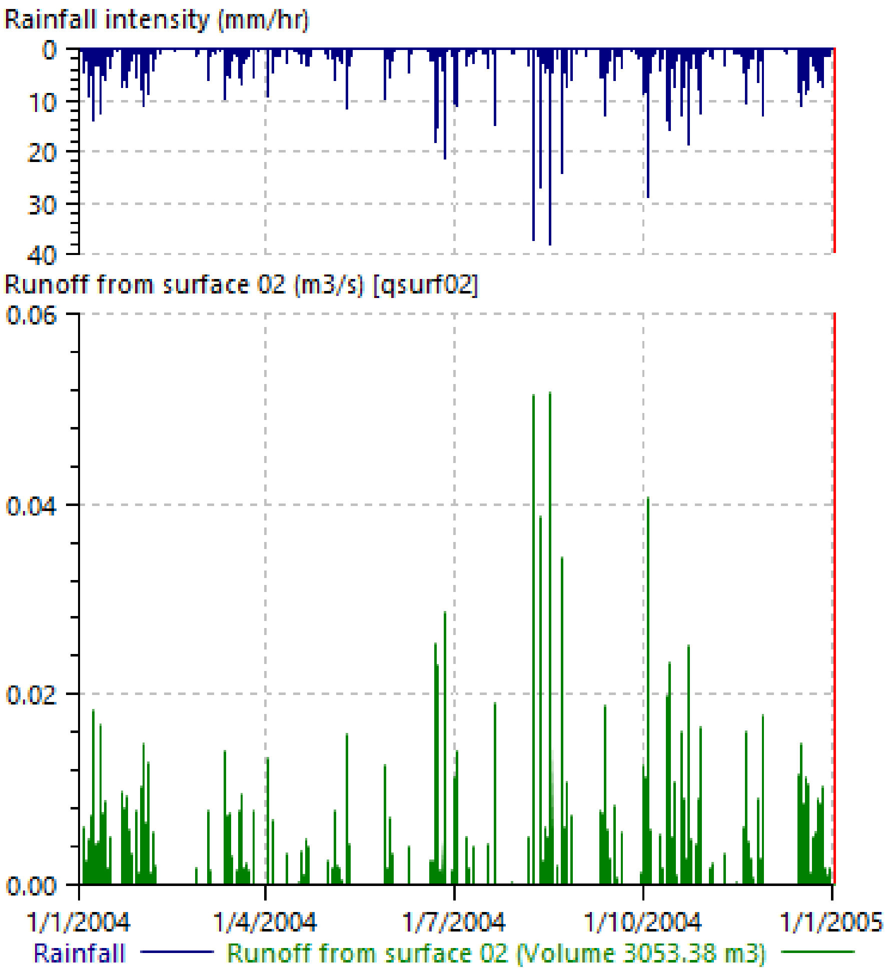

Figure 20: Runoff from the roof without an extensive green roof installed (Redev-35)

Figure 21 and Figure 22 show the flow (top graph on each figure) and volume (bottom graph on each figure) through conduits immediately downstream of certain green roofs without and with green roofs installed respectively. Table 6 below shows the corresponding green roofs to each conduit and a breakdown of the maximum flow, maximum volume and total volume through each conduit with and without the green roofs present

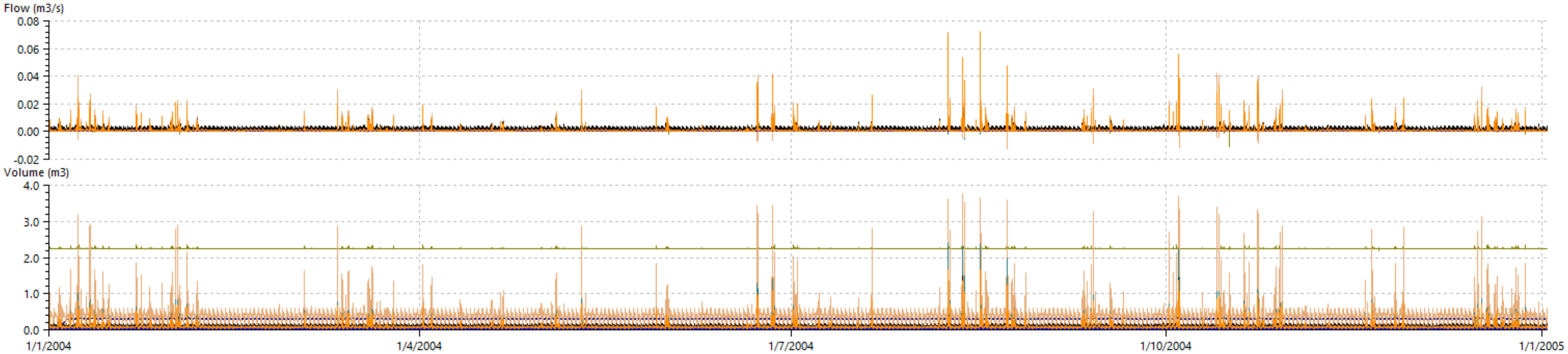

Figure 21: Conduits where only potential green roofs drain into it (no green roofs present)

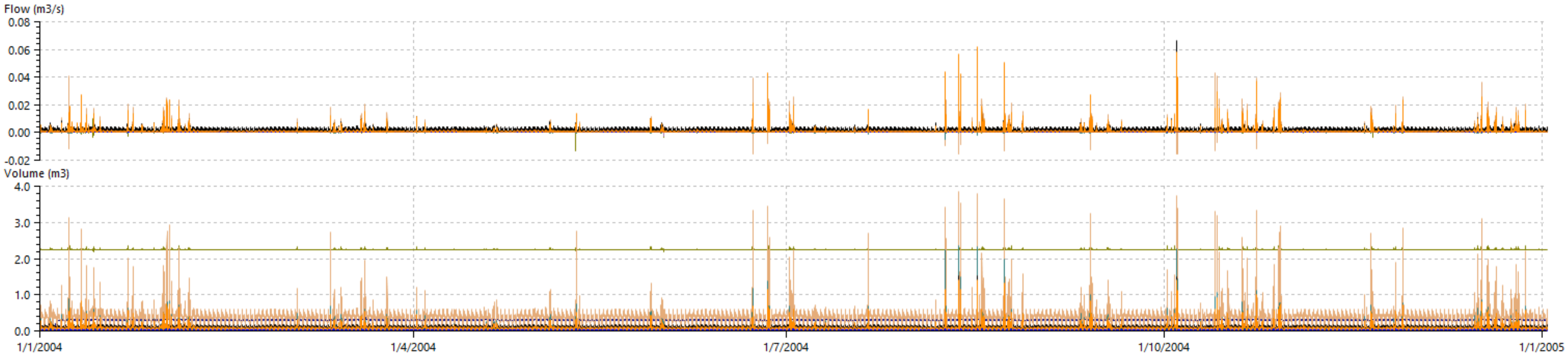

Figure 22: Conduits where only potential green roofs drain into it (green roofs present)

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Table 7: Green roofs draining to each conduit studied

Conduit ID	Roof area draining to the corresponding conduit	Type of green roof	Max flow without green roof (m^3/s)	Max flow with green roof (m^3/s)	Max flow difference (%)	Max volume without green roof (m^3)	Max volume with green roof (m^3)	Max volume difference (%)	Total volume without green roof (m^3)	Total volume with green roof (m^3)	Total volume difference (%)
SX47542508.1	Redev-36	Intensive	0.028	0.028	0.00%	0.786	0.795	-1.13%	4472.905	4174.483	6.67%
SX47543305.1	Redev-8	Intensive	0.028	0.026	-7.69%	0.265	0.249	6.43%	2782.395	2502.933	10.04%
SX47544304.1	Redev-9	Intensive	0.034	0.036	5.56%	1.814	2.086	-13.04%	2921.805	2502.474	14.35%
SX47544608.1	Redev-27	Intensive	0.006	0.010	40.00%	2.604	2.606	-0.08%	13034.831	12962.198	0.56%
SX47544609.1	Redev-26	Intensive	0.008	0.009	11.11%	1.283	1.284	-0.08%	6990.370	6961.249	0.42%
SX47545806.1	Redev-18	Intensive	0.043	0.043	0.00%	3.769	3.861	-2.38%	61215.111	60620.953	0.97%
SX47546302.1	Redev-34	Intensive	0.011	0.011	0.00%	2.428	2.353	3.19%	1028.947	953.794	7.30%
SX47546505.1	Redev-31	Extensive	0.025	0.026	3.85%	1.158	1.183	-2.11%	20596.622	20355.774	1.17%
SX47547702.1	Redev-4	Intensive	0.037	0.045	17.78%	0.300	0.313	-4.15%	25408.880	24975.612	1.71%
SX47547703.1	Redev-13	Extensive	0.019	0.028	32.14%	0.495	0.517	-4.26%	10031.115	9857.895	1.73%
SX47547704.1			0.021	0.025	16.00%	1.186	1.437	-17.47%	10033.129	9847.022	1.85%
SX47547804.1	Redev-16	Intensive	0.070	0.067	-4.48%	1.492	1.534	-2.74%	69278.599	68987.203	0.42%
SX47548704.1	Redev-30	Intensive	0.022	0.021	-4.76%	0.393	0.444	-11.49%	10034.741	9839.199	1.95%
SX47548705.1	Redev-6	Intensive	0.006	0.005	-20.00%	0.188	0.162	16.05%	4370.903	4324.602	1.06%
SX47549507.1	Redev-35	Extensive	0.073	0.062	-17.74%	1.678	1.415	18.59%	25070.037	24652.870	1.66%

Discussion

Overall analysis

As shown in Table 4 there is a decrease in the outflow from every building that had a green roof installed with the smallest decrease being 0.4% and the largest decrease being 15.7%. This provides evidence that installing green roofs on a larger scale will aid in reducing surface runoff. The overall reduction in volume of the outflow will reduce the amount of water spilt into the environment via CSO's as mentioned in Section 0.Previous studies formerly mentioned in section 0 show that the average retention rate observed was a lot higher, the minimum being 34%, than the above-mentioned results. However, the first two studies of green roofs that were being investigated were implemented in a warmer climate so there is a greater loss of rainfall due to evapotranspiration. The roof that Zhang *et al*. (2015) within the Yubei district the substrate is 150mm which is deeper and will therefore retain more water. The second study is investigating a larger green roof and has the equivalent depth as the intensive green roofs and therefore will also retain more rainfall.

Although both these green roofs can retain more rainfall the retention rate is substantially higher in previous investigations than in the study carried out throughout this report. This may be due to numerous things such as the weather conditions were different so different rates of evapotranspiration will occur, the areas of the green roofs will also have a significant effect on the retention rate, these studies may have also been carried out using isolated rainfall events therefore did not take into consideration the effect of the green roof already being saturated, as shown in Figure 4 and Figure 5 this is a considerable factor in dictating the runoff from the green roof. The studies mentioned may also only be looking at an isolated green roof and comparing equivalent areas of roof that aren't greened where as in a real-life situation the total area of the roof cannot be greened due to maintenance and obstacles on the roof. This study compares the original roof area against the effect of only 52% being greened this will reduce the difference in the volume of outflow. One of the main factor that may have altered the results is the inputted soil and mat properties inputted into the model as concluded by Wang *et al.* (2017). Due to the soil being an engineered mixture of aggregate sand and organic matter it is different from naturally occurring soils therefore an estimation of the properties was made using judgement and research. Further investigation into the effects of the soil properties may be needed to find the most realistic approach to modelling green roofs.

Figure 2 shows that as the area of the intensive green roofs increase the reduction in the total outflow also tends to generally increase however, the area of the extensive green roof has little or no effect on the reduction of the total outflow. This may be due to the shallower soil depths and therefore a small change in area would have a less significant effect than the intensive green roofs. It can also be seen that the intensive green roofs have a more significant effect in reducing the total outflow than the extensive green roof because the intensive green roofs have twice the soil depth and therefore can retain more water.

The percentage decrease for each type of green roof is shown in Table 5. This shows that intensive green roofs are 1.9 times more effective than extensive green roofs. These results were expected as the thickness of the soil used on the intensive green roofs are 100mm which is double the thickness of the extensive green roofs as mentioned above. This is the only factor that is altered between the two types of green roofs within the model.

Individual roof analysis
Figure 3 and Figure 4 show the effect an intensive green roof has on the total outflow without and with a green roof installed respectively. With an area of 0.015ha Redev-7 has the smallest area of intensive green roofs. There is a total volume reduction of 12.61m^3 which will have been lost due to evapotranspiration over the year this small reduction in flow is due to the green roof covering a small area, the total storage capacity of the roof is only 15m^3 which will have stored water and attenuate the flow. Although the roof only reduced the overall volume by a small amount it was still very effective in attenuating the flows these results support the conclusion Lee *et al.* (2015) reached that the antecedent dry days improved the water retention capacity of the green roofs. This is demonstrated in the period of 1/1/2004 and 1/7/2004 as most of the smaller peaks of outflow has been reduced significantly and at some points there are no peaks at all. This is shown significantly at the peaks just before 1/4/2004 as the first peak is reduced from 0.0007m^3/s to 0.0004m^3/s this is due to the attenuation effect of the green roof as the water will be stored within the soil layer and a small amount will be lost due to evapotranspiration. However due to this attenuation effect the second peak caused by ongoing rainfall has increased from 0.0008m^3/s to 0.009m^3/s when the green roof is present because the green roof would have already been saturated by previous rainfall so any additional rainfall will run off the green roof as if it was just a normal roof and the attenuated flow will also be reaching the sewer system therefore increasing the peak. This effect can also be seen during the largest rainfall. The first peak is reduced from 0.0013m^3/s to 0.0011m^3/s however due to saturation of the green roof and attenuation the second peak is increased from 0.0009m^3/s to 0.0014m^3/s. This is a larger increase in flow than the decrease but due to the attenuated flows going through the green roof and the green roof not being saturated anymore the third peak is reduced from 0.0013m^3/s to 0.009m^3/s therefore the green roof has reduced the flow and the effect the flow has on the sewer overall.

Figure 5 and Figure 6 show the effect an extensive green roof has on the total outflow without and with a green roof installed respectively. With an area of 0.036ha Redev-11 has the smallest area of extensive green roofs. There is a reduction of 25m^3 which has been lost to the atmosphere via evapotranspiration in the total outflow volume this is a small reduction due to this green roof only covering a small area as the retention capacity of the green roof is just 18m^3 which will have stored water and attenuate the flow. Like the intensive green roof there is clear evidence that extensive green roofs are effective at attenuating flows. The greatest decrease in flow when the green roof is present is 0.0031m^3/s to 0.0021m^3/s this is shown as the third peak during the largest storm. However, similarly to the intensive green roof the second peak is greater when the green roof is present due to attenuation and a fully saturated soil layer.

Figure 7 and Figure 8 shows the effect an intensive green roof has on the total outflow without and with a green roof installed respectively. With an area of 0.854ha Redev-18 is the largest intensive green roof. There is a total volume reduction of 701.39m^3 over the year. This is a significant reduction of flow which is to be expected as the green roof has the storage capacity of 854m^3. The same trends can be observed as with the smaller intensive green roofs in terms of the patterns within the peaks and the reduction in peaks during smaller rainfalls and the attenuation effect on the larger rainfalls. However, there is a change in the pattern of the peaks during the first storm. The largest intensive green roof has reduced the runoff significantly during the first bout of rainfall whereas the smallest intensive green roof increases the greatest peak during the first bout of rainfall. This could potentially be due to the fact that the largest green roof has a greater storage capacity so will be able to handle smaller rainfalls because it will take longer to become saturated.

Figure 9 and Figure 10 show the effect an extensive green roof has on the total outflow without and with a green roof installed respectively. With an area of 0.677ha Redev-35 is the largest extensive green roof. There is a total volume reduction of 457.64m3. This is a significant reduction of flow which is to be expected as green roof has a storage capacity of 338.5m3. The same trends can be observed as with the smallest extensive green roof. These four green roofs were chosen for analysis due to being the smallest and largest extensive and intensive green roofs. The remainder of the total outflow graphs for each sub catchment can be seen in Appendix B. the graphs tend to show the same pattern as the above graphs.

Outfall analysis

Figure 11 and Figure 12 show the volume within Outfall A without green roofs installed and with green roofs installed respectively. In general, there is limited difference in the volume of sewage through the outfall. This is due to the volumes being a lot larger than the local effects and therefore, there is a less significant difference in the volume. However, during the increased rainfall there is a slight difference in the peak volumes. The first period of rainfall there is a reduction in both peaks for the volume, there is a reduction of 2m^3 in the first peak and 1m^3 in the smaller peak. The greatest decrease in volume when the green roofs are installed is 3m^3, the smaller peak just before 1/7/2004, however this reduction in the volume of sewage at that specific point in time had a knock-on effect to the second peak of the storm and therefore there is a slight increase of 1m^3 in the larger peak of the volume of sewage just before 1/7/2004. Due to the attenuation effect of the green roof this happened numerous times such as during the second storm after 1/1/2004, the second storm after 1/10/2004 and finally the storm just before 1/1/2005.

Figure 13 and Figure 14 show the volume within Outfall B without green roofs installed and with green roofs installed respectively. Due to the outfall being at the end of the sewer system within the study area, the green roofs have less of an impact on the volume within this conduit. Therefore, the two graphs appear very similar in terms of time of peaks, trend and volume. Although the timing of the peaks remains the same when green roofs are present as there is a small reduction in the volume during larger peaks and there is a change in the trend of the peaks. For example, the smaller peak before the largest peak during the year is reduced when the green roof is present. This reduction in volume doesn’t have any effect on the largest peak which remains the same with or without the green roof. However, the two peaks just before 1/7/2004 exemplifies that green roofs can also increase the volume going through the conduit at a given time due to the effect of attenuation of the green roofs. The green roofs reduced the volume in the first peak but due to the attenuation of the green roofs the second peak is greater when the green roofs are present.

Green roof runoff breakdown analysis

Figure 15 and Figure 16 shows the breakdown of runoff from the remainder of the roof after green roof instillation and the runoff from the intensive green roof itself respectively. 58% of each roof was covered in green roof however, the runoff from the remainder of the roof is 92.88m^3. Figure 17 shows the runoff from the roof before a green roof is installed. 42% of the total volume off the roof before the green roof is installed is 1616m^3 which is replicated in Figure 15 as expected. However, 58% of the total runoff from the roof before the green roof is installed is 2232.68m^3 as shown in Figure 16 the runoff volume from the simulated green roof is only 1527.59m^3. This is a 705.09m^3 difference over the year this volume of water would have been lost due to evapotranspiration due to the wildflower blanket and water stored within the soil layer. These figures show that green roofs are an effective way to reduce the amount of flow within the sewer system. During smaller volumes of rainfall the green roof is effective in attenuating the flow effectively as shown in Figure 15 and Figure 17 there tends to be consistent small bouts of runoff however in Figure 16 during smaller storms there is no indication of any significant runoff this is evident during the period between 1/4/2004 and 1/7/2004.

Figure 18 and Figure 19 show the breakdown of the runoff from the remainder of the roof after the green roof is installed and the runoff from the extensive green roof itself. Figure 20 shows the runoff from the roof before the green roof is installed. The runoff from the green roof is greater than the runoff from the remainder of the roof this is expected as the green roof covers 58% of the total roof area. 42% of the total runoff before the green roof is installed is 1282.42m^3. This is replicated in Figure 18. 58% of the total runoff is 1770.96m^3 this is 460.67m^3 greater than the extensive green roof outflow volume, this reduction in volume will be due to evapotranspiration of the sedum and water retained within the soil. During smaller volumes of rainfall the green roof is effective in attenuating the flow effectively as shown in Figure 18 and Figure 20 there tends to be consistent small bouts of runoff however in Figure 19 during smaller storms there is no indication of any significant runoff this is evident during the period between 1/4/2004 and 1/7/2004.

Graphs shown in Figure 15, Figure 16 and Figure 17 illustrate the effects an intensive green roof has on the overall runoff from the roof. Graphs shown in Figure 18, Figure 19 and Figure 20 illustrate the effects an extensive green roof has on the overall runoff from the roof. As mentioned previously the difference in runoff over the year when there is no green roof installed and when the green roof is installed is 705.09m^3 and 460.67m^3 for intensive and extensive green roofs respectively. This demonstrates that the intensive green roof is more effective at reducing the overall runoff from the roof. However, both roofs are effective at decreasing the runoff which will aid in increasing the head room within the sewer system and help reduce flooding.

The area of the green roofs studied will influence the volume of runoff. The intensive green roof studied was sub-catchment Redev-18 with a total area of 0.854ha so the area of the green roof is 0.495ha at a soil depth of 100mm, which means the volume of water the green roof can retain at one time is 495m^3. Therefore, the least amount of water lost by evapotranspiration is 210.09m^3.
The extensive green roof studied was sub-catchment Redev-35 with a total area of 0.677ha so, the area of the green roof is 0.393ha at a soil depth of 50mm, which means the volume of water the green roof can retain at one time is 196.5m^3 therefore the least amount of water lost by evapotranspiration is 264.17m^3. These results suggest that the extensive sedum blanket is more effective at evapotranspiration than the intensive wildflower blanket. However, it is not certain that the green roof is fully saturated when the simulation has finished if the green roofs were dry then more evapotranspiration occurred from the intensive green roof than the extensive therefore this conclusion is not very reliable.

Conduit flow and volume analysis
Figure 21 and Figure 22 shows the flow and volumes within conduits downstream where the only runoff entering the conduits is from potential redevelopment or refurbishment sub catchments and green roofs respectively. Other conduits could not be analysed effectively as the runoff from other sub catchments will have a significant effect on the flow and volume within the conduits as shown in Figure 11, Figure 12, Figure 13 and Figure 14 the wider the range of the analysis the smaller the effect the green roofs have on the volume and flow within the conduit. Table 6 shows the corresponding conduit IDs analysed to the sub-catchments draining to that specific conduit.

Figure 21 and Figure 22 show an overview of the effects green roofs have on the flow and volume in the immediate downstream conduits in general green roofs aid in reducing the flow through the downstream conduits. This can be seen in the top graph of Figure 21 and Figure 22 the greatest peak between the dates of 1/7/2004 and 1/10/2004 when no green roofs are present is 0.07m^3/s and the peak that occurs at the same time when green roofs are present is 0.04 m^3/s. There is also a significant reduction in the amount of flow during bouts of smaller storms such as the period between 1/4/2004 and 1/7/2004 the central peak that occurs without green roofs present is 0.03m^3/s and at the same point the peak has been reduced to 0.01m^3/s this is the greatest reduction of flow. However, during times of recurring storms, due to the effects the attenuated flow and the saturation of the soil has on the flow, the flow within the conduit is greater with green roofs than without green roofs as demonstrated during the three peaks between 1/7/2004 and 1/10/2004. The first peak is reduced by 0.03m^3/s when the green roofs are present however, as the storm continues the green roof becomes saturated and the attenuated flow continues to percolate through the green roof soil layer the second peak is increased by 0.01m^3/s when the green roof is present. However, the third and final peak caused by the ongoing storm is reduced by 0.01m^3/s when the green roofs are present. Due to there being an overall greater decrease than an increase between the peaks the green roofs decrease the effect of flow within the conduits overall. This effect is also evident during the last bout of storms throughout 2004. The same trend is shown in the volume graphs.

Table 6 shows the breakdown for each conduit showing the max flow, max volume and total volume all with and without green roofs installed. The greatest increase in the max flow through a conduit is 67% due to it being such small flows this is only 0.004m^3/s increase in the flow when the green roofs are installed. The greatest decrease in the max flow through a conduit is 17% this is only 0.001m^3/s decrease in the flow when the green roofs are installed. Due to the flows being so small this reduces the certainty of the data as smaller flows are harder to measure accurately therefore, this reduces the reliability of the results. There is a greater variation in the flow throughout the conduits and there is no clear trend and therefore should not be used for further analysis.There is a smaller variation in the maximum volume than in the maximum flow within each conduit and there appears to be no correlation between the max volume and flow, the type of green roof or whether a green roof is installed or not. This may be due to there being such small flows through each conduit that although there is a significant difference in the runoff from the roof when the green roof is installed by the time this runoff has reached the conduit the small flows show no trend.

The installation of green roofs always aided in reducing the total volume within the conduits. The maximum percentage difference being 14.35% with a difference of 419.331m^3 and the smallest percentage difference being 0.42% with a difference of 291.396m^3. Due to the volumes being bigger this is a lot more reliable and accurate approach rather than comparing the smaller figures of the maximum flow and maximum volumes within the pipe. The average extensive decrease is 1.52% this is significantly smaller than 4.13% this is to be expected as the intensive green roofs have a deeper soil layer and can therefore retain more water. Intensive green roofs are also made up of a wildflower blanket whereas the extensive green roofs are made up of a sedum blanket therefore, the wildflower blanket is believed to have a greater effect on the runoff due to evapotranspiration from the plants and soil layer these results support this assumption.

Research question

The aim of this project was to examine the feasibility of reducing storm water runoff using green roofs in Plymouth city centre. Overall there is strong evidence that implementing green roofs within the city centre will reduce the runoff from the building that the green roof is installed onto. This is shown throughout the graphs and overall volumes extracted from InfoWorks as the average volume reduction over both types of green roof implemented is 2.75% which over the course of a year is quite a significant amount of volume.

There is also a clear advantage of implementing intensive green roofs wherever possible as the results show that they are twice as effective as extensive green roofs. This was expected as the only differences between the two green roofs is the depth of the soil layer and the vegetation. On an intensive green roof, the soil layer is twice as deep and a wildflower blanket is installed which has more comprehensive plant species which will transpire slightly more water throughout the year. As well as the green roofs reducing the overall volume of runoff it can be observed that they are very efficient at attenuating flows to the combined sewer system. During smaller storms there is clear evidence on the graphs that the green roofs can dissipate most of the smaller runoff peaks within the runoff graphs.

Through using PCC strategic masterplan to identify potential locations to install green roofs it showed the benefit of installing green roofs when refurbing or redeveloping buildings. By using this approach, it would cost less money and be easier to install the roof as building access will already have been in place. As mentioned in Section 0 there is also the potential for PCC to implement a policy where any new developments or refurbishments should have a green roof installed on to it to attenuate the flows to the sewer system.

This study was specifically designed for testing the effect of green roofs within the centre of Plymouth. Due to the makeup of Plymouth's sewer network and the buildings within Plymouth it was an ideal study site to identify the benefits and constraints of green roofs. Through using the inbuilt SUDS control editor within InfoWorks ICM it makes the method of modelling the green roofs easy to replicate into any network. However, this network would need to be built in InfoWorks ICM or an Innovyze product which allows transfers to ICM, it would also be advised that the network is verified to get accurate and reliable results which can be a lengthy and costly process for clients. Therefore, it is possible for this study to be easily replicated within different areas especially through the use of the integrated SUDS control editor.

For green roofs to be built effectively the roof would need to be flat or on a gentle slope as Viola *et al* (2017) discovered that as the slope of the roof increase the efficiency of the green roof reducing runoff decreased. As seen in the results the green roofs are a lot more effective when installed on a significant roof area and that intensive green roofs are also advised when possible (shown in Table 5). Therefore, it is advised that if a study were to be carried out in a different area it is revised whether the roofs are a suitable size and shape.

Justification of approach

InfoWorks ICM was used to model the sewer network and green roofs within this study, the main reason for using software is because InfoWorks is an integrated catchment modelling piece of software which is used to aid in projects all over the world therefore it is a tested piece of software and is designed for this specific application. Another main driver in the decision to use InfoWorks is that Arcadis had a verified network model of Plymouth already built this meant that the model would simulate how the network works in real life situation within a small tolerance. Therefore, the verified model allowed a more realistic approach to modelling the green roofs and the results extracted would be more reliable and accurate than if a new model were built for this particular study.

PCC strategic masterplan was used to decide where the green roofs should be located, the size of the green roof and the type of the green roof. The masterplan shows the planned development and refurbishment within the city centre for the next 20 years this enabled an accurate approach when modelling the green roofs. The strategic masterplan was also used to determine the projected population and the distribution of the population (see Table 1 and Table 2) within the city centre which was also used within the model.

Other approaches to model green roofs were studied the model using SWMM, modelled green roofs as a small network of reservoirs this approach integrated a lot of calculations and considered key characteristics of green roofs the model was calibrated using an experimental green roof and had very strong correlations which makes the model reliable to represent green roofs in France. The inbuilt SUDS control editor which was used in this study considered the same characteristics as the SWMM approach making it a more dependable approach to modelling the green roofs. The SUDS control editor was also created by a team of experts within Innovyze and would have been tested before being published for use by professionals.

Critical evaluation

A dependable approach was used in modelling the green roofs and sewer system by using a verified model within InfoWorks ICM, as the model has been designed and calibrated to real life situations. Through using the SUDS control editor, a consistent approach was made to all the green roofs across the study area this helped reduce any errors made using hand calculations or inputting individual green roofs and trying to replicate each type. However, the parameters needed within the SUDS control editor may vary and due to the soil used within green roofs being engineered differently depending on the type of the green roof, the company installing the green roof and the location of the green roof it is hard to put in the exact parameters to replicate green roofs exactly within a real-life situation. It is advised that these parameters are researched more and the effects the parameters have on the results are considered. Further studies may need to change the parameters for each different location and green roof being researched. Although the modelling software is based on various comprehensive calculations to simulate the behaviour of green roofs this investigation is relying solely on the results from the simulations. It is recommended that small samples of green roofs are investigated within the study area or a different approach to modelling green roofs is carried out to aid in verifying the results produced from InfoWorks.

The approach used to determine the location of the green roof was informed by the PCC strategic masterplan. This is a reliable approach as green roofs would realistically only be installed on such a large scale if the council brings out a policy that all new builds and refurbishments need to have a green roof installed. By using the PCC masterplan any planned refurbishments or redevelopments were identified and an appropriate green roof can be inputted into the model at appropriate locations. The masterplan was also used when determining the projected populations. As seen in Table 1 this allowed for a detailed population input into the model. However, the estimation for the population equivalent for the office and retail population was taken from a document that may be outdated as this was the only document available therefore reducing the accuracy of the population.

TSR rainfall was used as it is real life rainfall that has occurred over previous years collected by the MET office. The closest MET office rain gauge is located at Torpoint this is roughly 3.56km away. The rain within Plymouth will only be slightly different and will have little or no effect overall. The effect of climate change on the rainfall has only been crudely included by adding 10% to the rainfall. This approach was done for simplicity due to time constraints. If more time was available the effects of climate change would need to be investigated to get a more comprehensive analysis of green roofs as climate change may alter the volume of rainfall, the pattern of the rainfall and the weather conditions affecting evapotranspiration. These are all key factors affecting the green roof behaviour.

Conclusions

When comparing the overall outflow from each green roof it was clear that green roofs are effective at reducing the runoff from the roof with every green roof reducing the outflow. This corresponds with the same consensus as the studies carried out by Zhang *et al.* (2015); Gregoire & Clausen (2011); and Stovin, (2010). Although the general consensus was the same the modelled green roofs within this study showed a significantly smaller retention rate this may be due to numerous reasons such as depth of substrate, soil parameters and weather conditions. Further studies will need to be carried out to test these variables that alter the behaviour of green roofs.

When comparing the extensive and intensive green roofs it is clear that the intensive green roofs have a greater retention rate. This was to be expected as the soil substrate depth is twice as deep. This supports the conclusion surmised by Zhang *et al.*, (2015) stating that substrate depth is an important factor affecting the retention rate. These findings also correlate to the findings carried out by Zhang *et al.* (2015); Gregoire & Clausen (2011); and Stovin (2010) as shown across the studies as the green roof substrate increases the retention rate also increases. As well as reducing the volume of runoff from the roof areas the green roofs were also extremely effective in attenuating flows. During smaller storms the majority of the green roofs decrease the peaks of runoff. However due to this attenuation effect, during larger ongoing storms the peaks of runoff increase these observations verify the conclusions made by Lee *et al.* (2015) that increasing the antecedent dry days improves the water retention capacity.

Acknowledgements

This study would not have been possible without the technical support of the urban drainage modelling team within the Plymouth Arcadis office. I am particularly indebted to Simon Ainley modeller and leader of the urban drainage modelling team who gave me this incredible opportunity to work alongside the modelling team and provide technical support, and Abhijit Ghatge, senior modeller who helped me continuously throughout. I am grateful to my dissertation supervisor, Martin Borthwick who has offered me professional and personal guidance and whom responded to my questions and queries so promptly throughout my dissertation. Finally, I would like to thank the constant support from my family and friends who continually proof read my report and supported me through the ups and downs of my research.

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