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Reducing urban pollution from coastal settlements with green roofs

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Abstract

It was identified that traditional infrastructural methods for solving coastal pollution were becoming too costly and insufficient in combatting the effects of climate change. This report investigates the sustainable drainage method of green roofing as a possible approach to reducing coastal pollution. A generic computational hydraulic model was created, using Plymouth as a design template, to represent 3 different scenarios in which a combined sewage system would require overflow relief. Storm simulations were run through the scenarios to determine a set of baseline sewage spilling results. The simulations were rerun after allowances for green roofs, with substrates of 50mm and 200mm, were added into the model and these results were compared with those of the baseline tests. The 50mm substrate performed more cost-effectively per m^2 since storms did not fully saturate this thickness before subsiding and it was far cheaper to implement. The results of the storm simulations showed that retrofitting green roofs in Plymouth's city centre would reduce coastal sewage spilling counts by approximately 50% and volumes by approximately 66%. After conducting a simple cost-benefit analysis it was estimated to cost between £50 - £100 per m^2 to implement green roofing which equated to a total cost between £5.2 - £10.4 million to cover all suitable roof space. This investment was analysed and it was estimated that the scheme would begin returning upon the capital investment within 5-10 years of completion, depending upon collaborative investment and actual impact upon sewage network performance. Following the success of this research project and commercial interest, a collaborative research project has now been considered between Plymouth University, Plymouth City Council and ARCADIS. Further research on the subject, building from this report, has received funding with the possibility of future funding to cover a design proposal.

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1. Introduction

The coastline of the United Kingdom is a rapidly changing and diverse environment, pushed to its limits by the development of tourism, trade and unprecedented population growth. Climate change and the growing demands of the 21st century outweigh the capacity of the decaying Victorian infrastructure that, in many settlements, is still relied on to carry waste and storm water to treatment facilities. Making sustainable improvements to the urban environment is critical for delivering lasting results for the future of the communities within ARCADIS (2016).

The original Victorian sewerage networks were gravity fed and designed to accommodate combined flows, i.e. a combination of all wastewater and rainfall from urban areas, and convey them to the closest waterbody outfall. The waste would be carried out to sea and eventually disperse into non-harmful quantities, with the harsh saline environment eliminating most hazardous materials. These sewers were created, however, for the demands of 19th century Britain with a population of just 10.5 million in 1801 (Office for National Statistics, 2005). Increased population forced increases in urban expansion and density and most new estates connected their sewers directly into the main network, leading to increased waste and rainwater volumes in the system.

During the second half of the 20th century, the decline of coastal water quality had, for both humans and aquatic life, led to increased health risks and had visible negative effects on the coastal environment. In 1953, the Public Health Laboratory Service set up a committee to study the contamination of coastal bathing beaches by sewage. The first 5 years of results were summarised by the committee and concluded that:

- The great majority of the beaches studied were subject to contamination with sewage.
- Various salmonella serotypes, notably Salm. paratyphi B, were isolated in small numbers from a high proportion of sea-water samples.
- Four cases of paratyphoid fever probably due to bathing were recorded (Public Health Laboratory Service, 1959).

Further studies were undertaken in the UK, and elsewhere around the world, regarding similar issues. In 1974, the matter of microbial standards for bathing beaches and sewage treatment before discharge to the sea was discussed at an international symposium of 24 countries, the World Health Organisation (WHO) and the World Bank and deemed “unresolved” (International DSSO Symposium, 1974). The European Economic Community’s (EEC) response to this was the Bathing Water Directive (Council Directive 76/160/EEC). This directive was adopted as law and subsequently revised by the European Union (EU) 30 years later (Council Directive 2006/7/EC). It stated that to protect the environment and public health and prevent further deterioration of water quality, a reduction of the pollution of bathing waters was required. Likewise, the EEC passed similar laws regarding water quality with the Shellfish Waters Directive (Council Directive 79/923/EEC); this too was subsequently revised by the EU (Council Directive 2006/113/EC). It stressed the necessity to “safeguard certain shellfish populations from various harmful consequences, resulting from the discharge of pollutant substances into the sea.”

This presented a particularly pressing issue to the UK, being an island nation with its highest population densities adjacent to major rivers and the coast. The UK also suffers from a relatively high ratio of coastline to land mass and one of the longest coastlines of any nation, ranking 12th in the world and 2nd in Europe (World Resources Institute, 2000). Coastline measurements are highly debatable and change depending upon how they are measured and what sea level datum is used. The coastline of the UK at Mean High Water, including islands, is 31,368 kilometres (British Cartographic Society, 2008) with the main island of Great Britain measuring 17,820 kilometres (Ordnance Survey, 2016a).

1.1. Combined sewer overflows

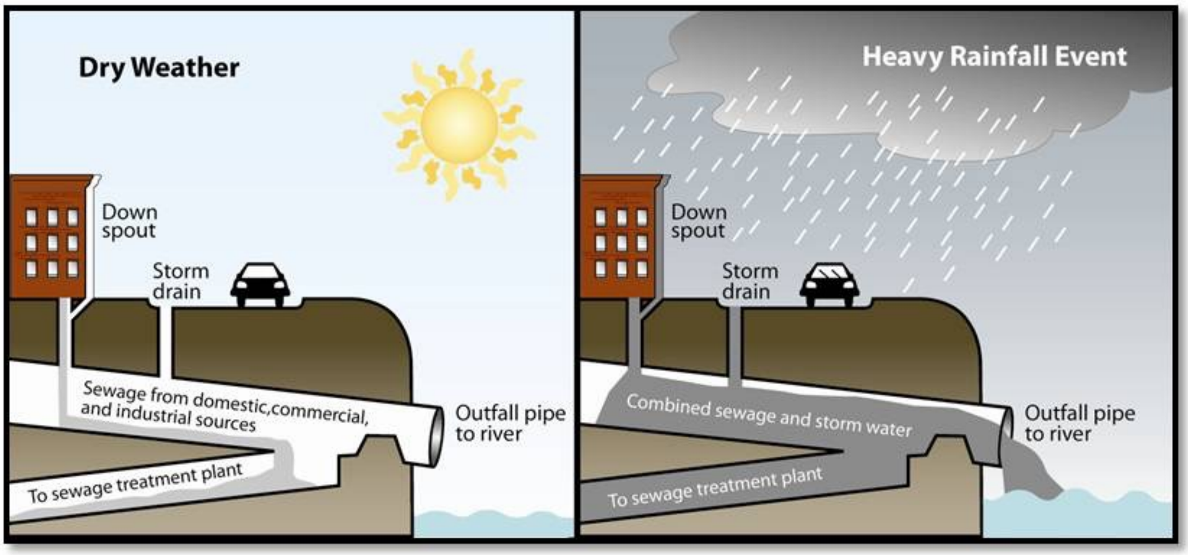

Figure 1. Images explaining the function of a CSO (Akron Waterways Renewed, 2017).

A Combined Sewer Overflow (CSO) is an hydraulic control in sewers which alleviates urban flooding. Physically, a CSO can be constructed in a multitude of different ways but it is essentially an exit point within a drainage system which allows flow to pass through it at a critical level to avoid pipes backing up from hydraulic overload. During dry periods, sewage flows through the system normally to the treatment works. However, during heavy rainfall, the pipes are unable to accommodate the increased flow rate and flows spill out of the CSO and into the environment (Figure 1).

The 12 UK water companies estimated that they owned a total of 20,233 CSOs that discharge to rivers and sea and that, of those, approximately 1 in 4 were monitored (British Broadcasting Corporation, 2009). This figure was indicative, not only of the necessity for CSOs in our wastewater infrastructure, but also, of the necessity for change if the environment is to be respected and maintained.

Modern standards governing waste water include:

- The Water Industry Act (UK Parliament, 1991a) which allowed appointed water undertakers (companies) to set consents for industrial sewer use and charge for noncompliance. This legislation allowed them to better regulate trade effluent to make sure that the disposal of seriously harmful chemicals and substances was in amounts or concentrations that would not significantly harm the anaerobic processes in the treatment works or, in the case of spilling, the environment.

- The Water Resources Act (UK Parliament, 1991b) which focused more on the aspects of water discharge to the environment. This legislation authorised the Environment Agency (EA) to set consents for discharge to watercourses. This meant that water undertakers also faced penalties for noncompliance with regulations.
- The Urban Wastewater Treatment Directive (Council Directive 91/271/EEC) which was a pan-European directive regarding waste water collection, treatment and discharge with the intention of regulating shared water bodies so that one member country's waste did not affect another. It mandated these processes in all urban agglomerations with a population of over 2000 people.

The financial implications for industries and water companies discharging illegally to the environment provided further incentive to properly regulate sewage discharge, in particular, CSOs.

1.2. Aim and objectives

To substantiate the necessity for sustainable approaches to reducing coastal pollution through analysis of the benefits of green roofing.

1. Investigate current coastal pollution (volume and frequency of CSO spills) from sewers in a UK coastal urban catchment, by means of a hydraulic model, based on the set of Wallingford HydroSolutions (1999) FEH (Flood Estimation Handbook) design storms with return periods between 1 in 2 and 1 in 100 years.
2. Ascertain the effects on CSO spills that strategically introducing green roofs to the city centre would provide by comparatively analysing the results from simulations with the city baseline and with the addition of green roofs.
3. Investigate the economic aspects of the project by conducting a simple cost-benefit analysis, determining an approximation of the time required for the project to break even and begin saving beyond the capital expenditure (CapEx).

Ultimately, the project was designed to provide a platform of research that will aid the initiation of further study into the area by identifying areas of uncertainty and making recommendations for future research. The project was designed to be generic and applicable to all similar coastal settlements, thus aiding the proposal of the scheme's widespread application across the coast of the UK.

2. Literature review

Figure 2. Bio-retention area in Melbourne (Susdrain, 2015).

Sustainable Drainage Systems (SuDS) are soft engineering approaches to alleviating urban flooding (Figure 2). They are designed to integrate natural processes of storm water mitigation into urbanised environments such as infiltration and evapotranspiration. The planning, design, construction and maintenance of SuDS have been widely researched at many levels and scales and, subsequently, CIRIA (2015) has produced guidelines for their implementation. Furthermore, British Water (2013) has published industry standard sizing criteria for SuDS, representing current best knowledge within the UK.

During his undergraduate project, Chan (2005) even converted the roof of the City College of New York's engineering department into an extensive green roof, hoping to extrapolate the results for city-wide benefits.

Unfortunately, typical applications are restricted to small areas or individual buildings because of constraints like planning permission, time, cost and, specifically in the case of green roofing, buildability; even the aforementioned British Water (2013) sizing criteria are limited to populations of 1000 people. British Standards and Eurocodes restrict over-engineering in the construction industry. In many cases, the addition of green roofing would require the structural elements of a building to be completely redesigned because they were only built to support normal roof loading. REIFA, a supplier and fitter of green roofing, states that the primary barrier to progress is the lack of public awareness and education and that, due to installation costs, government policy is not yet encouraging enough, especially considering the overall benefits (REIFA Green Roofing Solutions, 2015). If it is a matter of capital investment, and nationwide awareness, it is possible that a positive financial scheme, akin to the 2008 solar panel feed-in scheme (UK Parliament, 2008), offering a grant or reduction in water bills for those who install green roofs, could improve the situation.

Camillo (2013) investigated resolving New York City's (NYC) CSO issues with retrofit green roofs. Due to the relative similarity of issues causing CSO spilling in NYC and the UK, her work is particularly relevant. Contrary to the previously discussed ideology, the research conducted suggests that introducing utility fees for storm water contribution, based on a percentage of the impervious area in a plot of land, could incentivise the creation of green infrastructure, particularly in densely urbanised areas where green roofs are an option. In the same way that metering water use incentivises its conservation, a nominal charge for storm water contribution into the main sewerage network would also bring about a new mind-set for developers and land owners. Despite the low average residence rate for housing in the UK, 2.35 people per residence (Office for National Statistics, 2011), and the subsequent reduced volume of water that water companies would need to treat, the UK is far behind the majority of developed countries with just 38% of customers on metered payment (Great Britain. Office of Water Services, 2011).

NYC's local sustainability journalist, Verchot (2014), analysed the issue the following year, reporting further CSO spills and proposed that the solution was to promote green roofing over some of the city's impermeable surfaces. His article concluded by stating anecdotally that natives of New York do not swim on Coney Island after rainfall due to the sewage-polluted storm water runoff, however, that might change if more focus was put into growing outdoor plants and green roofs. The same public health issues are highlighted in guidance articles by the National Health Service England (2015), warning holiday-makers to stay out of coastal waters after storms, due to water contamination.

In fact, there is a lot to be learned from the US, which is, at present, considerably further ahead of the UK in terms of sustainable water infrastructure for the future. The Environmental Protection Agency (EPA), the US equivalent of England's EA, has issued a series of technical resources detailing the process of integrating green infrastructure into the current framework for CSO control (United States. Environmental Protection Agency, 2014). These nationwide plans for future and retrofit development of SuDS are indicative of forward thinking and, following their adoption, of progression.

2.1. Current projects and drivers

In 2011, the City of London published a set of 17 case studies of green roofs implemented since 1998, with the final phase of the latest project set to be completed by 2016 (City of London Corporation, 2011). The case studies summarised various aspects of the projects including:

- Associated areas (total roof and greened roof) with relative cost.

- A description of the green roof and its type.
- The project drivers.
- Benefits and barriers (Projected/achieved depending on completion date).
- A consideration of biodiversity.

A balance of both intensive and extensive green roofing schemes was included in the case studies; the former requires more regular maintenance and a larger roof loading capacity but can cater for a wide variety of plant species, whereas the latter requires minimal maintenance and is significantly lighter by comparison but plant species options are limited (Plant Connection Incorporated, 2016).

Drivers for the projects included providing outdoor amenity areas with a view for tenants and employees and seizing the opportunity for modern development since roof replacement was already required. In most cases, however, the main drivers appeared to be based upon competition, as opposed to a genuine concern for sustainability. Green roofs were used as a status symbol, to attract potential clients, or to obtain a high ‘Building Research Establishment Environmental Assessment Method (BREEAM) rating’; the Building Research Establishment (2016) assessment method is a means of grading buildings on their environmental impact and sustainability. Nevertheless, whether a primary or secondary consequence, the same result in storm water runoff reduction will be achieved.

All cases stated positive effects on biodiversity. Whilst biodiversity was not the major consideration of the green roofs, they have contributed to the introduction of habitats for birds, bats and insects. Naturally, most wildlife would have struggled or been unable to survive in the harsh urban environment.

Further to these case studies, Canada’s Green Roofs for Healthy Cities (2016) is a corporate organisation consisting of green roofing contractors and landscape architects. Their research expands upon the immediate, and primary, benefits of green roofing and includes investigation into further beneficial factors, both public and private. These factors can contribute to project proposals by offsetting building maintenance costs, improving visual and cultural attractiveness for clients and reducing pollution.

Public benefits, positively affecting the local area and wider community include:

- Aesthetic improvement, for the otherwise bleak and barren urban landscape, with multiple amenity, recreational and business uses such as the rooftop restaurant at 1 Poultry in London (City of London Corporation, 2011). These can also contribute to public health and well-being.
- Likewise, public health and well-being can be improved through the mitigation of the urban heat island effect and improvement of air quality by reducing the ratio of urban to greened surfaces, thus increasing the natural processing greenhouse gases.
- Waste diversion both from the use of recycled materials and by prolonging service life of roof elements.
- Local job creation and educational opportunities where stages from design to manufacture, implementation and maintenance can be studied as well as the biological and environmental aspects.

- Further to the biodiversity benefits identified within the City of London Corporation (2011) case studies, green roofing can provide a habitable mid-point for migratory species that would, without suitable living conditions, be separated by large urban areas.

Private benefits, positively affecting the owners and users of the building include:

- Improved energy efficiency and fire retardation following the increased insulation provided by the stratum and retention of water.
- The additional insulation also reduces electromagnetic radiation by up to 99.4% (K.A. Hossmann, 2003) and noise pollution by 50 decibels (S.W. Peck, 1999).
- The increased value of the building, its relative ease to sell or let and the employee satisfaction all financially benefit the owner of the building (Wilson, 2005). The work also established that employees are more likely to want to work in a building with a green roof and stay employed with the respective company.

2.2. Cost and efficiency

The City of London Corporation (2011) reported that build costs ranged between £50 - £600 per m^2 of greened area and showed an average cost of £173 per m^2. Generally, costs correlated positively with the level of the building being greened although this is not conclusive since the wide variation of costs can be attributed to many other factors such as materials, purpose and location. It is important to note that these case studies represent single building projects in the centre of London and that larger projects, away from the capital, such as those proposed in this project, would benefit from economies of scale and price in logistics and materials needed.

The Renewable Energy Hub UK (2016) gives an approximation of £100 per m^2 for extensive and £150 per m^2 for intensive green roofs with the latter reducing immediate runoff by up to 90%. It stresses that prices vary widely with factors such as professional employment i.e. landscape gardeners, structural engineers and architects, accessibility, structural reinforcement and the desired quality.

In similar, relevant, studies into green roofing, average annual retention rates of 66% (Fassman, et al., 2010) and 85% (Palla, et al., 2011) were recorded with average peak storm flow attenuation rates of 93% and 97% respectively. Fassman, et al. (2010) analysed results of 50-70mm extensive substrates, whereas Palla, et al. (2011) investigated an intensive substrate of 200mm. These values provided a basis for green roof retention and attenuation rates in different scenarios in the model.

2.3. Current legislation

Recent UK legislation regarding flooding (Scottish Parliament, 2009; UK Parliament, 2010) promotes the use of sustainable drainage to improve water quality, the environment and public health and safety.

In 2011, the responsibility for existing private gravity sewers, which connect into public systems in England and Wales, was transferred from the landowners to the water companies, increasing their remit nearly twofold. Water UK (2012) produced Sewers for Adoption, the current industry standard for new developments, which includes, but is not limited to, guidance on controlling pollution, separating foul and storm flows, suitable materials and mechanical and electrical specifications.

2.4. The future for coastal pollution and the urban environment

Professor Aurigi (2016), of Plymouth University, comments that Plymouth and other cities cannot sustain themselves on tourism alone; if cities intend to compete in the modern world, they need to “find an identity”, utilise rooftops for farming and power generation and escape the post-Blitz Modernist flat-roof architectural style. Aurigi (2016) speculated that the economic future for Plymouth would thrive with urban development in the city centre, particularly inimitable development and utilisation of unused space. This alluded to the fact that exploiting unused flat-roof space for green roofing is not only in the interest of British cities today but also for years to come. Green roofing would provide amenity, functionality and architectural uniqueness to an otherwise bland and underdeveloped city skyline whilst increasing storm resilience and, therefore, combating coastal pollution.

The future of sustainable approaches to solving coastal pollution can be observed, in part, in the city of Toronto, Canada which is situated on the coast of Lake Ontario. The city passed an innovative bylaw which required green roofs to be constructed on all new buildings of 2000m^2 or greater gross floor area (City of Toronto, by-law No 583-2009) in keeping with the self-declared ‘Toronto Green Standard’. Toronto aimed to reduce its “infrastructural demands and environmental impacts” for the future and promote itself as a pioneer of sustainability. As a forerunner of green development, should its efforts prove successful, Toronto could potentially pave the way for future legislation in the UK and other countries.

3. Methodology

NB: The model created within this project could not be defined by the Wastewater Planning Users Group (WaPUG) classification system (Wastewater Planning Users Group, 2002) since it did not fully conform to it. Instead, the WaPUG code of practice was referred to for industry guidance on key parameters. The nonconformity was brought about primarily due to the theoretical nature of the research. The WaPUG defines hydraulic models into categories based upon the resolution of the model, e.g. the size of sub-catchments and population within. No consideration was made for specific sub-catchment shapes or sizes (they were selected based upon property boundaries and topography) or population, due to their negligible effects beyond the fact that houses are present; therefore, a model Type could not be defined.

3.1. Process

Background mapping (Ordnance Survey, 2016b) was collected and simplified by fragmenting it into individual layers and removing unnecessary elements. The building polygons were augmented to include their areas. UK Government (2014) LiDAR data was imported into the model and colour scaled to provide a reasonably accurate estimate of the sewerage layout due to gravity.

The network models were created to fit their given scenarios as described in section 3.5. They consisted of a set of manholes connected by conduits, leading to overflows (simulating discharge into pump stations or treatment works). The networks served sets of sub-catchments whose boundaries were defined mainly through observation of current property and road boundaries, combined with an understanding of the topography.

The base scenarios were calibrated as described in section 3.7 and green roofed sub-scenarios were created from these by changing their characteristics to model the change in flow dynamics brought about by the addition of SuDS as described in section 3.4.3.

The design storms described in section 3.6 were simulated through the scenario networks and the results of spilling volume and frequency at CSOs recorded for comparative analysis.

A sensitivity analysis, explained in sections 3.8 and 4.4, was conducted to determine the dominant parameters in the model.

3.2. Study site selection

Figure 3. Location of Plymouth with respect to the UK (Google Maps, 2017a).

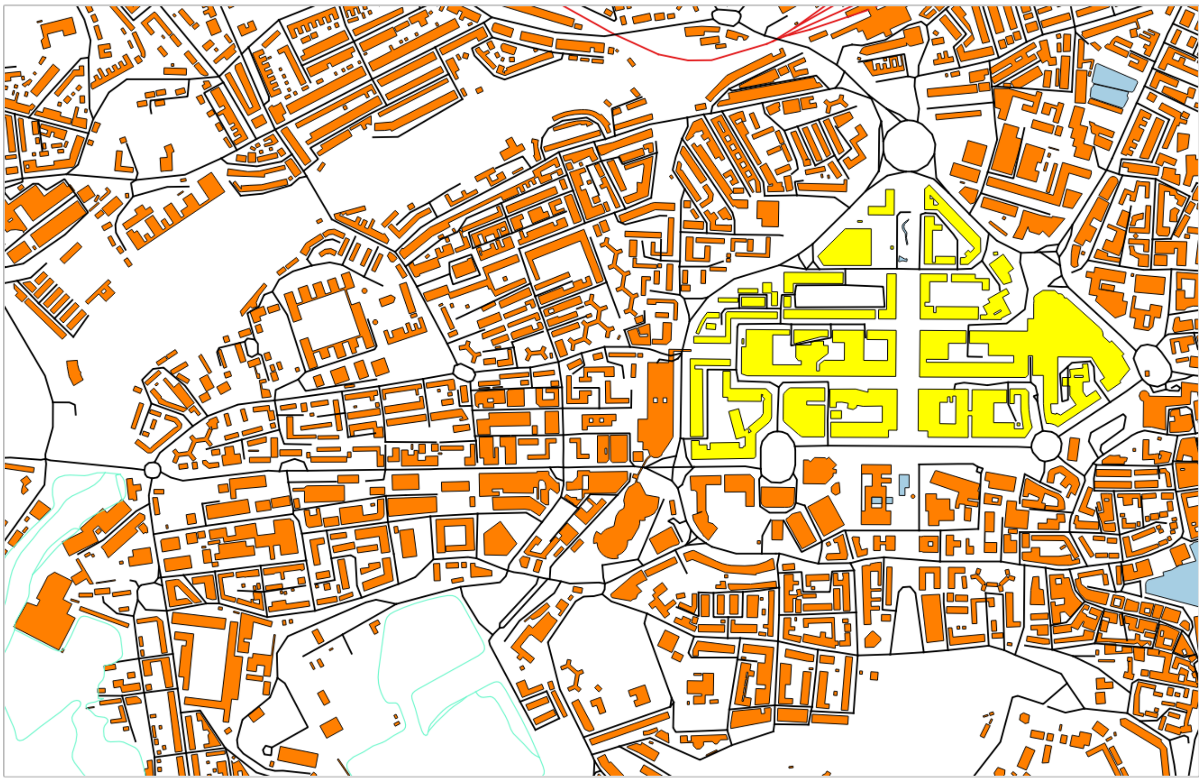

Figure 4. Mapping - Plymouth city centre shape and point data.

Plymouth (Figure 3), represented in plan in Figure 4, was selected as the study site for the project for the following reasons:

- Shape data for areas of buildings and roads and point data for topography was freely accessible, comprehensive and up to date.
- The catchment was known in detail by local industry so advice was readily available on subjects such as historical background, hydrology and current network performance.
- The locality meant that first-account observations of the integrity and composition of roofs could be made to support the satellite photography and inform judgements made for model parameters.
- Its age and history of growth in population and economy have led to a retrofit underperforming Victorian drainage network.
- Its size and strategic importance during WWII made it, and a great many other coastal settlements, prime targets for bombers; as such, it was flattened during the Blitz and later rebuilt with the Modernist architectural style that included flat roofs.
- Most importantly, Plymouth is synonymous with the quintessential British coastal settlement. Its generic physical and social geography make it a good base choice of coastal settlement as it shares features with most others.

3.3. Software used

QGIS (Quantum Geographic Information System) is an open source platform for the visualisation and manipulation of geospatial vector and raster files (Dodsworth, 2008). This software package (QGIS Development Team, 2016) was used to edit and interrogate the background mapping shapefile data. This was largely attributable to the free access and relative simplicity of use. Its open-source community-contribution nature meant that online user support was readily available for all processes and, as such, time taken learning to manipulate data within the software package was significantly reduced.

InfoWorks Integrated Catchment Modelling (ICM) is a platform for simulating integrated hydrodynamic interactions between natural and manmade environments in 1D and 2D (Innovyze, 2017). This software package (Innovyze, 2016) was used to create the model and simulate and analyse the effects of storms. ICM is currently widely regarded as the industry standard and Arcadis freely offered the use of their licences and processing network for the project. Furthermore, technical advice was available from industry experts in the use of ICM and how its calculations were derived.

3.4. Analysis of parameters - assumptions and limitations

3.4.1. Mapping and sub-catchments

Upon interrogation of the layers, it was calculated that the average roof coverage in the city centre was 43% whereas the adjacent estate had 31% coverage (Tables 1 and 2). Further to this, by studying aerial mapping and visiting the areas in question, it was assumed that the remaining area in the city centre (57%) was entirely paved whilst the adjacent estates had an approximate equivalent share of paved to permeable surfaces (34.5%:34.5%). The same investigation also supported the simplification that, for modelling purposes, the entire roofed area of the city centre may be assumed flat and suitable for green roofing.

3.4.2. Sewerage network

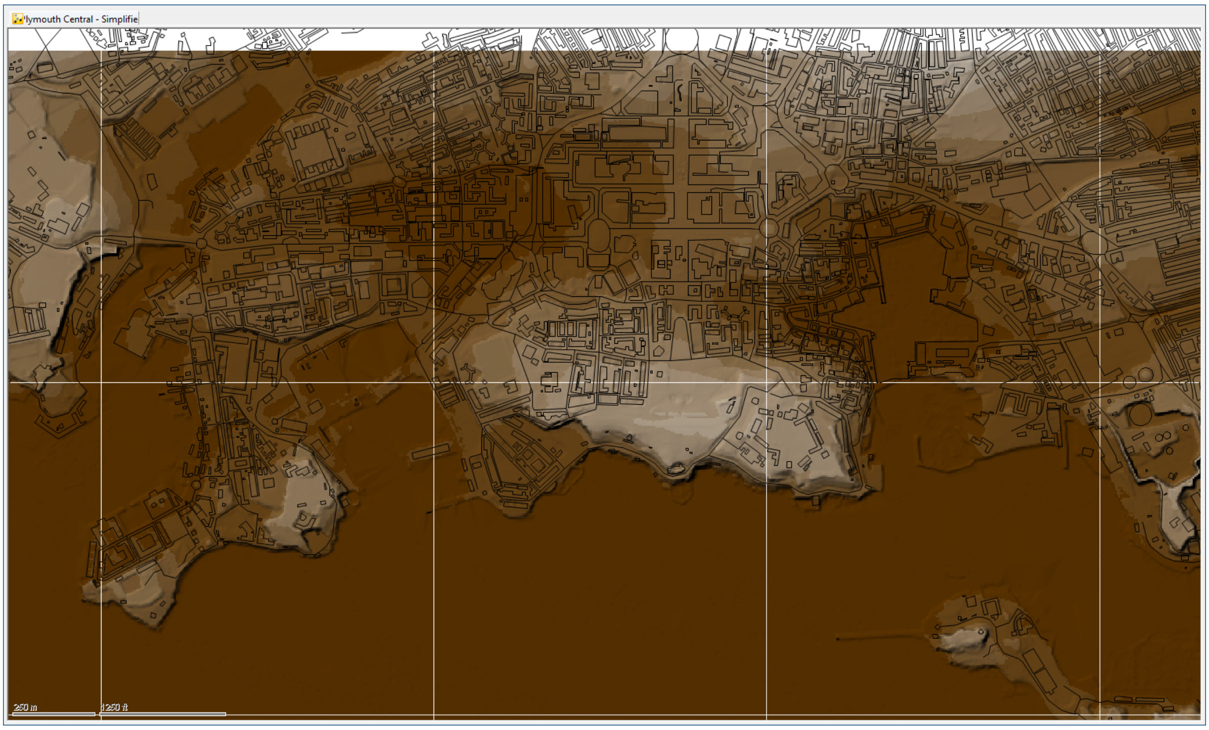

Figure 5. Thematic LiDAR – Topography of Plymouth Sound, city centre and adjacent estates.

The initial network layout was created under the assumption that the system would gravitate from higher points in the topography to lower points i.e. from light to dark areas in Figure 5. This simplification does not account for flows from pumped rising mains.

Conduits have been designed in accordance with standard manufacturing diameters, i.e. multiples of 150mm.

Given the age and history of Plymouth and other similar coastal settlements, it was assumed that the sewage infrastructure within, and adjacent to, the city centre was entirely combined and, for modelling purposes, no consideration has been made for separated sewers beyond the fact that CSOs in cities could also represent weirs in dual manholes, simulating contamination between the two systems.

Due to their relatively negligible effect, determined by the sensitivity analysis in section 3.8, on flows in storm conditions in a network with large diameter conduits, foul flow, infiltration and head loss coefficients over manholes have been omitted from the design considerations.

Since this investigation covers generic hydraulic design issues and not operational issues (which are specific to locality), it has been assumed that pipes in the network would self-cleanse sufficiently; as such, no consideration for this has been included in the design.

Each manhole has been designed with a 2m freeboard between the ground level and the level of the highest chamber roof of an adjoined conduit. This is a conservative 0.8m more than the recommended minimum 1.2m (Water UK, 2012) to account for topographical inconsistencies.

In practice, a sewerage network would be designed to accommodate a 1 in 30 year return period storm (Water UK, 2012); beyond this, localised flooding may occur where water simply cannot enter the system fast enough due to induced throttling. For this reason, the networks designed for the three scenarios have been calibrated to this limit, despite being tested with as high as 1 in 100 year events.

3.4.3. *Green roofing*

In section 2.2, depths of 50-70mm and 200mm were identified as representative of extensive and intensive green roofing substrates, respectively. As such, the model scenarios were tested with 50mm and 200mm substrates. Agvise Laboratories (2017) give the volumetric holding capacity of loam (a topsoil containing a large amount of organic matter, typically used in gardening for its nutritional benefits and ability to retain rainwater) as 85.1%. Additionally, it was assumed that an average of 75% of roof areas could be viably greened based upon satellite imagery and observations made during the site investigation. This accounts for obstructions such as outer roof walls, ventilation ducts and maintenance access.

To apply these factors to the model, a storage node was implemented for each sub-catchment to mimic the characteristics of green roofing i.e. the rainwater falling on the roofs flowed into the storage node until it was full then continued into the main network, paralleling a green roof becoming fully saturated before diverting runoff into a sewer.

0.01 m^3/s was lost across the system (0.001 m^3/s per sub-catchment) to facilitate this method due to initialisation limitations within the software. This was considered negligible in comparison with the total flow rate since even just the yearly average spilling flow rates for the CSOs in Figure 8 ranged between 0.69-6.00 m^3/s on top of the full-bore flow conditions of the network.

3.5. Scenarios

Based upon prior experience in hydraulic modelling, three base scenarios were created to represent the standard conditions for which the addition of a CSO in a network may be necessary in the design. Having previously modelled and analysed many different networks, an understanding of what constitutes a steep, average or flat gradient was assumed and led to the scenario values chosen.

- Scenario 1 – A catchment with steep topography in the extremities of a network suddenly plateaus through its main trunk. Conduits have been represented, in the steep section, by a gradient of 1 in 50 and a gradient of 1 in 250 in the plateau. The CSO has been placed at the point with the greatest change in gradient, adjacent to the area under consideration for greening.
- Scenario 2 – Two large sub-catchments gravitate into the same outgoing conduit. A topography of average steepness (1 in 150) has been adopted for the entire network. The CSO has been placed at the point of intersection, notably far from the area under consideration for greening.
- Scenario 3 – A catchment with gradually flattening topography which is sensitive to flooding (for reasons such as a low tolerance to storm surges or local commercial damage). A four-stage network design was adopted to correspond with the topography (1 in 150 – 1 in 200 – 1 in 250 - Flat). Multiple CSOs were implemented to compensate for the changing gradients.

Each of the three base scenarios branched to two additional scenarios (representing the 50mm and 200mm substrate depth green roofs) for a total of nine separate scenarios.

3.6. Rainfall event generation

Rainfall events were designed using the FEH statistical method with the following input parameters:

- Antecedent Depth - An antecedent depth of 10mm was used (this is a default parameter built into ICM).
- Evapotranspiration - Evapotranspiration was defined as 2.5mm in Summer and 1mm in Winter. Innovyze (2013) states that for the UK, the following relationship (Equation 1) provides a reasonable estimation of the rate of evapotranspiration.

Where:
(1)
 represents the potential evapotranspiration rate (mm/day).
 represents the day of the year number (1-365).

Values shown in Figure 6 range between 0-3mm throughout the year. Average values were taken for the UK seasons under the assumption that the warmer months are May-September and the colder months are October-April.

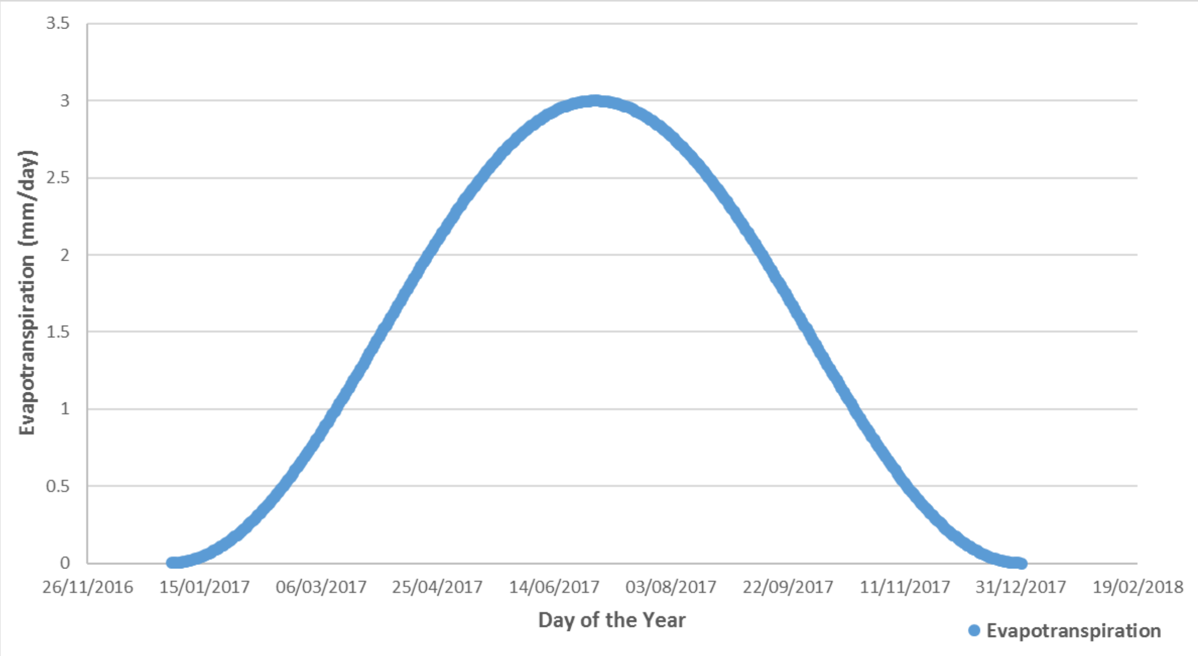

Figure 6. Rate of evapotranspiration in the UK (Appendix H – Evapotranspiration).

- NAPI (Net Antecedent Precipitation Index) - Soil type 2 was used as an average parameter for the model because Plymouth and other large settlements on the south coast range between soil types 1 & 3 (HR Wallingford, 1981a)

A conservative Standard-period Average Annual Rainfall (SAAR) value of 1000mm was adopted from the comparison of the Wallingford Procedure's (HR Wallingford, 1981b) 1941-1970 dataset value of 1000mm with the National River Flow Archive's (Centre for Ecology & Hydrology, 1993) 1961-1990 dataset value range of 950-1000mm.

These parameters provided NAPI values of 0.35 in Summer and 1.75 in Winter (Margetts, 2002).

- Rainfall profiles – As per Arcadis' industrial standard method for obtaining a 'full' set of key rainfall events, summer and winter profiles were created for storms with return periods of 1 in 100, 1 in 50, 1 in 30, 1 in 20, 1 in 10, 1 in 5 and 1 in 2 years, with durations of 30, 60, 120, 240, 480, 720 and 1440 minutes for a total of 98 simulations per scenario.
- Return period - The Peaks Over Threshold (POT) return period type was used to allow for storms which occur more frequently than once per year, i.e. 2 in 1 and 4 in 1 year events, since the original objectives included these more frequent storms. The simulations failed to produce data for these return periods and, therefore, the objectives were changed with the omission of storms occurring more frequently than once in two years.

The key empirical principle that underpins this computational modelling method is the derivation of the POT scale; it is derived from the relationship between flow and the return periods of storms. The Environment Agency (2010) suggests that for site-specific cases, it is best practice to collect rainfall data in the local area and analyse those storms once a sufficient set has been recorded. In this generic and hypothetical case, however, the return periods of storms are derived theoretically from the average intervals between storms of equal scale that occurred during the FEH rainfall records.

3.7. Model calibration

Initially, a 6-month flow survey of Plymouth from 2013, which included comprehensive rainfall and flow monitor data, was considered to calibrate the model. This approach was abandoned due to commercial sensitivity. In hindsight, this was fortuitous since such precise data would only have been relevant to the Plymouth catchment and would not have provided results generic enough to be applied elsewhere. Following this, the industry standard FEH statistical method was adopted for calibration.

Each network scenario was individually calibrated to ensure that all CSOs had just begun to spill once a 60-minute duration design storm, with a 1 in 5 year return period, was simulated. The storm duration and magnitude were representative of an average rainfall event significant enough to overload a typical combined sewer system that pre-dates modern infrastructural techniques and guidelines. This method was considered a reasonable approach to the attainment of a spilling baseline, based upon Arcadis' industrial guidance, with which to compare the effects of the addition of green roofs.

A 60-minute duration winter storm with a 1 in 30 year return period was simulated through the network to ensure there were no instances of hydraulic overload upstream of the CSOs. 60-minute duration winter storms with 1 in 3 and 1 in 5 year return periods were simulated to define lower and upper boundaries, respectively, of flooding within the system. Using these boundaries, conduit diameters and CSO spill levels were adjusted iteratively until the system behaved in the desired manner, i.e. the 1 in 5 year storm spilled over the CSO and the 1 in 3 year storm did not.

3.8. Sensitivity analysis

After the main investigation, a sensitivity analysis was conducted to understand and comment on dominant model parameters that, with a relatively small change in value, had a significant effect on the output. Results were analysed to ascertain critical locations and points in time in the scenarios and simulations respectively.

4. Results

4.1. Tables

Table 1. Summary of sub-catchment areas.

City Centre Subcatchments		Adjacent Estate Subcatchments	
Subcatchment ID	Total area (ha)	Subcatchment ID	Total area (ha)
MH01	4.847	MH12	10.383
MH02	2.592	MH13	10.924
MH03	2.396	MH14	10.654
MH05	1.844	MH15	20.87
MH06	2.812	MH16	10.281
MH07	3.673	MH17	10.243
MH08	4.582	MH18	15.154
MH09	3.539	MH19	6.784
MH10	2.973		
MH11	3.032		
Total	**32.29**	**Total**	**95.293**

Table 2. Summary of roof polygon areas compared to the total areas in Table 1

City Centre Polygons		Adjacent Estate Polygons	
Total Area (ha)	Area Ratio	Total Area (ha)	Area Ratio
13.75	0.43	29.28	0.31

Table 3. Summary of tank sizing based upon assumptions of areas suitable for greening.

Representative Tank Sizing for Green Roofing						
Green Roof	Area (ha)	Greenable Area Fully Saturated (ha)	Greenable Area Fully Saturated (m2)	Area Conversion to 1m Depth (m2)	Green Roof	Area Conversion to 1m Depth (m2)
50mm01	2.08	1.33	13301	665	200mm01	2660
50mm02	1.12	0.71	7116	356	200mm02	1423
50mm03	1.03	0.66	6574	329	200mm03	1315
50mm05	0.79	0.51	5061	253	200mm05	1012
50mm06	1.21	0.77	7716	386	200mm06	1543
50mm07	1.58	1.01	10078	504	200mm07	2016
50mm08	1.97	1.26	12574	629	200mm08	2515
50mm09	1.52	0.97	9714	486	200mm09	1943
50mm10	1.28	0.82	8157	408	200mm10	1631
50mm11	1.30	0.83	8323	416	200mm11	1665
Total	**13.88**	**8.86**	**88615**	**4431**	**Total**	**17723**

4.2. Graphs

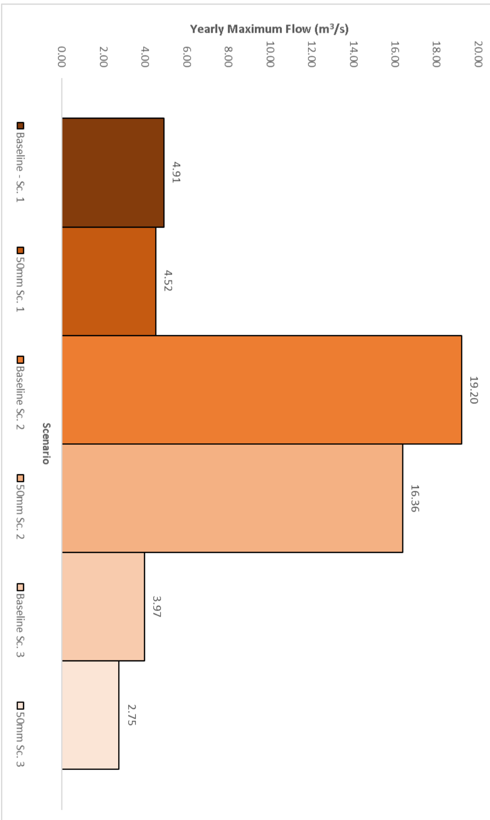

Figure 7. Comparison of yearly maximum flows between the 50mm substrate green roofing and the baseline scenarios.

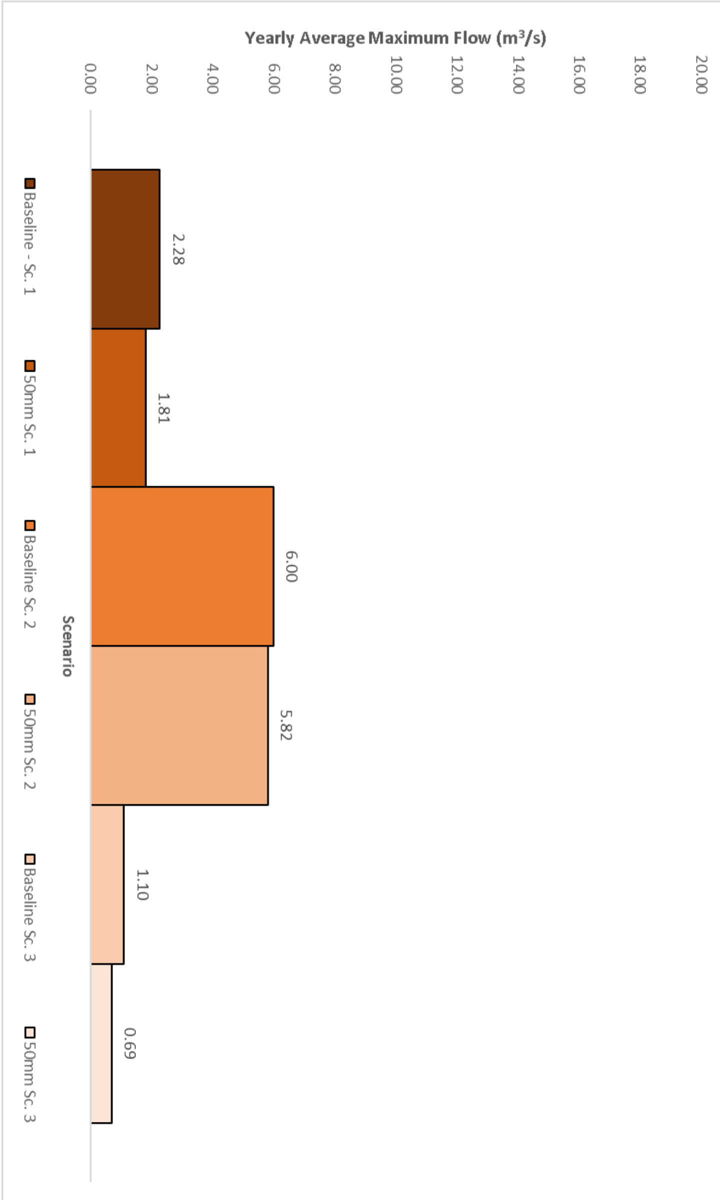

Figure 8. Comparison of yearly average maximum flows between the 50mm substrate green roofing and baseline scenarios.

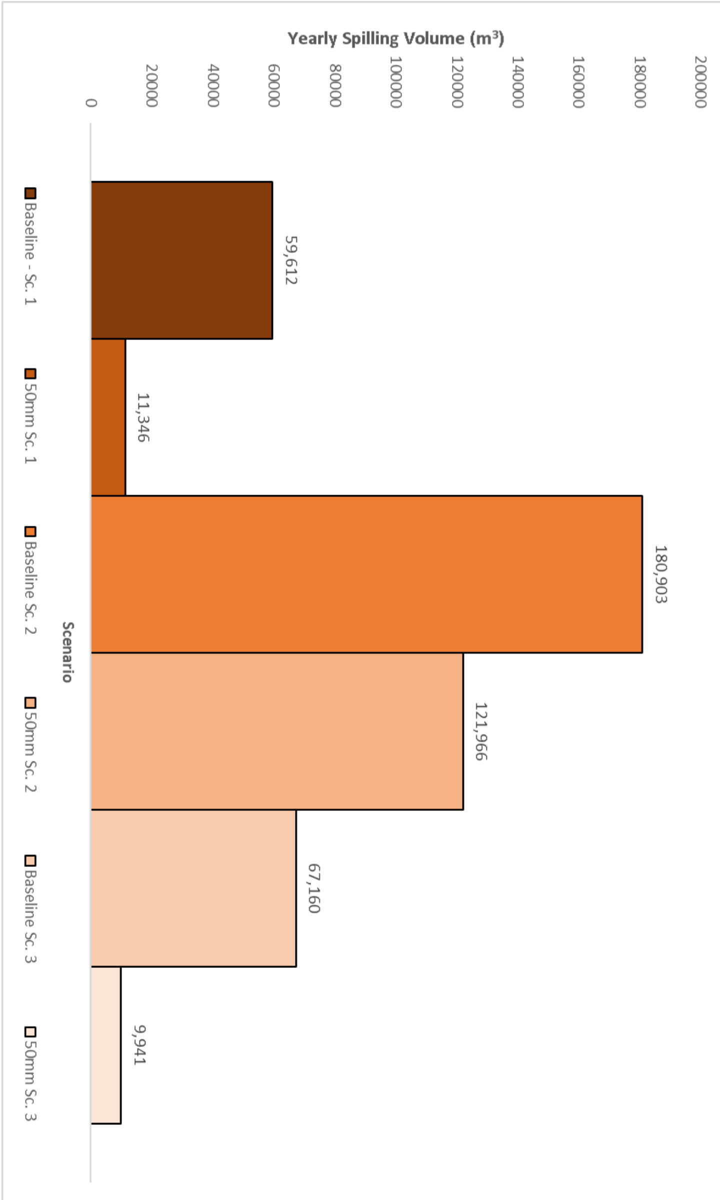

Figure 9. Comparison of yearly spilling volumes between the 50mm substrate green roofing and baseline scenarios.

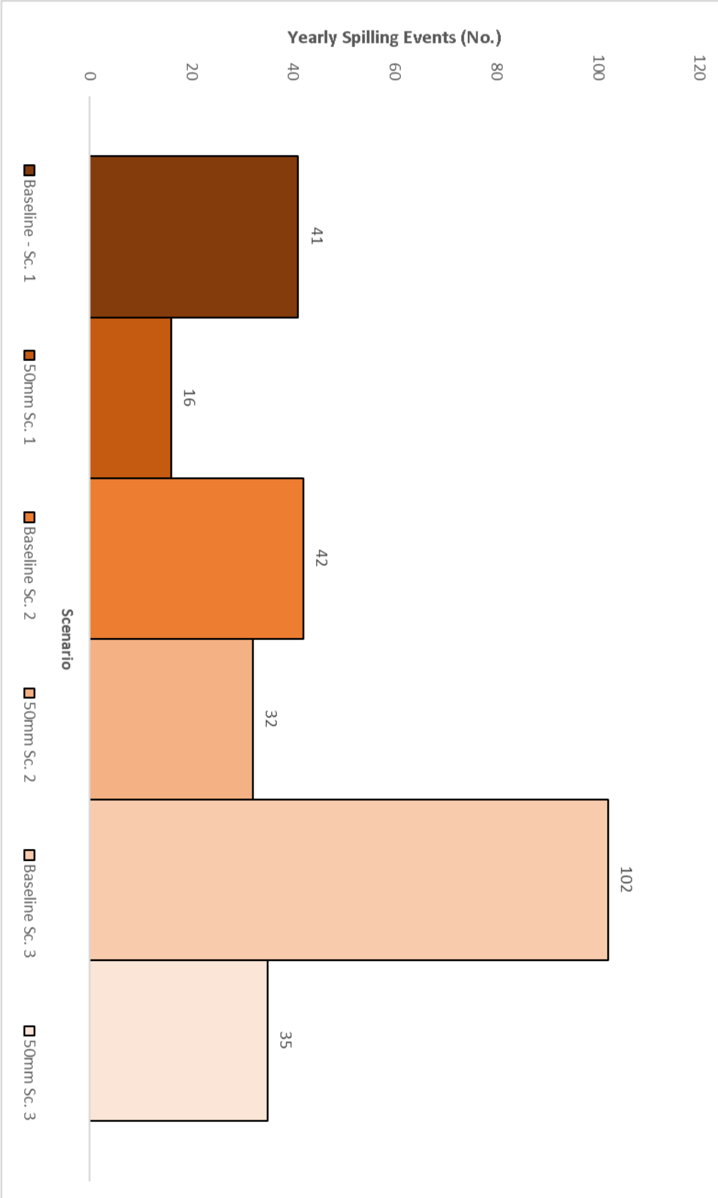

Figure 10. Comparison of yearly event counts between the 50mm substrate green roofing and baseline scenarios.

4.3. Analysis of results

Areas of sub-catchments and roofs within them were extracted from the model and summarised in Tables 1 and 2 respectively; the ratios of roof area to total area in Table 2 were then derived from these values and represented in hectares (the base unit of area in *ICM*).

Suitable areas for green roofing (Table 3) were determined by applying the reduction factors described in section 3.4.3; 0.851 to account for the capacity of water retention in the substrate and 0.75 to account for the average realistic amount of roof space that could be assigned to green roofing. The resulting areas were converted to standardise the depths to 1m to more easily understand the capacity of each storage node and compare it with others in m^3.

Across the 3 scenarios:

- Figure **7** displays an average reduction of 18% in yearly maximum spilling flow rates.
- Figure 8 displays an average reduction of 20% in average yearly maximum spilling flow rates.
- Figure 9 displays an average reduction of 66% in yearly spilling volume.
- Figure 10 displays an average reduction of 50% in yearly spilling events.

Results have been quoted as percentages because, due to the hypothetical nature of the experiment, the actual figures are meaningless. The important aspect of the results is the relative change and this can more easily be visualised and understood by potential collaborators and investors.

Using values of £50 - £100 per m^2 for green roofing, identified in section 2.2, over the area of $104130m^2$, shown in Table 3, a total cost of £5,206,522 - £10,413,044 was calculated for Plymouth's city centre.

4.4. Outcomes of the sensitivity analysis

NB: Whilst multiple parameters were tested, only those which made a significant impact on the results have been commented upon.

In the case of the topographically flatter scenarios, the volume of water was the major issue because of the slow rate at which flow was passed forward though the system. Spilling occurred during relatively frequent events and spilled for longer as the system failed to drain itself quickly. This lead to spilling event and volume results being skewed towards Winter storm events which do not achieve the levels of intensity of Summer storm events but carry more volume.

Adjusting the pipe roughness had a relatively minimal effect on the shorter and flatter pipe sections. Contrary to this, however, roughness had a more significant effect on the longer and steeper pipe sections due to Bernoulli's principle; i.e. the effects of frictional head loss accumulated linearly with distance and parabolically (with a second order power) with velocity.

Although not of immediate concern to the experiment carried out in this report, it should be stated that the result of low flow rates in combined systems can lead to a build-up of silt and debris and is of significant concern when considering operational issues. Allowing the flow rates in pipes to reach this level would have been an area of sensitivity in the consideration of the longevity of the assets.

5. Discussion

NB: It is of importance to state that the method adopted within this investigation is just one element of a range of possible solutions and that other strategies were considered, during the planning phase, but disregarded due to the limitations of time, resources, understanding and perceived rate of success; i.e. estimations of how likely it was that investors would be interested in them based upon factors of buildability, cost and impact.

5.1. 50mm - 200mm substrate comparison

Both thin (50mm) and thick (200mm) media performed within the same percentile of volumetric improvement from the baseline conditions in the model simulations and in nearly all simulations there was no difference (to the nearest m^3 of spilling volume). No change in spill count was observed between the two media in any of the simulations. Considering the increased construction costs associated with deeper substrates due to the logistics of moving and placing more material and the increased static loading acting on the building, the 200mm thickness option was disregarded and omitted from the comparative graphs shown in Figures 7, 8, 9 and 10.

The conclusion drawn from this result is that area, as a variable, has a greater effect than depth and, to achieve the optimum performance in storm mitigation, area should be maximised. It should be noted, however, that this result relates to in-catchment CSOs only (the focus of this investigation) and the 200mm substrate may be more significant for different strategic CSOs such as those located at sewage treatment works (STW) or those affected by backwater. At STW flow rates do not necessarily correlate directly to rainfall due to differing times of concentration for contributing catchments. Tunnels and large low-level trunk sewer systems are susceptible to spilling out of CSOs because, once they reach their capacity, the only flow that can be passed forward is that which is pumped; if the pump is incapable of exceeding the incoming flow rate, the pipe will fill and any further rainfall, even that of small storms, will cause spilling events at the CSO.

5.2. Acceptable water quality

The EA conduct water quality analyses in water bodies throughout the year but put emphasis on the quality of 'designated bathing waters', especially during 'bathing seasons' (May 15th - September 30th) as there are more users during this time and public health is at greater risk. It was stated that local councils must display current information, provided by the EA, on the water quality of bathing waters and include a quality rating symbol of Excellent, Good, Sufficient, Poor or Swimming prohibited or advised against to ensure the public are aware of health issues (Great Britain. Department for Environment Food & Rural Affairs, 2016a). These ratings are based on sampling data taken over 4 years.

A statistical report was released stating that, of the 413 English bathing waters, 407 met the minimum criteria of the Bathing Water Directive discussed in section 0 (an improvement of 1.4% from 2015) and, of those, 287 were considered to be 'Excellent' (Great Britain. Department for Environment Food & Rural Affairs, 2016b).

From experience, it is known that to meet the minimum criteria for bathing water quality, a maximum of three significant spills (greater than 50m^3) during a bathing season are generally allowable. An individual spilling event is considered as two spills if it exceeds 12 hours and an additional spill is counted for each subsequent 24 hours; i.e. at 36 hours it becomes 3 spills etc. Additionally, a maximum of 10 spills per year are allowable in 'shellfish waters'.

The water quality testing is based upon a minimum of 16 separate samples (Council Directive 2006/113/EC) and of those samples, none can exceed the microbial concentrations given in Figure 11. However, in the current tumultuous political climate, these standards may well be considered for revision but further comments at the time of writing this report would only be speculative.

For inland waters

	A	B	C	D	E
	Parameter	Excellent quality	Good quality	Sufficient	Reference methods of analysis
1	Intestinal enterococci (cfu/100 ml)	200 (*)	400 (*)	330 (**)	ISO 7899-1 or ISO 7899-2
2	Escherichia coli (cfu/100 ml)	500 (*)	1 000 (*)	900 (**)	ISO 9308-3 or ISO 9308-1

(*) Based upon a 95-percentile evaluation. See Annex II.
(**) Based upon a 90-percentile evaluation. See Annex II.

For coastal waters and transitional waters

	A	B	C	D	E
	Parameter	Excellent quality	Good quality	Sufficient	Reference methods of analysis
1	Intestinal enterococci (cfu/100 ml)	100 (*)	200 (*)	185 (**)	ISO 7899-1 or ISO 7899-2
2	Escherichia coli (cfu/100 ml)	250 (*)	500 (*)	500 (**)	ISO 9308-3 or ISO 9308-1

(*) Based upon a 95-percentile evaluation. See Annex II.
(**) Based upon a 90-percentile evaluation. See Annex II.

Figure 11. Water quality classification - Maximum pollutant counts (Council Directive 2006/113/EC*)*.

It should be noted that, due to the relative proportions of coastland to population, maintaining these standards is most challenging for the Southwest. This area is home to both the largest coastal remit for any of Britain's individual water companies and the lowest population; i.e. the most work with the least resources.

5.3. Cost-benefit analysis

Assuming that all buildings would sufficiently support green roofing (see section 6.2), with only minor exterior changes, and taking into consideration the relatively low heights of the majority of flat-roofed buildings in Plymouth and other coastal settlements and the economy derived from the scale of the project, it can consequently be assumed that the cost of the project would be at the lower end of the scale identified in section 2.2; i.e. green roofing would cost £50-£100 per m^2. This would equate to a total cost of approximately £5,200,000-£10,400,000.

What is more important to discuss than the CapEx, however, is the saving that would be made as a direct result of the scheme's implementation and how this affects total expenditure (TotEx). A saving will be made on operational expenses (OpEx) since a smaller volume of water will reach the sewers and, therefore, less water will require treatment. The main treatment works and ancillary assets, such as pumping stations, would require less damage remediation and general maintenance since they would not be functioning at such a high capacity during storms.

As well as OpEx savings, another major contribution to the costs of treating waste water are the fines incurred from failure to comply with regulations. From experience of working in the water industry, it is known that the Office of Water (OFWAT), the UK water regulatory body, fines £80,000 for each instance of property flooding, whether the issue is operational or hydraulic. Missing performance targets (spill counts) and serious pollution incidents can result in OFWAT fining water companies millions of pounds, and indeed have done during the process of writing this report. Specific figures and references to such events have not been included due to commercial sensitivity.

The results shown in Figure 10 show an average reduction of 50% in spill counts across the three scenarios. Figure 9 displays a volumetric spill reduction of 66% across the three scenarios. Whilst the results collected from this investigation are hypothetical, regarding the specific resulting values, the reduction of both spill counts and volumes as a percentage provides a relatively accurate approximation of the effect that green roofing would have. Certainly, a proportionate reduction in fines would result in savings of millions of pounds per year although this cannot be assumed.

Although it is most likely that the water company would take responsibility for the project, it is in the interest of those who would benefit from the scheme to invest and therefore subsidise the CapEx. Possible additional stakeholders for the project include, but are not limited to, the EA, the local council, local and national businesses, local and national charities, private investors and the public (both residents and tourists). The locality would benefit from job creation for the construction and maintenance of the project and if the rooftop gardens were accessible to the public, tourism would likely spike as people would be drawn to visit them. The influx of visitors to the city centre would bring commerce to shops and transport links as well as providing opportunities for independent businesses to start up. The amenity factors associated with greening would also likely cause property values to rise and increase the general standard of living as well as reduce the maintenance and building costs described in section 2.1. Charities and institutions that are actively *for* the environment, such as Surfers Against Sewage, Healthy Air, the EA and the Chartered Institution of Water and Environmental Management would be inclined, both politically and financially, to support schemes designed to limit and prevent pollution.

It is not possible to calculate a precise timescale for capital return based upon the information available but it can be assumed with confidence, by considering the aforementioned savings and possible subsidising parties, that the scheme would pay for itself within a decade of its inception. Given both the size and frequency of fines issued by OFWAT in recent years, it could even be argued that water companies cannot afford not to take on schemes of this nature and scale. If such fines were to continue at their current rate and enough additional investors were interested, the scheme may even reach its breakeven point within 5 years.

In recent years, efforts have been made in the infrastructure industry to change the CapEx design philosophy to a more “TotEx-centric” mindset (ARCADIS, 2014); i.e. rather than taking on projects based upon what they cost today, taking on projects based upon their estimated lifetime cost including factors such as maintenance, demolition and impact upon the environment. It is these factors which more accurately determine the cost of a project and hence, the bills that are charged to customers. Investing a higher CapEx to reduce TotEx would likely bring down customer service charges, attracting more customers. Calculating TotEx is, unfortunately, considerably more difficult than calculating CapEx since it looks further into the future and, therefore, more uncertainties are included. Green roofing, whilst expensive to invest in initially, is a perfect example of a ‘TotEx-centric’ approach to solving infrastructural issues. The associated ongoing costs are almost negligible in comparison with current solutions. The OpEx costs are low and maintenance is easy since hardy low-growing green roof plants require little attention beyond a gardener checking that they are growing and ensuring they get enough water during dry periods. This maintenance could also be adopted by the property owners in return for a reduction in utility bills. The major factor concerning TotEx, though, is the disparity in subsequent CapEx. Subterranean assets are not resilient to change and require interim CapEx when they no longer function as intended, due to damage, blockage or change in use such as increasing the impermeable area of the catchment or the flow rates which reach the section in question. In many cases, infrastructural maintenance is neglected because it is logistically difficult or dangerous or simply deemed too expensive; in these cases, when issues do arise, it is often too late to resolve the issue and the only solution is to replace the asset. Remedial action against the resultant flooding damage to the urban and natural environments is likely to be expensive and negatively impact public relations. Failure in green roofing is easily remedied since assets are accessible and cheap to replace and the ensuing effects on the catchment are insignificant.

5.4. Challenges and limitations

The topic was widely researched prior to the creation and testing of the model. Sections 1.0 and 2.0 are evidence of this but, as with any scientific paper, it was not possible or practical to read all relative published literature so as to consider the preliminary research to be exhaustive. As far as reasonably possible, a balanced and relatively extensive selection of sources was chosen and studied; naturally, however, some details of interest or importance, whether in support or opposition to the methodology and findings within this report, will have been overlooked.

Initially, the creation of the model and storm simulations proved challenging since the *ICM* software package was vast and complex and required extensive understanding of the hydraulic parameters and processes to model them. This would have proven impossible within the time frame of the project if it were not for the base of prior knowledge from experience as a hydraulic modeller, the willingness of industry experts to support the project and the compendium of guidance topics within the software. Meticulous research was required to understand the software enough to confidently describe the procedure and present the findings. This was, in part, due to a concern which arose during the early stages of the project in that limited understanding of *ICM* would lead to it becoming a ‘black box’; i.e. an explanation would be given for the input parameters but the process by which the software simulated storms and produced the results would not be fully understood and hence, their representation in the report would be weak and conclusions drawn from them would be erroneous.

The datasets for predicting rainfall (Centre for Ecology & Hydrology, 1993; HR Wallingford, 1981b) and soil type (HR Wallingford, 1981a) and the method by which FEH storm events are created are all dated with some data having been collected as far back as 1941. The validity of these methods is especially concerning considering that they are based on 70-year-old empirical research and are used for planning structures designed to accommodate weather conditions that, statistically, only occur once in 30 years; even extensive research and testing is unlikely to accurately predict events which will occur a century later. Despite this, these datasets and this method are the current industry standard and until they are superseded by future research, they are the most accurate of their kind.

The main challenges faced during the project, however, were to achieve the objectives free of charge, since the project was not funded beyond the access to the software, and only through the use of publicly available data, since the primary datasets for infrastructure and actual spill counts require licences and are commercially sensitive; hence the use of a hypothetical generic model designed using assumptions based upon educated judgement and research.

The results of the project, whilst numerically accurate, are only as accurate as the assumptions that they are based upon. The predominant limitation to the accuracy of the experiment is the assumption that a hypothetical and significantly simplified model of what is, in reality, a vastly intricate process actually represents it sufficiently to give credence to conclusions drawn from the results.

6. Conclusion

The purpose of this research, was to investigate whether or not green roofing is worth wide-scale investment. The network performance improvements observed during this project, the economic advantage that increased scale provides and the possibilities for investment and wider collaboration have led to the conclusion that **the implementation of strategic green roofing is a viable strategy for urban water management** and should be considered with equal or greater precedence than more traditional infrastructural methods. It is suggested that green roofing be considered for all future development, i.e. all new builds match retrofit designs. Consideration of SuDS in buildings during their design stage would further reduce the associated initial costs since no additional structural analysis would be required. The future for the adoption of research of this kind is still entirely dependent upon changing modern industry’s ethos and approach towards tackling pollution and prioritising the environment over profit.

Given the opportunity to redo the project, with all the knowledge gained thus far, efforts would be made to investigate additional cities and create models and simulations using real datasets from the respective water companies. This would reduce the number of assumptions required during the model build and creation of storms thus eliminating much of the accumulated uncertainty.

Given the opportunity to continue with the project from its current stage, efforts would be made to investigate the modular system described in section 6.1 and to create a physical model of said system with which to conduct first-hand research.

6.1. Modular sustainable drainage systems

Whilst the results of green roofing have shown a significant improvement to the impacts that CSO spills have on the environment, they alone are not the solution but a part of it. The next step for this research is to investigate the addition of a combination of different SuDS to create an optimised modular system which passes storm water through them all in a 'green corridor'. For example, green roof overflow could be diverted into drainage basins in roundabouts or a series of bio-retention strips alongside roads. In addition to removing the impermeable areas of roofing from densely urbanised areas, roads and paved areas could be redirected through oil filters to drain into these SuDS. These additions would utilise unused space and provide a network of SuDS working in harmony towards the shared goal of combating pollution in a highly cost- and space-effective manner. Eventually, it may even be possible to stop combined sewage spills altogether without having to dig deeper than is required to plant saplings and shrubbery.

6.2. Recommendations for further research

Many aspects of this investigation could be changed or refined in future research but the main areas identified during the process of producing this report were as follows:

- Consideration of cities different to Plymouth, i.e. running the same simulations through different map layouts. A limitation of this experiment is that, whilst generic scenarios were considered, it ultimately revolves around the same layout. In any experiment, multiple sets of relative data allow for outliers to be identified and eradicated and averages obtained; this would also improve the genericity of the results, making them more widely applicable.
- Consideration of the increased rate of evapotranspiration in greened areas and the rate of absorption during rainfall. These factors would likely vary considerably due to seasonal change, age of plants and antecedent soil conditions. Further investigation into this area may also provide a different result for the optimum depth since deeper substrates will support larger plants which will have higher rates of evapotranspiration and absorption than their smaller counterparts supported by the 50mm substrate.
- Consideration of the challenges and costs associated with periods of extreme weather such as drought or frost. Maintenance would be required to ensure that the plants did not dry out and if this was not carried out, plants would have to be replaced.
- Consideration of the effects of storms which occur more frequently than once in two years. Analysis of the cost to benefit optimisation for these 'regular' storms should be made. It is likely that stakeholders and investors would be interested in how their investments would perform on a day to day basis to understand the immediate benefits.
- Consideration of partial investment. It is also likely that investors would be interested in having a more detailed breakdown of the results, e.g. if they were unable or unwilling to invest the necessary funds for the entire project, they may still be interested in investing a lesser amount and understanding to what extent would that prevent pollution; i.e. 'For what cost could the environment be

protected from pollution from storms which occur as frequently as once in 5, 10 or 20 years?'

- Consideration of multiple infrequent storms in fast succession. The model and simulations described in this report account for storms which act exclusively of each other. Statistically it is unlikely, but still possible, that a series of rare storm events will occur sequentially, exacerbating the effects of each subsequent storm. In reality, this has been observed multiple times in recent years with events such as the flooding and storm damage in Somerset (British Broadcasting Corporation, 2014a), Cumbria (British Broadcasting Corporation, 2015) and Dawlish Warren (British Broadcasting Corporation, 2014b).
- Consideration of the cost of ensuring the structural stability of buildings. The case may be that the roofs of some buildings would not sufficiently support the addition of green roofing and, whether they do or not, full structural analysis of the buildings would have to be carried out by engineers to assess this.
- Consideration of the reduction of uncertainty brought about by collecting first-hand data and physical approach as opposed to theoretical. A part or full-scale build of a green roof to collect first-hand data would negate the necessity for the assumptions of area and performance made in section 3.4.3. This project spanned a period of 7 months but given a greatly increased time frame (several years), with which to conduct the experiment, the rainfall data collected from this could also inform decisions made in the creation of storms. It is likely, however, that multiple green roofing sites would need to be created and monitored over a large area to maintain the genericity of the project.
- Consideration of future advancements in hydraulics, hydrology and improved modern datasets. An issue with working at the limits of current knowledge is that conclusions drawn will be less valuable as new data supersedes old data and empirical methods are refined. Future research could modernise the process and results of this project.
- Consideration of the cost to benefit comparison between green roofing and foul and surface water system separation or blue roofing. Further projects could identify whether separating roofs from the system and diverting them to water bodies or retaining the water in storage trays to evaporate would be viable solutions to coastal pollution. Such projects could compare the respective TotEx and return timescales for CapEx with those identified in this report.
- Consideration of the implications of the UK leaving the EU. At the time of writing this report, article 50 had been triggered and with it, 2 years of uncertainty over current EU legislation. This may not require further research if the UK decide to keep to the current standards of wastewater management. The dismissal or revision of these standards would not render the results of this investigation obsolete but would leave them incomplete and requiring modification of parameters and redefinition of the criteria for which pollution is acceptable.

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