2019

Water butts as sustainable (urban) drainage systems (SuDS) devices

Ridout, D.

Ridout, D. (2019) 'Water butts as sustainable (urban) drainage systems (SuDS) devices', The Plymouth Student Scientist, 12(1), p. 263-304.
http://hdl.handle.net/10026.1/14689

The Plymouth Student Scientist
University of Plymouth

*The Plymouth Student Scientist, 2019, **12**, (1), 263-304*

Water butts as sustainable (urban) drainage systems (SuDS) devices

Daniel Ridout

Project Advisor: Dr John Davies, School of Engineering, University of Plymouth, Drake Circus, Plymouth, PL4 8AA

Abstract

Heightened levels of urban development and population rise, combined with increased precipitation resulting from climatic variations, have escalated runoff rates within urban areas, causing urban flooding and polluting of watercourses. Implementing effective drainage solutions to manage these effects is essential to promote sustainable economic, environmental and social development. Larger-scale SuDS implementation has seen a rise in recent years. However, according to current literature, small-scale property-specific SuDS solutions require further research before implementation is possible, to develop guidance on optimum setups and assess performance levels. This gap in literature directed the aim of this project to determine if, and how, domestic water butts can perform as SuDS devices, to provide storage and attenuation, with the aim of reducing surface runoff and urban flooding. This project utilised physical modelling to explore different outlet options and generate original data related to the outlets, and numerical modelling (Excel) to quantify the benefits achieved by using a water butt with restricted flow outlets as a SuDS device. The main conclusion is that under the storm conditions used within the model, water butts can perform as SuDS devices by providing temporary storage and reducing runoff volumes conveyed to sewer systems during a storm event. Conclusions related to water butt setups suggested that larger capacity water butts, outlets that provide significant restriction, and drawdown levels at half the capacity or below, provide better SuDS performance. Finally, the project identified that simple outlets should be the primary outlet solution to provide consistent operation and SuDS performance, whereas siphon outlets should be used where storm events consistently guarantee adequate runoff to fill the water butt above the upper bend of the siphon.

Introduction

The following section outlines the aims and objectives of this project, discussing the background, research gap and report structure.

Background

The current approach for managing surface water in urban areas is a subject of detailed discussion, the outcomes from which are essential for future development that is socially, economically and environmentally sustainable.

Managing surface water has become increasingly important due to the human-induced, negative effects that urbanisation, climate change and pollution can have on the natural hydrological cycle. Butler and Davies (2011) identified that urbanisation produces higher and steeper peaks in river flow due to increased runoff rates from impermeable surfaces, and introduces pollutants from human activity into watercourses. Recent climatic variations, according to Hamill (2011), have caused increased temperatures resulting in more water vapour in the atmosphere and hence more precipitation. In order to combat these changes, sustainable solutions for surface water management are required. Sustainable (urban) drainage systems (SuDS), which are commonly regarded as a series of management approaches, control surface water accounting for water quantity, water quality, biodiversity and amenity collectively (Susdrain, 2012a). Woods Ballard et al. (2015) believe that surface water should be managed to deliver maximum benefit to society and the environment. They continue explaining that these benefits can be achieved with SuDS, to redefine surface water as a valuable resource rather than a problem.

Research gap

Attenuation and water storage are two aspects of SuDS design that are often utilised for limiting urban flooding and pollution discharged into watercourses (Butler & Davies, 2011). Commonly, storage is achieved through large capacity underground detention tanks, however, for small-scale property specific schemes, water butts may have the potential, if retrofitted, to perform alike. Rainwater butts can often remain at full capacity if not drained through human activity e.g. gardening. In this context they provide a single function – storing rainwater for gardening – however if modified could possess the potential to perform as a SuDS device. Woods Ballard et al. (2015) identify water butts as a type of RWH system however state that in their current form, they do not guarantee storage. According to Butler & Davies (2011) for a water butt to attenuate rainfall effectively, it must allow for some overflow to the drainage system to create some capacity for subsequent rainfall events. Butler & Davies (2011) and Woods Ballard et al. (2015) both explain how robust evidence quantifying the potential of water butts performing as SuDS devices during storm events is currently limited, and suggest additional modelling and research be undertaken.

This study takes the concepts of SuDS design, attenuation and water storage, and quantifies the potential of a water butt performing as a SuDS device, identifying if significant benefit can be achieved. In completing this research, this study intends to address the gap in industry knowledge and provide evidence for how such a system could operate. With this knowledge, drainage engineers, housing developers and homeowners have the chance to incorporate or retrofit water butts into designs, to reduce urban flooding and its associated impacts.

Aims and objectives

In order to address the research gap identified above, this project has three objectives.

Objective 1*:* Manufacture a prototype 'attenuation water butt' and undertake physical modelling, to determine how such a device could release water slowly and compare the effectiveness of different setup arrangements.

Objective 2: Create and run a numerical model imitating the operation of a water butt as an attenuation SUDS device.

Objective 3: Determine the effect of varying storm parameters on a water butt and the parameters that are most influential on its performance.

Successful completion of these objectives will fulfil the aim of this project:

Determine if, and how, water butts can provide storage and attenuation, to reduce surface runoff and urban flooding, with a view that urban developers, drainage engineers and homeowners can integrate such devices to promote social, economic and environmental sustainability.

Structure

The structure of this study will commence with a review of current literature to critically analyse existing research relating to the project aim, and identify gaps in research. Subsequently, a methodology describing the two modelling approaches will be presented explaining the rationale for selection, before the data obtained from each type of modelling is presented and analysed. Finally, several conclusions will be drawn relating to the research aim, summarising with the limitations of this study and recommendations for additional research.

Literature review

Introduction

The following sections analyse current academic literature relating to sustainable drainage practices, the main focus being storage and attenuation, introducing the potential possessed by water butts in performing as SuDS devices, aiming to reduce urban runoff, flooding, and their associated impacts. Currently, major opportunities exist for recycling water, specifically through storage of water in cities for secondary uses (Head, 2009), which contributes towards sustainable development. Initial sections describe underlying natural and artificial concepts, continuing with current SuDS management approaches and limitations, closing with detailed analysis of water butts performing as SuDS devices.

Water on earth and the hydrological cycle

Water on Earth repeatedly undergoes a process of being reused, recycled and purified through the '*Hydrological Cycle'*. Commonly identified as the '*Water Cycle'* it can be described as the continuous movement of water on the Earth's surface, through the Earth's soils and geological materials, and into the atmosphere (Cech and Pennington, 2010). Woods Ballard et al. (2015) explain that it maintains a balance of water circulation through evaporation, precipitation, infiltration/groundwater recharge, and absorption and transpiration by plants.

Urban drainage

Urban drainage systems date back to around 3000 BC (Susdrain, 2012a) and are essential in urban development due to the interaction between human activity and the natural water cycle (Butler & Davies, 2011).

Stormwater

Blockley (2005) defines stormwater as the flow of water from a catchment after heavy rainfall or precipitation. Butler & Davies (2011) claim that incorrectly draining stormwater could cause inconvenience, damage, flooding and further health risks. Whilst flowing over urban surfaces, stormwater can collect pollutants which can pollute natural watercourses and, in the case of fertilisers, lead to Eutrophication. Hamill (2011) lists the potential pollutants contained within stormwater: chemical spills (oils/cleaning products), de-icing chemicals, heavy metals, emissions, corrosion and abrasion from vehicles, grit, street litter, organic matter, animal faeces, fertiliser and nutrients. Butler & Davies (2011) state that safe and efficient drainage of stormwater is particularly important to maintain public health and safety and to protect the receiving water environment.

Where precipitation falls onto a developed catchment, infiltration rates are low due to a lack of permeable surfaces. Consequently, puddles or pools form on impermeable surfaces, which according to Martin et al. (2001) cause inconvenience for pedestrians and are dangerous for road users. Martin et al. (2001) continue, explaining puddles that stagnate can become a health hazard and a breeding site for mosquitoes, as well as being unsightly and foul smelling. In addition, waterlogging near structures where infiltration rates are low may, according to Martin et al. (2001), contribute to ground heave, subsidence, dampness and damage to property.

Traditionally, drainage engineers designed systems to protect public health & prevent local flooding by removing water from source as quickly as possible (Woods Ballard et al., 2015). These systems transported wastewater or stormwater to treatment plants or nearby watercourses respectively. Combined sewers, which account for 70% of older sewers in length (Butler & Davies, 2011), carry foul sewage and surface runoff in the same pipe to a water treatment plant (Martin et al., 2001). A limitation of combined sewers occurs during heavy rainfall, when sewers can burst, through combined sewer overflows (CSO). The overflowing water, a combination of wastewater and stormwater, travels to nearby watercourses. This regularly results in contamination, which along with being unpleasant for nearby residents, results in a reduction in the number of aquatic plants and animals (Martin et al., 2001). Susdrain (2012a) state that water quality issues have become increasingly important, due to pollutants from urban areas being washed into rivers or groundwater. Continuing, Susdrain (2012a) claim, once polluted, groundwater is extremely difficult to clean up. According to Martin et al. (2001), CSO overflows were thought to be acceptable since the sewage was diluted by rainwater, reducing pollution, and the flows in receiving watercourses provided further dilution. However, Martin et al. (2001) acknowledge it is now recognised that combined sewer overflows can cause serious pollution and significant investment is being made across the UK to minimise their impact.

During the past 50 years, combined sewer installation has decreased, being replaced by separate foul and surface water systems (Stewart, 2015). Separate sewers account for around 30% of sewer systems in the UK by length (Butler & Davies, 2011), and are where wastewater is piped to the wastewater treatment works, while surface water is piped to nearby watercourses (Woods Ballard et al., 2015). The concept, according to Stewart (2015), was that stormwater could discharge directly to watercourses, meaning only wastewater had to be treated, resulting in a more sustainable system.

According to Woods Ballard et al. (2015), separate sewers reduce the risk of CSO overspills. Nevertheless, Woods Ballard et al. (2015) also claim that separate sewers still transfer pollutants present in runoff from urban surface directly to receiving waters. Butler & Davies (2011) support using separate sewers, stating CSO spills and the associated pollution are avoided. However, Butler & Davies (2011) also recognise a disadvantage that, although constructing two pipes instead of one does not cost twice as much, further costs occur due to slightly wider excavations and an additional, relatively small pipe. Butler & Davies (2011) summarise, outlining that the main limitation is that in practice, perfect separation between stormwater and wastewater is effectively impossible to achieve.

Incorrectly connected pipes, can also contaminate stormwater sewers. For example, if a developer connected wastewater pipes to a stormwater sewer through malpractice or ignorance, unintended mixing of the two types of flow would occur, eventually leading to contamination of nearby watercourses (Butler & Davies, 2011). To avoid this, many towns now utilise partially separate hybrid systems (Butler & Davies, 2011).

Urbanisation

The process of urbanisation, in terms of drainage impact, involves replacing natural permeable surfaces such as grass, marshes and forests, with artificial and impermeable surfaces such as concrete and tarmac.Urbanisation also includes human migration from rural to urban areas for economic advancement (Thorbeck and Troughton, 2016). Consequently, urban communities become densely populated causing water requirements to increase for applications such as disposal of bodily waste (Butler & Davies, 2011).

DEFRA (2008) estimate that average water use in England is approximately 150 litres per person per day, equivalent to nearly one tonne of water per week, which they claim is high compared to other countries. Butler & Davies (2011) suggest a behavioural approach to explain why usage is high. Just as it is a standard convenience in a developed country to turn on a tap to fill a basin, it is a standard convenience to pull the plug to let the water disappear. This highlights the point that water users may disregard the effects of leaving a tap running or not reusing water on the urban drainage system and therefore, do not proactively aim to reduce water usage/intake.

The addition of impermeable surfaces to the hydrological cycle, affects water distribution at each stage. Butler & Davies (2011) state that artificial surfaces increase the amount of surface runoff in relation to infiltration and therefore, increase the total volume of water reaching the river during or soon after rainfall. Analysing a typical hydrograph for a rainfall event explores this concept further. Urban areas produce hydrographs with high peak runoff levels that occur early in the storm. Butler & Davies (2011) explain that surface runoff travels quicker over hard surfaces and through sewers than it does over natural surfaces and along streams. This means that the flow will both arrive and die away faster, generating a greater peak flow. A key observation in hydrographs for rural and urban catchments is that as catchment areas becomes more rural, peak runoff levels reduce and the storm duration increases. Urban drainage is essential to reduce flood risk, protect human activity, and prevent contamination of natural watercourses, and with potentially another 2.5 billion people on earth by 2050 (Thorbeck and Troughton, 2016), it is essential that these drainage systems are sustainable.

Sustainable (Urban) Drainage Systems (SuDS)

Sustainable (Urban) drainage systems have come to the forefront of urban drainage due to high levels of urbanisation, increased population, and therefore water supply and demand, and more extreme weather events linked to climate change. It is well understood in industry that urban drainage systems are struggling to cope with current precipitation levels, resulting in a rise in flood frequency and magnitude in urban areas. Hamill (2011) supports this view, stating that rapidly piping water from ever-expanding artificial, impermeable surfaces, is unsustainable, makes flooding worse and alters the natural state of rivers and groundwater. Hamill (2011) uses the example of England in 2007 to illustrate the issue when there was widespread, disruptive surface water and sewer flooding of urban areas. The event Hamill refers to is the 2007 summer floods. According to the Met Office (2011), torrential downpours in May, June and July 2007 left large swathes of the country under water as rainfall was followed by widespread flooding.

Hamill (2011) explains that sustainable drainage aims to avoid problems with flooding and pollution by controlling the quantity and quality of surface runoff at source, using 'soft' engineered systems that copy nature. Hamill (2011) continues explaining that SuDS encourage natural processes within the water cycle including interception, infiltration, evapotranspiration and storage at source. In principle, SuDS aim to avoid or limit impacts of extreme weather events like the floods in 2007. The Flood and Water Management Act (2010) is an act to make provision about water, including provision about the management of risks in connection with flooding and coastal erosion. The act describes sustainable drainage as managing precipitation with five main aims:

(a) Reducing damage from flooding

(b) Improving water quality

(c) Protecting and improving the environment

(d) Protecting health and safety

(e) Ensuring the stability and durability of drainage systems.

Woods Ballard et al. (2015) outline the philosophy of sustainable drainage systems as maximising the benefits and minimising the negative impacts of surface water runoff from developed areas. Woods Ballard et al. (2015) describe the positive impacts of surface water labelling it as a valuable resource, which should be reflected in the way it is managed and used in the built environment. Currently, existing drainage systems waste significant quantities of water. Woods Ballard et al. (2015) estimate that almost 25% of all water supplied is still lost through leakage. Avoiding this would provide significant savings in water supply and energy, creating a more sustainable system. In urban areas, water can provide more than just drainage benefits. According to Woods Ballard et al. (2015), it can add and enhance biodiversity, beauty, tranquillity and the natural aesthetics of buildings, places and landscapes.

Progression of the holistic approach

As stated up to now, there are many applications and aims for SuDS, however they all feed into one main design approach outlined by Woods Ballard et al. (2015). In traditional drainage design, only three categories existed within a non-holistic approach. Water quantity gained primary consideration, conveying runoff away from cities and towns as quickly as possible, managing risks from flooding and poor sanitation (Susdrain, 2012b). Categories such as water quality and amenity received very little consideration.

The first SuDS systems aimed for a more holistic approach where surface water drainage systems provided combined water quality control, water quantity control and amenity value (Martin et al., 2001). All categories interconnected and had equal consideration with the ideal solution fulfilling all three. Currently, the approach for SuDS design has moved towards a four-category system. Known as the 'four pillars of SuDS design', the holistic approach includes, water quantity, water quality, amenity, and biodiversity, where all categories have equal consideration. This latest holistic approach to SuDS design moves from the philosophy of conveying runoff as quickly as possible from urban areas to a philosophy where surface water is a valuable resource and is managed for maximum benefit (Susdrain, 2012b).

SuDS for storage and attenuation

According to Butler & Davies (2011), storage is an integral element in SuDS, and combined with attenuation the two elements manage runoff in developed sites and contribute to the prevention of urban flooding. In practice, the two processes can combine as attenuation storage, which relates to the volume in which runoff is stored when the inflow to the storage is greater that the controlled outflow (Woods Ballard et al., 2015). The Environment Agency (2013) state that the aim of 'Attenuation Storage' is to limit runoff rates into the receiving water to similar rates that occurred before the site was developed. They go on to say 'attenuation storage' can occur at one or several different locations using a variety of SuDS or other storage techniques. Limiting the rate of runoff helps prevent sudden surges of water in sewers and nearby watercourses. Without attenuation storage, heavy rainfall events could cause urban flooding, heavy scour of rivers, and environmental damage.

The 'SuDS and other storage techniques' introduced by the Environment Agency (2013) above are defined by Woods Ballard et al. (2015) as components that control the flows and, where possible, volumes of runoff being discharged from a site, by storing water and releasing it slowly. These devices may not solely carry out storage or attenuation, and Woods Ballard et al. (2015) expand on this, stating these systems may also provide further treatment of the runoff, identifying ponds, wetlands and detention basins as such systems. In some circumstances, whilst runoff is being stored, it may progress through the water cycle via different stages. For example, Woods Ballard et al. (2015) estimate that, for permeable paving, up to 30% of the water stored under the paved surface can be evaporated.

Attenuation hydrograph

Attenuation can be illustrated graphically using hydrographs based on rainfall events for 'pre-development', 'post-development' and 'post-development with attenuation techniques'.

A post-development, hydrograph highlights the issues with current urban drainage: high peak runoff rates occurring early in the storm. A pre-development hygrograph demonstrates a much lower peak runoff rate, and a longer duration to reach the peak, due to lower runoff rates and greater infiltration. A post-development with attenuation storage graph, demonstrates a combination of the previous two. The initial rate of runoff is high due to impermeable surfaces in urban areas. However, once the maximum runoff rate set by the attenuation device is reached, the hydrograph peaks. Runoff continues at the same rate due to the restrictions on discharge rate applied by the attenuation device (e.g. vortex flow control). This illustrates the attenuation storage tanks filling as Q_{in} is greater than Q_{out}. Once the rainfall event has ended, and the Q_{out} exceeds Q_{in}, the tank drains. The reduced peak runoff rate provides benefit as watercourses and sewers receive a constant, manageable discharge. This also limits flood risk in the immediate watercourses.

Water butts and rainwater harvesting

Digman et al. (2012) define rainwater butts as small-scale water storage devices that collect rainwater from the roof via the drainpipe. Direct harvesting at or near source for garden watering has been common practice for many years (Woods Ballard et al., 2015). During this time, the use of water butts for direct harvesting has been limited to domestic watering during dry periods when there is garden water in the container (Woods Ballard et al., 2015). However, their potential as SuDS devices is a relatively new concept that requires further research. Woods Ballard et al. (2015) emphasise this need, stating water butts do not guarantee that storage will always be available, unless the system is designed so that any water stored above a set threshold drains slowly to the downstream drainage system or to a soakaway. Butler & Davies (2011) support this view stating that for a water butt to be effective in providing attenuation for stormwater management, it must allow for some overflow to the drainage system so there is some capacity for the next rainfall. Woods Ballard et al. (2015) continue, highlighting the lack of robust evidence regarding the potential effectiveness of such components during significant events and the lack of guidance on the size of orifice and storage volume required to ensure suitable performance levels. Woods Ballard et al. (2015) summarise stating that modelling is required.

Water quality – roof runoff and storage

Andoh and Declerk (1999) explain that urban runoff is typically highly polluted with pathogenic & organic substances that pose public health threats during flood events. However, urban runoff can pass over many different surfaces that determine their levels of pollution. For example, pollution in residential roof runoff is significantly less than runoff from roads, with the former having a pollution hazard level of ‘very low’ (Woods Ballard et al., 2015). Consequently, there is no objection to infiltration of roof runoff (Butler & Davies 2011). Martin et al. (2001) claim that additional contamination is preventable by collecting water as near to the source as possible. Water butts fill that role well, extracting water directly from the downpipe.

As described above, roof runoff stored in containers is generally of low or no pollution (Helmreich & Horn, 2009). However, it is not immune from further pollution/health risks relating to mosquito populations. Townroe and Callaghan (2014) explain that water butts within the UK are becoming increasingly common in residential gardens because of climate change and weather patterns that increase the pressure on water resources. Townroe and Callaghan (2014) go further, explaining that water butts and their contents provide a habitat and a food resource for mosquito larvae; hence, expansion of the mosquito population is possible potentially leading to increases in mosquito-human contact. Townroe and Callaghan (2014) quantify that mosquito densities are higher in urban containers as opposed to rural ones, with densities of 100±21.3 and 77±15.1 mosquitoes per container respectively. Mosquitoes can carry high-risk diseases such as malaria; however, in the UK they currently play no part in the transmission of any diseases (Woods Ballard et al., 2015). Townroe and Callaghan (2014) summarise, predicting that the combination of increased urban domestic water storage and climate change will alter the mosquito population dynamics in the UK. This could have a negative effect on amenity value and aesthetics.

Public acceptance of water butts and rainwater harvesting

Drainage systems such as sewer networks are usually owned by private organisations as revenue earning assets that include maintenance and operation as additional responsibility (Butler & Davies, 2011). Butler & Davies (2011) highlight that the situation is not as clear for SuDS schemes, as many are considered as landscape features, which would normally fall under the responsibility of local authorities. Bray (2001) highlights this issue of 'SuDS ownership' as a major barrier to SuDS use in the UK, and overcoming it would benefit widespread SuDS application. Susdrain (2012c) argue this point stating it should not be seen as a barrier to SuDS delivery, and should instead be seen as an opportunity to ensure SuDS continue to deliver their benefits.

Water Butts and rainwater harvesting devices pose a different challenge, as the maintenance responsibility lies with the property owner (Woods Ballard et al., 2015). Susdrain (2012c) support this, explaining that SuDS components within private property are the responsibility of the landowner or property manager. Therefore, for water butts to function sustainably as individual SuDS devices, maintenance from the property owner must be undertaken. Acceptance of such a device is also required and may be achieved by the property owner receiving amenity benefit. The four pillars of SuDS design outlined by Woods Ballard et al. (2015) include water quantity, water quality, amenity and biodiversity. For water butts, and SuDS in general, Butler & Davies (2011) believe that to provide an amenity benefit, the benefit must be perceived as such by the public, or SuDS owner. Amenity benefits could be financial, as using less water can provide a benefit to the consumer with lower bills (Susdrain, 2012d), or aesthetic via landscaping, which water butts have helped to maintain.

The effectiveness of using water butts for attenuation may depend on the involvement of property owners. The more properties that engage and install water butts, the greater reduction of storm runoff rates. The potential for this benefit has been widely considered by professionals in industry. Woods Ballard et al. (2015), Hamill (2011), Susdrain (2012d), Andoh & Declerk (1999) and Butler & Davies (2011) all outline the potential possessed by attenuation water butts, and Woods-Ballard et al. (2007) summarise, stating that if designed appropriately, water butts can be used to reduce rates and volumes of runoff for small, frequent events. However, it seems from current literature that the acceptance and participation in such a property-owner-managed system may determine the level of success.

Climate change

Blockley (2005) defines climate change, as the long-term fluctuations in temperature, precipitation and all other aspects of the earth's climate. In recent times, the earth's climate has shown significant change, with Hamill (2011) claiming that the earth has warmed by 0.74ºC over a 100-year period and by 0.4ºC since the 1970s.

These temperature increases have consequences on precipitation levels and therefore flood risk. According to Hamill (2011), rising temperatures result in more water vapour in the atmosphere, hence more precipitation. Butler & Davies (2011) quantify this claiming that the temperature rises will cause a 10% increase in annual precipitation levels by the end of the century. However, Murphy et al. (2009) argue that annual precipitation amounts will see little change, explaining that precipitation distribution will see fluctuation with more precipitation falling in the winter resulting in drier summers. Drier summers may cause more frequent water shortages (Woods Ballard et al., 2015), reduction in soil moisture content of 40% or more over much of England, and more intense and more frequent summer storm events (Butler & Davies, 2011).

According to Butler & Davies (2011), heavy winter rainfall will become more frequent, with intensities currently experienced once every 2 years becoming 5-20% heavier by the 2080s. Wetter winters could mean that globally the likelihood of urban flooding increases (Hamill, 2011), potential for sewer flooding and associated CSO spills increases (Butler & Davies, 2011), and pollution from sewer/CSO floods increases. Due to changes to the existing climate, the challenge of managing surface water effectively within urban environments is becoming more intense (Woods Ballard et al., 2015). In the summer, as water becomes scarcer, it is likely to increase in value as a resource (Woods Ballard et al., 2015). Head (2009) predicts that by 2025, two thirds of the earth's population may encounter water stress. Changes to water management methods may therefore be obligatory including increased storage and recycling of runoff in urban areas. Head (2009) supports this, explaining there are major opportunities for using recycled water.

Increased precipitation in the winter and dry spells in the summer may prompt changes or additions to current urban drainage systems with Hamill (2011) estimating a UK investment of £5 billion in new water resources over the next 30 years, if climate change occurs as predicted. SuDS may be one area where a significant proportion of that funding is spent. Head (2009) believes that currently people are wasteful with water resources, claiming people do not recycle vast quantities of treated wastewater, do not collect and use local rainwater, and allow vast quantities of treated water to leak away. Using SuDS or other water management systems to recycle, collect and store water could reduce the demand for potable water and the associated energy required for treatment (Head, 2009). Woods Ballard et al. (2015) support the use of SuDS for helping developments to increase their resilience to climate change and urban intensification, claiming they offer a more adaptable way of draining surfaces. Murphy et al (2009) also support the use of SuDS, identifying that the solutions for climate change impacts are increased infiltration and above ground storage devices, and more widespread rainwater catchment and reuse. The adoption of SuDS to combat climate change should be relatively simple as the technology is already available and is not excessively expensive (Head, 2009).

Current SuDS design accounts for climate change impacts with 'uplift factors' for rainfall intensity, peak river flow, and sea level (Woods Ballard et al., 2015).

However, many sources dispute the exact ‘uplift factors’ due to varying views of impact levels.

Literature review summary

Based on the above literature related to sustainable urban drainage systems for attenuation, and water butts, several initial observations can be gathered. Generally, existing sewer systems are struggling to cope with current runoff rates, and are transporting significant levels of pollution into local watercourses, damaging river ecology and human property, and disrupting human activity. The implementation of SuDS devices is widely viewed as an effective and sustainable method of managing increased surface stormwater runoff, flood risk and associated damage, resulting from urbanisation and climate change.

SuDS implementation is widely supported and, in many cases, is one of the primary drainage solutions for new developments. SuDS devices for attenuation provide an effective way of reducing peak runoff rates and associated flooding, and their introduction into urban development, be it new or retrofitted, is widely encouraged. Processes such as urbanisation, climate change and human migration all increase the amount of water within a catchment area. The way in which water is managed has changed over the years to a stage where water is treated as a valuable resource rather than a nuisance. One obvious solution for managing water in this way, which is widely supported, is the use of SuDS.

Overall, water butts, with restricted flow outlets, are widely considered, on plot, small-scale SuDS devices. However, their wide scale implementation is currently limited due firstly, to a lack of research regarding their potential in reducing surface runoff and flood risk, secondly, a lack of guidance on optimum setups to release stored water and thirdly, issues with SuDS ownership and property-owner engagement. Many sources suggest that further research into using water butts as SuDS devices is required.

Methodology

The following section outlines the research methods used in this project, which were physical and numerical modelling. After being introduced, the rationale for selecting the two methods is explained through defining their specific contributions towards the research aim, followed by comments on accuracy and reliability.

Physical modelling

The aim of the physical modelling was to test a full-scale prototype water butt fitted with different outlets to firstly, gain an insight into the processes that occur in a water butt performing as a SuDS device, and secondly, obtain original data for the numerical modelling. Davies (2016) advocates physical modelling, explaining, you can see physical phenomena first hand, and can test important principles and theories with real data. As this project focused on a small-scale hydraulic prototype, physical modelling was an appropriate research method.

Initial concepts

Three concepts were considered initially, however, only two were pursued. Appendix A presents the three concepts alongside initial drawings, comments on their advantages and disadvantages, and justification for the dismissal of the third concept.

The two concepts pursued were:

Concept A: Simple outlet - with orifice restriction.

Concept B: Siphon outlet - with orifice restriction.

Model setup and fabrication

Water butt construction

Appendix B outlines the physical model construction process and orifice insert fabrication process.

A risk assessment was completed to identify possible risks that could be encountered during testing & construction.

Additional testing setup

Additional equipment included: 15-litre bucket, stepladder, quick-grip clamps, digital timer, digital scales and a tape measure (Figure 1 & Figure 2).

Figure 1: Digital scales & bucket

Figure 2: Siphon testing setup

Preliminary testing

Watertight testing

Safety was essential during laboratory testing. Therefore, to ensure the model did not leak, a water-tightness check was undertaken. The water butt was filled and observed for 30 minutes - no leakage occurred, indicating a watertight model.

Figure 3: Discharge-measuring device on hydrology bench

Discharge measurement
Prior to testing, the discharge-measuring device installed on the hydrology bench (figure 3) was checked to have adequate capacity for the proposed testing. The check revealed that a 2mm orifice outlet (minimum to be tested) did not register a readable discharge rate. Consequently, a time-volume method was used, whereby a bucket collected the discharge and a digital timer recorded the duration of discharge. Assuming that 1 litre of water = 1 kg, the discharge was calculated by weighing the contents of the bucket and dividing it by the duration of discharge, producing results in litres per second. This method was used throughout testing to maintain consistency within the results.

Testing procedure
The testing procedure for calculating discharge for each concept was identical, however, the pre-testing setups differed slightly.

Concept A – simple outlet setup
The objectives of the simple outlet testing were to determine the variation in outlet discharge rates through different orifice sizes. The setup procedure for a single simple outlet with a 2mm orifice is outlined below.

Before each test:

1) The water butt was filled to a predetermined water level 500mm above its base.
2) Digital scales were set to discount the bucket self-weight.
3) The 2mm orifice was inserted into one of the pipe attachments. (Figure 4)
4) The second outlet pipe was filled and closed at the tap.
5) The end of the pipe was fixed at a total head of 1400mm.
   (Total head remained constant during Concept A testing)

Concept B – siphon outlet setup
The objectives of the siphon testing were to determine the effect of total head on discharge rate, and calculate loss coefficients for each orifice size using the Bernoulli equation. The setup procedure for a siphon outlet with a 2mm orifice and a total head of 1.4m is outlined below.

Before each test:

- Repeat steps 1) to 5)

6) The upper bend of the siphon was positioned 235mm above the outlet, supported by a clamp. A roll of tape helped prevent kinking. (Figure 5)

Figure 4: 2mm orifice insert

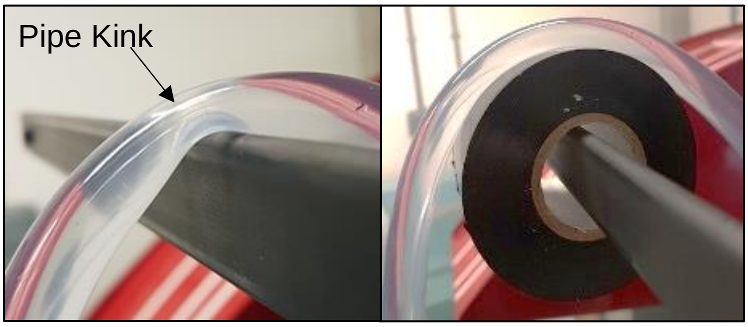

Figure 5: Tape roll to prevent pipe kinking.

<u>Discharge measurement</u>
The pipe tap was opened to allow discharge to fill the bucket, which was timed for 30 seconds for concept A and 60 seconds for concept B. After these times, the pipe taps were closed and the weight of discharge was measured using digital scales. The assumption that 1 litre of water = 1 kg converted the weight to volume. This volume was divided by the discharge time (30 or 60 seconds), producing discharge in litres per second. Head loss was measured on the 8mm 'water level pipe' with a mm scale rule.

For concept A, the process was repeated for all orifice sizes (2, 4, 6, 8, 10, 12mm) operating through both one and two outlet pipes (Figure 6).

Figure 6: 2mm, 4mm, 6mm, 8mm, 10mm orifice inserts

For Concept B, the process was also repeated for the five orifice sizes, however also under nine total head positions (1400, 1200, 1000, 800, 600, 400, 300, 200 & 100mm). Total head positions were achieved by clamping the end of the pipe to the frame of a stepladder that had been marked up with each total head.

Figure 7: Pipe tap clamped at 1200mm total head

To maintain high accuracy and reliability of experimental results, three repeat readings were taken, and a final average was calculated for each test.

In total, 36 tests were completed for concept A and 162 for Concept B.

Theory

The physical modelling was based on the Bernoulli equation:

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + Losses \qquad (1)$$

For the physical modelling, a number of simplifications to this formula were made:

$P_1 = P_2 = P_{ATM}$ (*Therefore, both pressure head variables cancel*)

$V_1 = 0$ *(Assumed zero at the water surface within the water butt)*

Losses = $\frac{KV^2}{2g}$ *(Due to orifice restriction and pipe friction)*

This gives the simplified formula:

$$\boldsymbol{h} = \frac{\boldsymbol{V^2}}{\boldsymbol{2g}} + \frac{\boldsymbol{KV^2}}{\boldsymbol{2g}} \qquad (2)$$

Losses coefficients were calculated using the below equation:

$$K = \frac{\left(h - \frac{V^2}{2g}\right)}{\frac{V^2}{2g}} \qquad (3)$$

Where:

h = Total Head

V = Pipe Velocity

K = Losses Coefficient

g = Gravitational Constant (9.81m/s^2)

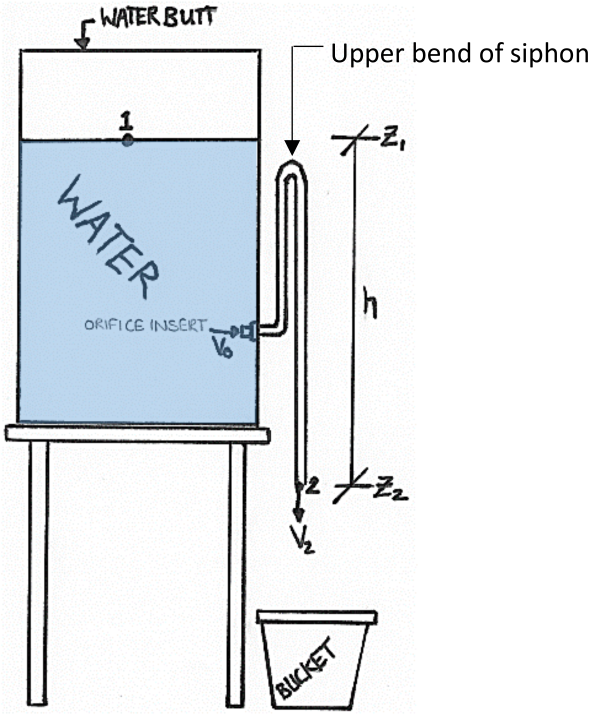

Figure 8: Indicative water butt drawing with associated Bernoulli equation parameters

Accuracy and reliability

All tests were repeated 3 times and averaged, to allow anomalous results to be identified, giving the results greater reliability. Vernier callipers were used to obtain accurate measurements for orifice dimensions to one-hundredth of a millimetre. A 10 second delay was used for opening the tap, e.g. for 30 seconds discharge duration, the tap was opened after 10 seconds and was closed after 40 seconds. This avoided starting the timer and opening the tap simultaneously, a potential cause of human error. At the beginning of testing, the inflow pipe was submerged in the water butt. It was observed that total head remained constant even after significant discharge had occurred. It was concluded that as discharge occurred, residual water within the outflow pipe replaced the discharged volume. Consequently, the inflow pipe was removed to gain accurate total head readings.

Human errors resulting from fatigue may have occurred due to the large number of tests undertaken, (Total tests = 198). Such errors include not setting the scales to discount the bucket self-weight after each test, incorrectly reading from a millimetre scale rule, and variations in discharge time depending on when the tap was closed. Using clamps to secure pipes at total head positions could have deformed the pipe and restricted flow, and may not have been at the exact total head position. Alternative methods for achieving total heads could have been explored. The losses coefficients obtained in the physical modelling are specific to the orifices and setups used within this project. Other setups and orifice designs may produce different losses coefficients. To improve the accuracy of the results, alternative methods for measuring discharge and achieving total head values could be explored e.g. ultrasonic flow meters. This may reduce testing time, allowing further research to be undertaken.

Numerical modelling

The aim of the numerical modelling was to use the observations and data obtained from the physical modelling to quantify the benefits of introducing a water butt and assess how the benefit changed in different storm conditions and water butt setups.

The numerical modelling was completed in Microsoft Excel. Other softwares including MatLab were considered. However, greater familiarity and competence with Microsoft Excel confirmed the software choice.

The numerical modelling used ‘time-varied inflow’ data to determine the effectiveness of a water butt performing as a SUDS device by quantifying the reduction in volume of runoff conveyed to sewer systems. Time-varied inflow was sourced using the ‘Flood Studies Report 50 percentile summer storm profile’ presented on page 91 in Urban Drainage, which, according to the authors Butler and Davies (2011), is recommended by the Wallingford Procedure for the design of drainage systems. This profile represents the storm with a hyetograph that is more peaked than 50% of all other summer storms. Time-varied inflow was used instead of block rainfall, as the results obtained are unrealistic. This is because rainfall intensity varies with time throughout the storm (Butler and Davies, 2011).

To analyse the impact that different storm conditions and water butt setups had on the effectiveness of a water butt as a SUDS device, a set of design parameters and assumptions that would remain constant throughout all tests were produced.

Design parameters

Table 1: Numerical modelling design parameters

A **Mean Rainfall Intensity**	**B** **Catchment Area**	**C** **Water Butt Capacity**	**D** **Orifice Size**	**E** **Storm Duration**	**F** **Drawdown Level**	**G** **Siphon Height (Concept B)**
mm/hr	m^2	m^3	mm	minutes	m^3	m^3
10	20	0.2	2	60	0.025	0.16
		200 litre	0.002m		(1/8 x Capacity)	(80% Capacity)

Water butt dimensions

Table 2: Water butt dimensions used in numerical modelling

H Internal Diameter	I Uniform Cross-sectional Area	J Outlet Pipe Length below water butt base	K Outlet Pipe Diameter	L Water Butt Height (Capacity ÷ Cross-sectional Area)			
				100 Litre	150 Litre	200 Litre	210 Litre
m	m^2	m	mm	m	m	m	m
0.5	0.196	0.5	12.0	0.509	0.764	1.019	1.070

Numerical modelling conditions & assumptions

A) Before every storm event, the water butt is assumed completely empty, being drained below the drawdown level by human activity (gardening).

Although possible, this assumption is optimistic due to the random nature of human activity. However, it allows the model to use the maximum storage capacity, determining the peak capability of a water butt performing as a SUDS device. It may apply better to summer months when human activity is generally higher.

B) The internal diameter of the outlet pipe is 12mm, like in the physical modelling.

As mentioned previously, time-varied inflow data was obtained using the '50 percentile summer storm profile'. The profile produces 'percentage of mean intensity' values throughout the storm, which were converted into rainfall intensities. For example:

In a storm with mean rainfall intensity 30mm/hr, the percentage of mean intensity (% Peakedness), 25% of the way into the storm, is 52% or 0.52. See figure 9.

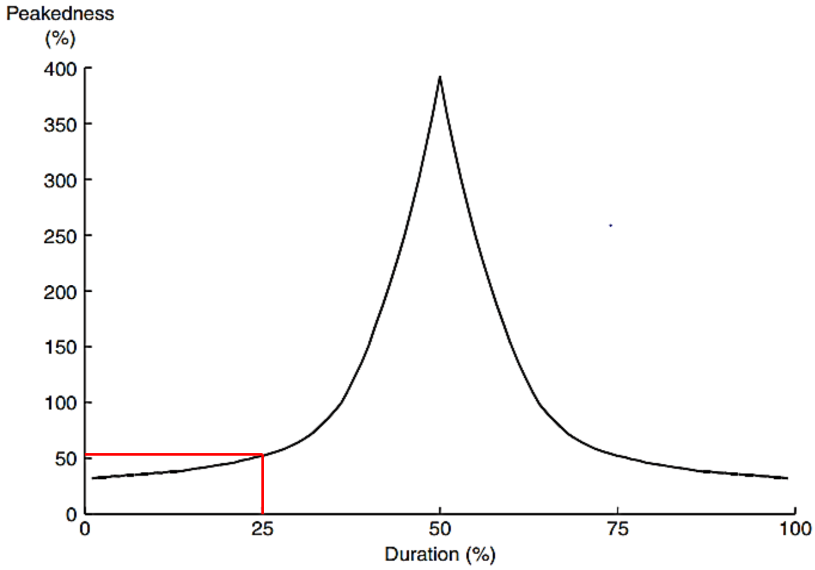

Figure 9: FSR 50 percentile summer storm profile (Butler and Davies, 2011)

This produces a rainfall intensity 25% into the storm of 0.52 x 30 = **15.6 mm/hr.**

Rainfall intensities were obtained at every 5% of the storm duration, producing an adequate but not excessive number of data sets.

The operation of a water butt as a SUDS device during a storm event was then divided into three phases within the model:

Phase 1: The water butt fills from completely empty to the drawdown/outlet level. During this time no discharge to the sewer system occurs.

Phase 2: The water butt fills above drawdown/outlet level to full capacity, at a rate of Inflow-Outflow. If outflow is greater than inflow, the water butt will not fill.

Phase 3: The water butt is at full capacity. Discharge is equal to the rate of runoff. Once the storm event finishes, the water butt drains to the drawdown level, through the outlet, at a discharge relative to the total head.

With the design parameters inputted into the model, two hydrographs were produced. A hydrograph without the water butt being used, and a hydrograph with the water butt installed.

To identify the effects of different storm conditions on the performance of a water butt, each parameter from the design parameters was varied. See table 3 below:

Table 3: Parameters varied in the numerical modelling

A Mean Rainfall Intensity	**B Catchment Area**	**C Water Butt Capacity**		**D Orifice Size**	**E Storm Duration**	**F Drawdown Level**		**G Siphon Height (Concept B)**	
mm/hr	m^2	m^3	Litres	mm	Minutes	m^3	x capacity	m^3	% of Capacity
5	10	0.10	100	2.0	15	0.025	1/8	0.12	60
10	20	0.15	150	4.0	30	0.050	1/4	0.14	70
20	30	0.20	200	6.0	60	0.075	3/8	0.16	80
30	50	0.21	210	8.0	75	0.100	1/2	0.18	90
40	75			10.0	90	0.125	5/8	0.20	100
50	100			12.0	120				
	120			(No Orifice)	180				
	150								

For each parameter, two new hydrographs were produced, allowing the effect of varying each parameter to be visualised.

The numerical modelling, like the physical modelling, also investigated the differences between Concept A (orifice outlet) and Concept B (siphon outlet). To achieve this, identical spreadsheets were created for water butts discharging through a siphon and through a simple orifice. In total 77 storm events were analysed.

The velocity of water in the outlet pipe was calculated using the equation:

$$V = \sqrt{\frac{2gh}{1+K}} \qquad (4)$$

The discharge from the outlet was calculated using the equation:

$$Q = A_{Pipe} \times \sqrt{\frac{2gh}{1+K}} \qquad (5)$$

Where:

K – Losses coefficient calculated in the physical modelling
A_{Pipe} – Area of outlet pipe (12mm Diameter)
h – Total head (m)
g – Gravitational constant (9.81m/s^2)

Accuracy and limitations

The outlet discharges were taken as constant during every 5% time step. In reality, outlet discharge would constantly vary as the water butt filled and emptied, changing the total head. Results, therefore, may not follow the exact trend expected in reality, however to fulfil the objectives of this project the results were deemed accurate enough. To improve the accuracy, rainfall intensities could be obtained at every 1% of the storm duration. Due to the above limitation, the exact time at which the outlet discharge commences is unknown. The exact time could be calculated by interpolating between the two values before and after outlet discharge commences, however this would be a time-consuming process for all 77 storm events. Rainfall intensities calculated at every 5% of the storm give accurate enough results to provide an indication of when the orifice starts discharging. In addition, once water level reached the drawdown level, the outlet discharge was initially taken as constant. In reality, there would be a gradual increase in discharge rate as the water filled the pipe or primed the siphon, and as water level exceeded the drawdown level. In practice, this effect may be negligible considering the whole storm, however is worth noting.

Finally, using alternative computer softwares for numerical analysis could have increased the amount of parameter combinations that were analysed. This would provide a more thorough optimisation procedure. The number of possible storm event combinations was far in excess of what could be achieved using Excel. Other softwares such as MatLab, which have the capability to run iterations of calculations automatically, may have been able to model a significantly larger number of parameter combinations, and therefore increase the accuracy and scope of the optimisation procedure.

Results and analysis

Physical modelling results

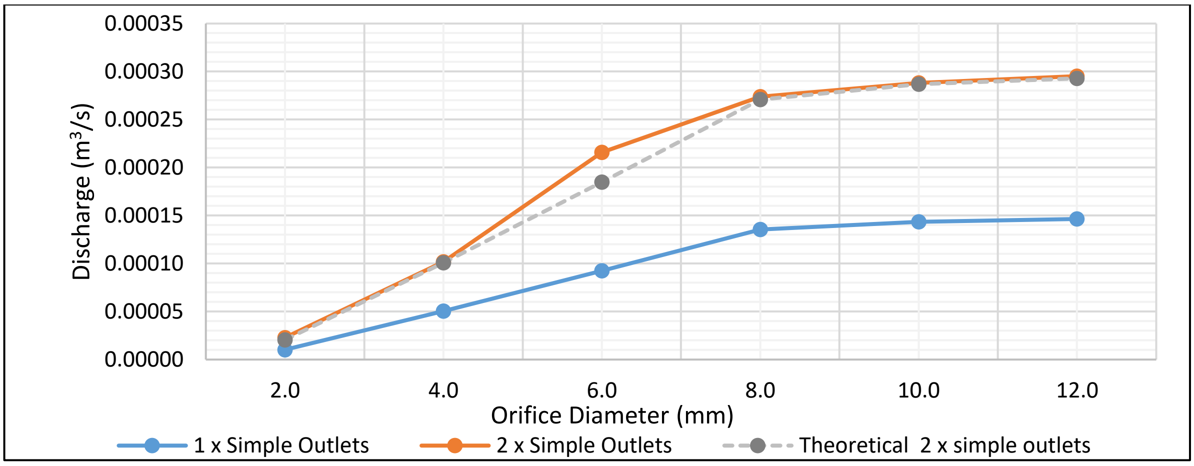

Figure 1: Discharge against orifice diameter for one and two simple outlets (Concept A)

Figure 10 shows the variation of discharge as orifice diameter increases. The blue and orange lines display discharges for one and two outlets respectively. The grey dotted line indicates the expected results from introducing a second outlet.

The general trend on both lines is a gradual increase in discharge as orifice diameter increases from 2mm to 8mm. Once orifice size exceeds 8mm, the rate of increase of discharge decreases. This may be because the 8mm and 10mm orifice sizes provide less restriction into the 12mm pipe compared to the smaller orifices, therefore the discharges see less variation.

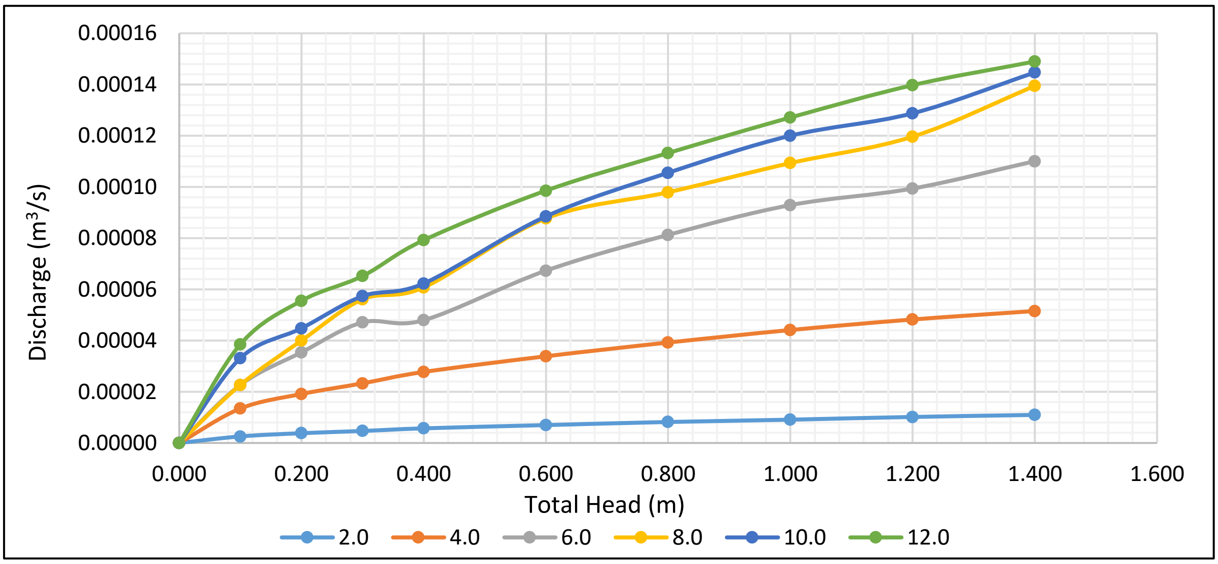

Figure 2: Discharge against total elevation head for siphon outlet (Concept B)

Figure 11 displays the variation of discharge as total head increases. Each line represents a different orifice size, see key.

Figure 11 shows that, generally, as total head increases discharge also increases. This is confirmed by the Bernoulli equation stated earlier where, as total head increases, velocity must also increase, consequently generating a larger discharge assuming cross-sectional area remains constant (Q=VA).

Table 4: Discharges comparison from Concept B testing

Total Head (m)	Orifice Diameter					
	2mm	4mm	6mm	8mm	10mm	12mm
	Discharge (m^3/s)					
1.4	0.0000110	0.0000515	0.0001101	0.0001394	0.0001447	0.0001490
1.2	0.0000102	0.0000482	0.0000994	0.0001196	0.0001287	0.0001398
1.0	0.0000091	0.0000441	0.0000929	0.0001093	0.0001200	0.0001271
0.8	0.0000082	0.0000392	0.0000813	0.0000979	0.0001055	0.0001133
0.6	0.0000070	0.0000339	0.0000673	0.0000877	0.0000885	0.0000986
0.4	0.0000057	0.0000277	0.0000479	0.0000608	0.0000623	0.0000792
0.3	0.0000047	0.0000233	0.0000471	0.0000561	0.0000574	0.0000652
0.2	0.0000038	0.0000191	0.0000354	0.0000400	0.0000448	0.0000556
0.1	0.0000026	0.0000135	0.0000227	0.0000227	0.0000331	0.0000385

Table 4 shows that the Concept B discharge results follow the expected trend. As orifice size and total head increase, discharge increases. High and low discharges are highlighted green and red respectively.

Table 5: Losses coefficients (K) determined from physical modelling.

Orifice Diameter (mm)	Loss Coefficient, K (Siphon Outlet)	Loss Coefficient, K (Simple Outlet)	Percentage Difference (%)
2	3184.4	3268.3	2.60%
4	132	145.1	9.90%
6	34.4	30.6	11.00%
8	24.8	19	23.20%
10	19.7	17.3	12.40%
12	15.1	16.6	9.90%

Table 5 presents the losses coefficients obtained from Concept A and Concept B testing. The two data sets show good correlation with the highest percentage difference between values being 23.22%. Although this may seem high, percentage difference values can be distorted small magnitude numbers, which is the case here.

The losses coefficient represents all losses within the setup, including friction in the pipe and restriction due to the orifice, hence the velocity in the simplified Bernoulli equation is the pipe velocity. Losses coefficients for 2mm and 4mm may seem high, however, due to the extreme restriction provided, the losses experienced would be significant, justifying such high magnitudes.

Physical modelling analysis

Physical modelling provided an opportunity to witness the physical processes occurring in a water butt with restricted flow outlets, and explore practical capabilities of an almost real-life model. This focused the numerical modelling to a setup that would perform well and be practical. Three key observations were made. The 2mm orifice generated losses coefficients of 3268.3-3184.4 for concept A and B respectively, which indicates a significant energy loss due to the restriction from the orifice. Understandably, a 2mm orifice is itself a small space for water to pass through, however when accounting for friction effects from the orifice walls, the clear unaffected flow path is reduced further. The velocity through the orifice is therefore likely to be very small. This is confirmed by the discharge rates from the 2mm orifice reaching a maximum from both tests of 0.000011m^3/s at 1.4m total head with a siphon outlet.

Relating this to the simplified Bernoulli equation above, to maintain the same total head with a smaller velocity through the orifice, the loss coefficient (K) must increase. As the orifice size increases, the discharge, and therefore velocity, through the orifice also increases. For example, the 6mm orifice obtains a maximum discharge of 0.00011m^3/s at a total head of 1.4m, approximately 10 times the discharge through the 2mm orifice. Relating this again to the simplified Bernoulli equation, to maintain the same total head with a higher velocity, the losses coefficient (K) is reduced. Consequently, K-values for the 6mm orifice reduce to 30.6 - 34.4.

The above observations indicate that the water butt is behaving as predicted with the Bernoulli equation, and that the losses coefficient and velocity share an inversely proportional relationship.

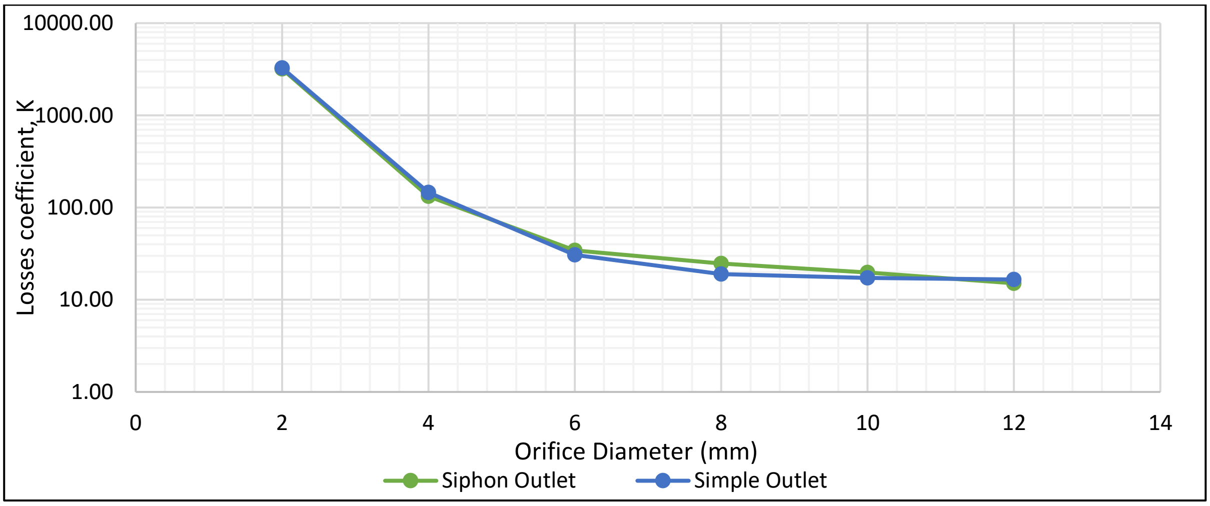

Figure 12: Losses coefficient against orifice diameter for simple and siphon outlets

Figure 12 above shows the losses coefficients for concept A and concept B testing. It is observed that the two testing methods produced comparable results, suggesting they are reliable and accurate. The K values are very similar for 2mm, 4mm and 6mm orifices. Slight variations may be caused by deviations in the time at which the tap is closed. At higher flow rates, more water is flowing out of the pipe per second and therefore the exact time at which the tap is turned off can have more effect on the experimental results. Put simply, any variation in the 'time for discharge' has a more significant effect on discharged volume for higher flow compared to lower flows.

Numerical modelling results & analysis

What is optimum performance?

A water butt performing optimally as a SuDS device only reaches full capacity and starts discharging to sewers once a storm event finishes. This removes 100% of roof runoff from the sewer system 'during the storm event'. The water butt should also drain fully after the storm event to leave maximum capacity for the next rainfall event.

Hydrograph Features

The following features apply to all figures/hydrographs in this section. *Unless stated otherwise, the 'design parameter storm conditions' are used*. The orange line represents the *'pre-water-butt discharge rate'* or the unaffected discharge rate to the sewer before installing a water butt. The blue line represents the discharge rate after installing a water butt. The blue shaded area between the lines represents the volume of runoff removed from the sewer system, stored in the water butt *during the storm.* The red shaded area represents runoff volumes discharged to sewers in addition to existing volumes *during the storm*, because of introducing a water butt.

Table 6: Features of hydrographs produced in the numerical modelling

Hydrograph Features	
	Pre-water-butt discharge
	Post-water-butt discharge
	Volume of runoff removed from sewer
	Volume of runoff added to sewer
	Post-water-butt peak discharge

Design parameter storm conditions - simple outlet

The first results obtained from the numerical model relate to the design parameters.

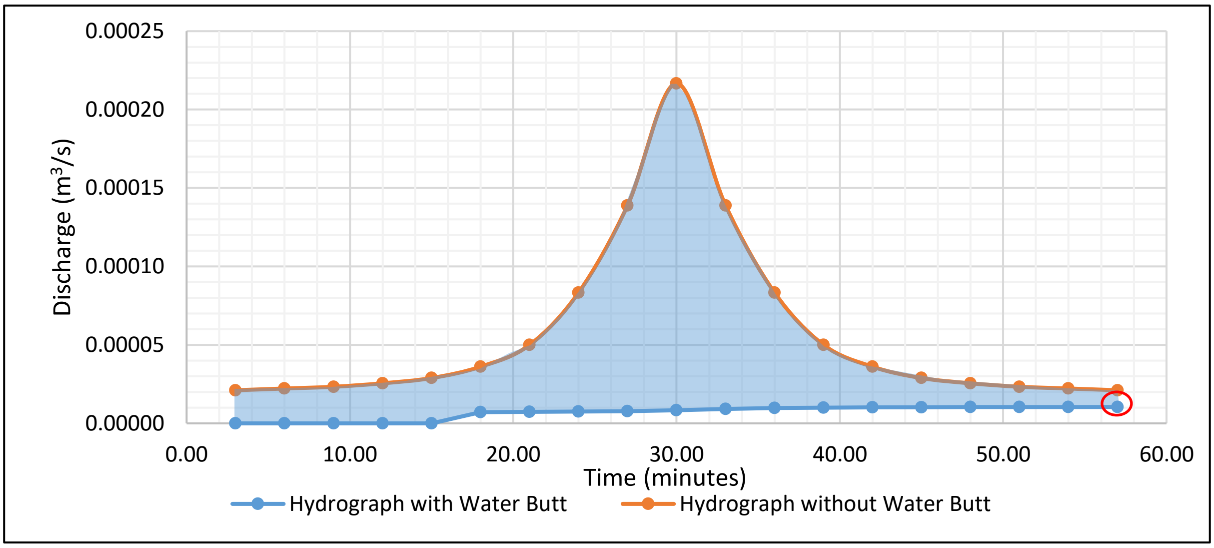

Figure 13: Hydrographs using the design parameters – simple outlet

As mentioned earlier the operation of a water butt occurs in three phases (see section 3.2.3). In figure 13, phase 1 occurs between 0-15 minutes and phase two occurs between 15-60 minutes. Phase 3, the draining of the water butt, can be seen on figure 14 starting at 60 minutes where, although the storm event has ended, the blue hydrograph continues until water in the butt drains to the drawdown level.

Figure 13 firstly shows that the water butt does not reach full capacity and therefore does not overflow. Consequently, under the design parameter storm conditions, introducing a water butt reduces peak discharge compared to pre-water-butt conditions, to 0.0000105m^3/s at 60 minutes when total head is greatest. Secondly, the discharge rate increases gradually as the storm progresses. This is due to the water butt filling and the total head increasing. These observations are as predicted and are simple to understand. Further analysis is presented in later sections.

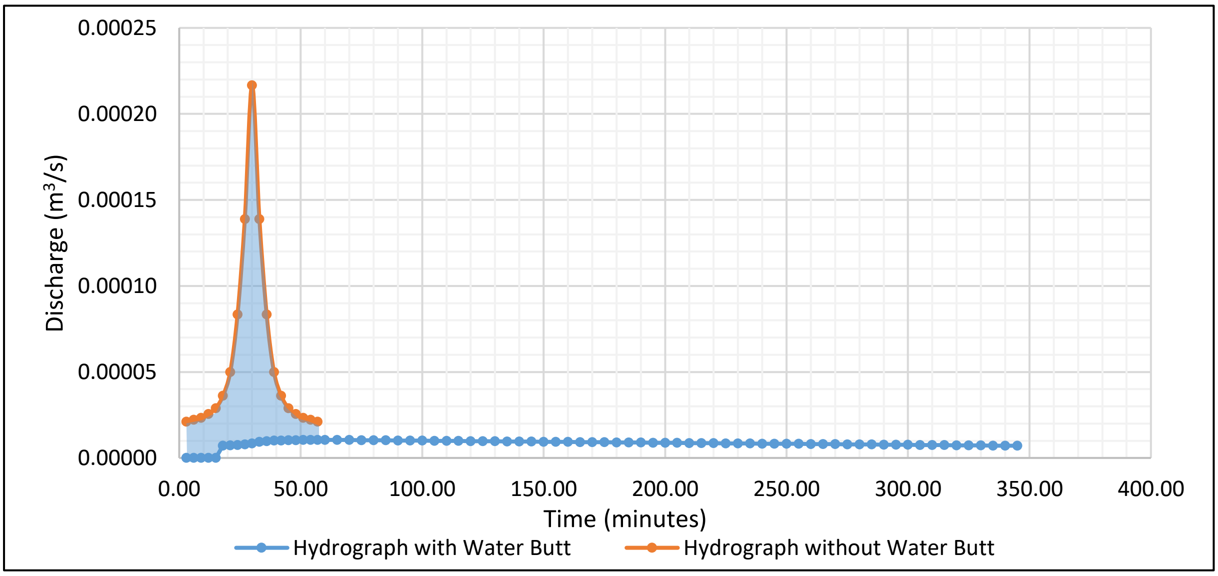

Figure 3: Full hydrographs using the design parameters – simple outlet

Design parameter storm conditions – siphon outlet

The second set of results obtained, again relate to the design parameters.

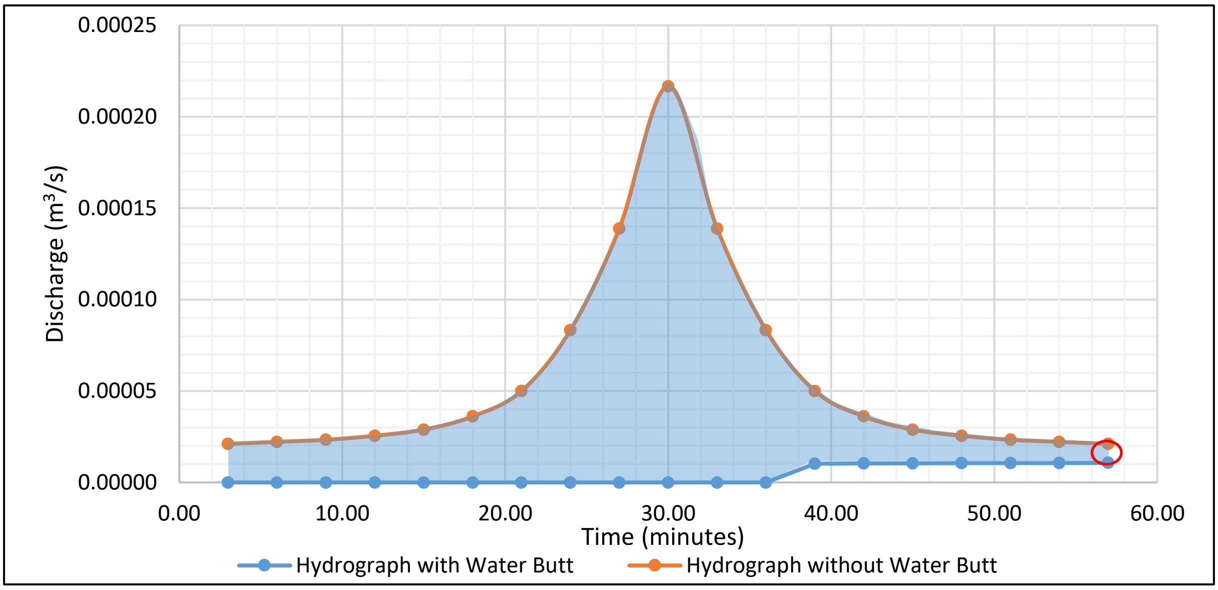

Figure 15: Hydrographs using the design parameters – siphon outlet

The key difference between using a simple and siphon outlet, shown in figures 13 and 21, is the time at which discharge occurs from the outlet. The siphon only allows discharge once the upper bend has been exceeded. Therefore, a larger proportion of the water butt is filled before outlet discharge commences. This can be seen in Figure 15, where the outlet discharge is delayed to 36 minutes.

Due to the outlet discharge commencing later, the volume of runoff stored and removed from the sewer system increases. Consequently, the water level and therefore total head in the water butt is higher, causing phase three to increase in duration to 370 minutes compared to 345 minutes as shown in figure 16.

Due to the reduced peak flow rates and reduced runoff volumes conveyed to the sewer during the storm, it can be concluded that for a storm event *with the design parameters*, significant benefit is achieved through introducing a water butt with either a siphon or simple outlet to provide temporary storage and attenuate runoff. In this case, a siphon outlet provides more benefit, removing a larger volume of runoff from the sewer system. It must be noted that this only applies to a design parameter storm event.

To assess how different water butt setups affect SuDS benefit, water butt capacity, orifice size, and drawdown level were varied. Storm conditions were also varied (see table 3), however, high numbers of possible combinations along with restrictions on page and word count meant further analysis could not be presented in this report.

Variations in water butt capacity

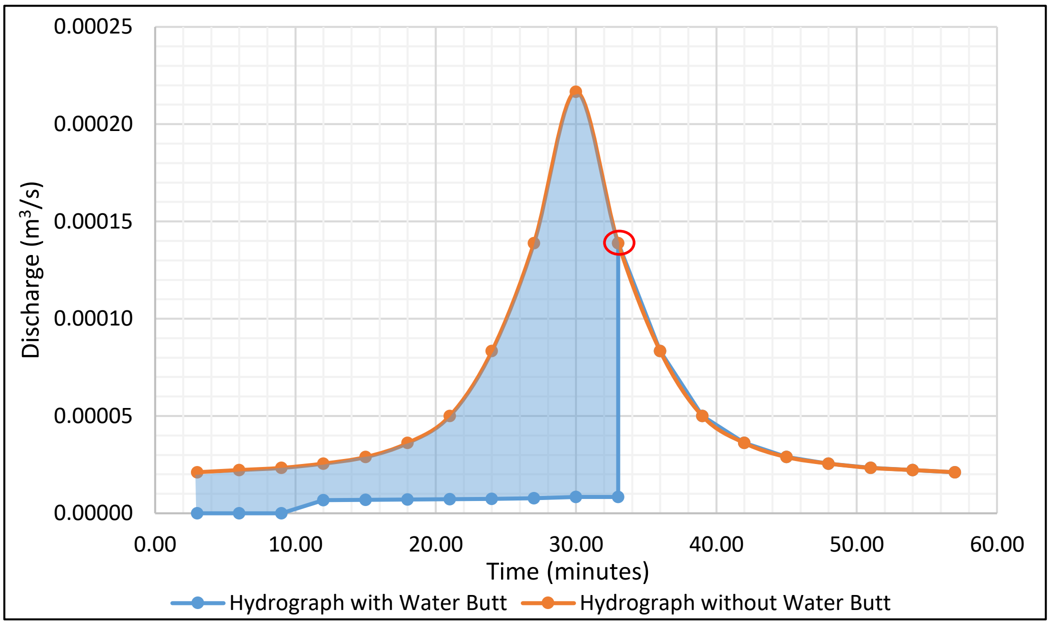

Figure 16: Hydrographs using 100-litre water butt – simple outlet

As a general observation, as water butt capacity increases, the volume that can be removed from the sewer system also increases.

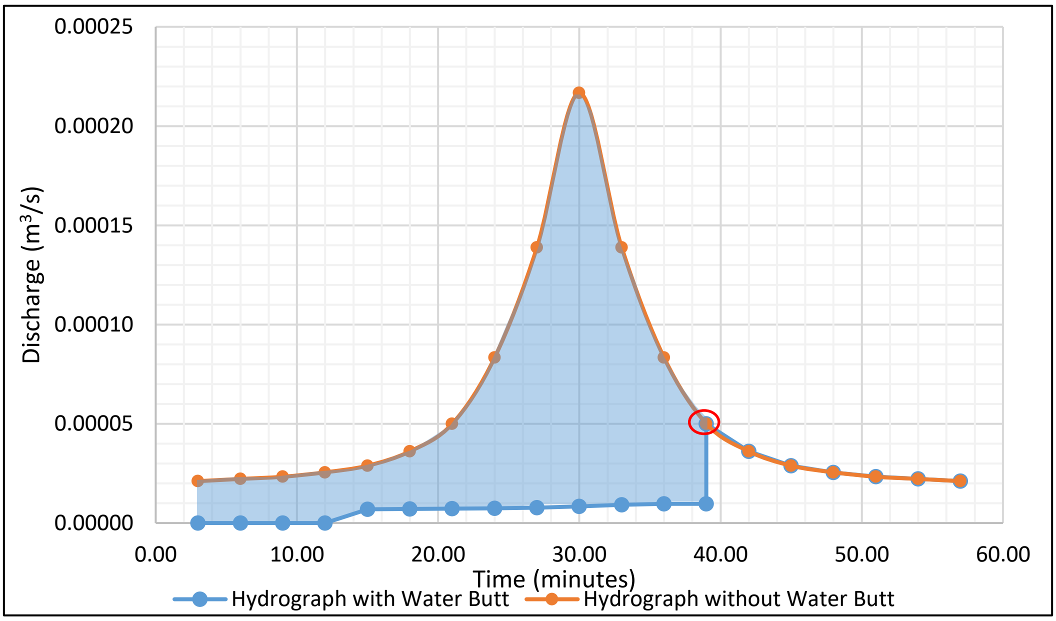

Figure 17: Hydrographs using 150-litre water butt – simple outlet

Figures 16 and 17 display hydrographs for 100-litre and 150-litre water butts under a *design parameter storm event*. It is clear to see, when comparing figures 16 and 17, that an additional 50 litres of storage increases the volume of runoff removed from the sewer system during the storm event (blue shaded area). Consequently, the time at which full capacity is reached, and the water butt overflows, is delayed to 39 minutes compared to 33 minutes (6 minutes or 10% of storm duration later). An increased capacity also reduces peak discharge rate, with the 150-litre water butt causing a 77% reduction compared to only 36% for a 100-litre water butt. Note, these statistics relate only to the design parameter storm event.

Although these observations show an improvement in terms of SuDS benefit, in both cases, full capacity is still reached before the storm ends. Hence, increasing the capacity further should improve the water butt's performance as a SuDS device.

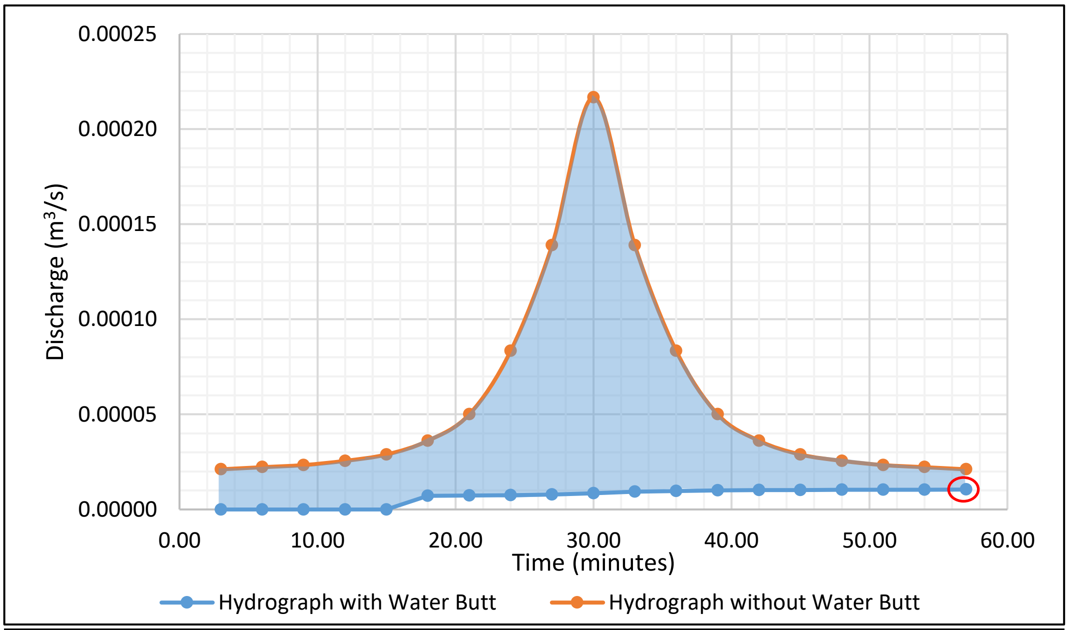

Figure 18: Hydrographs using 200-litre water butt – simple outlet

Figure 18 displays hydrographs using a 200-litre water butt. In this case, the water butt only uses a maximum of 88% capacity. Consequently, the only discharge to the sewer system is from the outlet. Outlet discharge peaks at 0.000105m^3/s, over 95% lower than the peak pre-water-butt discharge rate, and 50% less than the lowest pre-water-butt discharge. Therefore, by installing a 200-litre water butt, all discharges throughout the storm reduce significantly, when operating in a design parameter storm event.

In theory, as the water butt does not fill, the volume of runoff conveyed to the sewer system *during the storm* could be a 100% reduction, were it not for outlet discharge. However, as explained above, outlet discharges are almost insignificant compared to pre-water-butt rates and are not likely to contribute dangerous volumes to sewer systems. A siphon outlet may provide a more effective solution, discussed later.

It is important to recognise that each water butt has outlets situated at a level 1/8 times water butt capacity, meaning as water butt capacity increases, the volume stored below the outlet increases (see figure 19). Consequently, outlet discharge commences later as capacity increases, as shown in figures 18, 19, and 20.

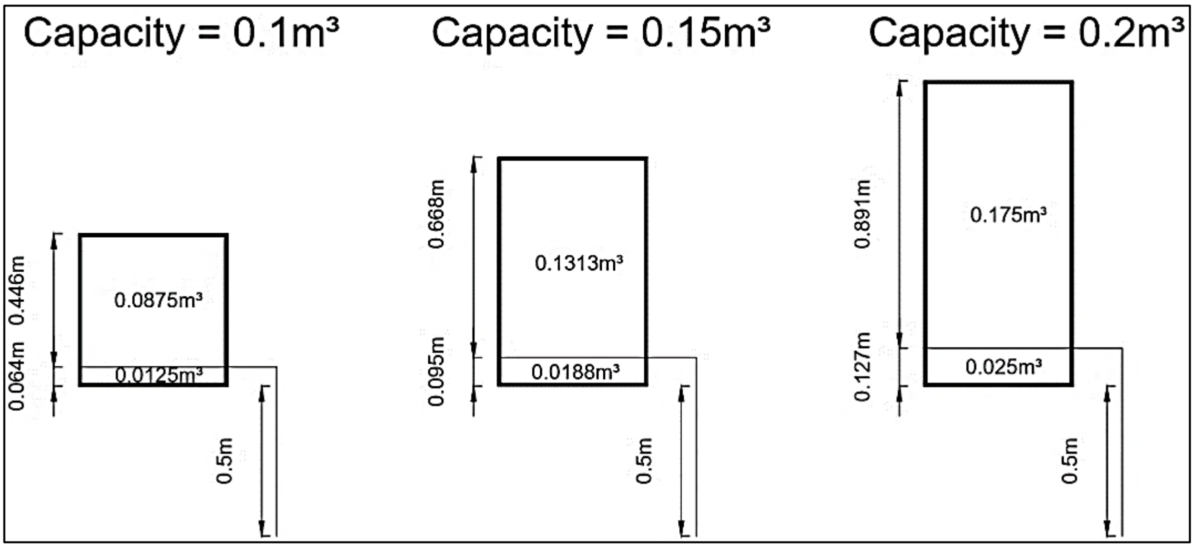

Figure 19: Drawdown levels for 100-, 150- and 200-litre water butts, at 1/8 times capacity

Siphon Outlet
Alternative siphon outlets with an upper bend at 80% capacity were also modelled for all water butt capacities.

100-Litre and 150-Litre Water Butts - Siphon
The 100- and 150-litre water butts again reach full capacity and overflow. However, by using siphon outlets, full capacity is reached 3 minutes earlier than the corresponding simple outlets. Consequently, for this case, peak discharge increases compared to the simple outlet, decreasing both setup's effectiveness as SuDS devices. A benefit however is that discharge to sewers is delayed, as outlet discharge commences only when 80% capacity is reached, therefore more of the storm is runoff-free.

200-Litre water butt - siphon
In contrast, a siphon outlet significantly increases the effectiveness of a 200-litre water butt as a SuDS device.

As shown in figure 20, discharge is delayed by a further 21 minutes compared to a simple outlet, to 36 minutes. This means more of the storm is runoff-free and therefore benefit as a SuDS device increases, under the design parameter storm conditions. Furthermore, a siphon outlet allows a greater proportion of the water butt to be utilised, increasing from 88% capacity for a simple outlet to 95% capacity. Consequently, less capacity is unused/wasted giving this setup greater efficiency.

As discovered earlier, the effectiveness of a water butt as a SuDS device increases with capacity. However, as stated in the literature review by Woods Ballard et al. (2015), along with managing water quantity, SuDS must also manage the other three pillars of SuDS design - water quality, biodiversity and amenity. Using water butts with capacity >200 litres would, in many cases, be difficult to implement without negatively affecting the three other pillars of design. For example, introducing water butts with >200 litre capacity provides homeowners with increased water volumes for gardening. However, the larger water butts may be considered an eyesore by some, negatively affecting amenity. Also, as explained by Townroe and Callaghan (2014) in the literature review, storing large volumes of standing water increases the risks of stagnation and mosquito reproduction. This reduces amenity value through increased mosquito-human contact and decreases water quality.

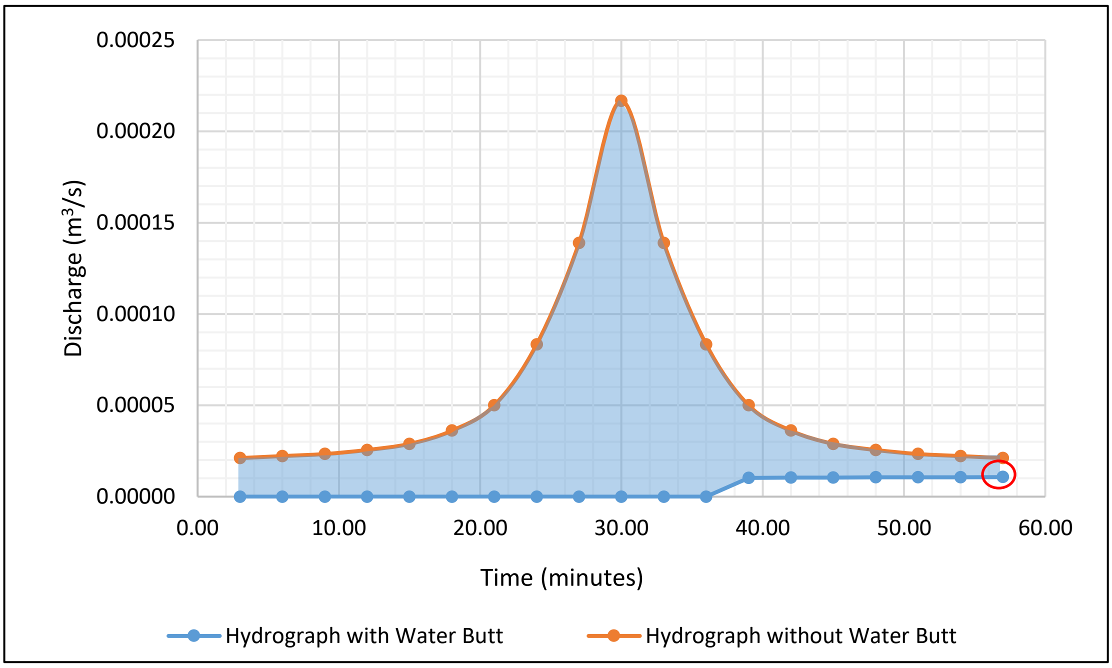

Figure 20: *Hydrographs using a 200-litre water butt – siphon outlet*

Water Butt Capacity Recommendation

Using the above observations, a 200-litre water butt effectively attenuates runoff during a storm event, and performs well as a SuDS device adhering to the four pillars of SuDS design, *when operating in a design parameter storm event*.

Variations in orifice size

As explained earlier, orifice diameter primarily determines outlet discharge and contributes towards determining the net inflow or RoF. For example:

Inflow rate at peak rainfall intensity (MI = 10mm/hr) = ***0.0002167 m³/s***

2mm *Orifice Discharge rate =* ***0.0000084 m³/s*** *→ Net Inflow/RoF =* ***0.0002083 m³/s***

6mm *Orifice Discharge rate =* ***0.0000727 m³/s*** *→ Net Inflow/RoF =* ***0.0001440 m³/s***

10mm *Orifice Discharge rate =* ***0.0000905 m³/s*** *→ Net Inflow/RoF =* ***0.0001262 m³/s***

Consequently, orifice diameter also contributes towards determining the time at which full capacity is reached:

$$\textbf{Time to fill (s)} = \frac{\textbf{Water Butt Capacity } (\textbf{m}^3)}{\textbf{Net Inflow Rate } (\textbf{m}^3/\textbf{s})}.$$

Therefore, in theory, as orifice diameter increases, the time at which full capacity is reached decreases. Initial predictions suggested that the greatest SuDS benefit would be achieved using an orifice size that minimised outlet discharge, and therefore runoff volumes conveyed to sewer systems. However, the orifice size should also avoid an outlet discharge that causes a rate of emptying (RoE) (i.e. outflow>inflow) in the water butt instead of a rate of filling (RoF) (i.e. outflow<inflow), which could increase discharge compared to pre-water-butt rates.

Results obtained using the design parameter rainfall intensity (10mm/hr) poorly represented the effects of varying orifice size. Therefore, to ease comparison and examine the capability in a more extreme storm, 20mm/hr was used.

Figures 21 and 22 display hydrographs for 2mm and 4mm orifices under design parameter storm events. Firstly, it is clear to see that as the orifice diameter increases the outlet discharge increases. As outlined earlier, a higher outlet discharge rate decreases the net inflow to the water butt. Consequently, the time at which full capacity is reached in figure 22 is delayed to 36 minutes compared to 33 minutes for the 2mm orifice. Peak discharge rate for the 4mm orifice is also therefore reduced, achieving a 61% reduction, compared to a 36% reduction for a 2mm orifice. Although full capacity is reached 3 minutes later by increasing the orifice size, the 4mm orifice produces a significantly larger outlet discharge, and therefore increases runoff volumes entering the sewer system whilst the water butt is filling. These two factors theoretically result in the same volume discharged to the sewer system, as both water butts fill, albeit at different rates. Exact volumes discharged to sewers could be calculated with further analysis.

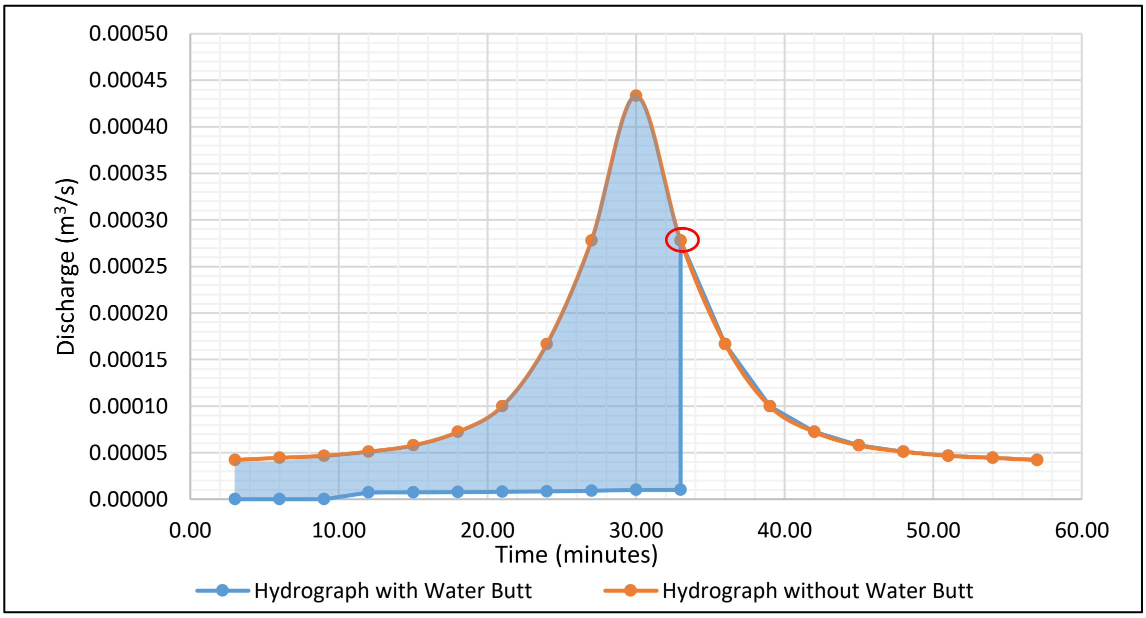

Figure 21: Hydrographs using a 2mm orifice – simple outlet

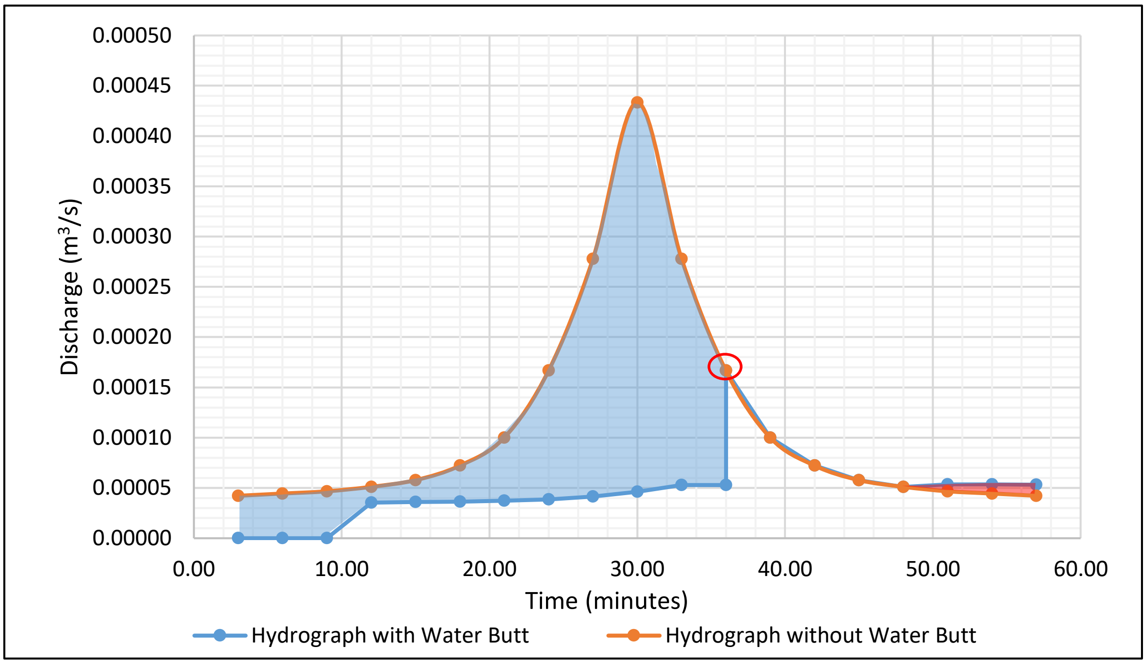

Figure 22: Hydrographs using a 4mm orifice – simple outlet

Rate of Emptying (RoE)

In figure 22, between 48-57 minutes outlet discharge rate is greater than inflow rate from runoff, resulting in a 'net outflow' or RoE. This is an unfavourable effect, as the outlet discharge is greater than the pre-water-butt discharge and the water butt is draining instead of storing. The extent of this effect is primarily dependant on rainfall intensity as a higher rainfall intensity increases the inflow rate from runoff therefore returning to a RoF. Although this somewhat reduces a water butt's effectiveness as a SuDS device, for the storm conditions used in the numerical modelling, the effect can be considered negligible as the increase in discharge in figure 22 is minimal.

Water level stalling

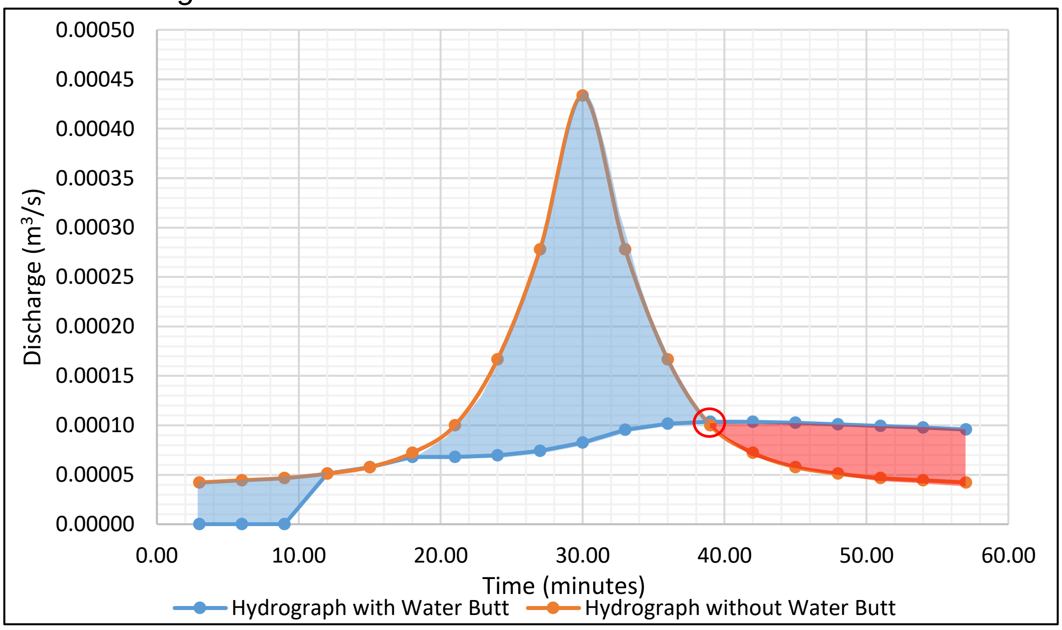

Figure 23: Hydrographs using a 6mm orifice – simple outlet

Figure 23 displays a hydrograph for a 6mm diameter orifice. The total head calculated once outlet discharge commences at 12 minutes is 0.66m. This generates an outlet discharge of 0.0000692m^3/s, however inflow rate from runoff for the storm conditions used in the numerical model is only 0.0000511m^3/s. Consequently, the outlet is limited to discharging runoff only as quickly as it enters at 0.0000511m^3/s. This is shown on the graph as the blue and orange lines being identical. The water level in the tank therefore stalls/remains at outlet level until the inflow rate exceeds 0.0000692m^3/s (18 minutes), generating a net inflow, filling the water butt.
In reality, the total head at outlet level is 0.627m, however due to the time steps in the numerical model the exact point at which the outlet discharge commences is unknown, and therefore 0.66m is calculated. A total head of 0.627m still produces an outlet discharge greater than inflow rate.
This effect is unfavourable as during this time the water butt provides no purpose as discharge to sewers from the outlet is the same as pre-water-butt rates.

Rate of Emptying (RoE)
In figure 23, between 39-57 minutes, outlet discharge is greater than inflow rate from runoff. This effect is similar to figure 22, however on a larger scale. The red shaded area suggests that significantly more runoff is conveyed to sewer systems at this stage in the storm, compared to pre-water-butt rates. The high outlet discharges are due to high water butt water levels/total heads, combined with a larger orifice size.

This is an unfavourable effect as outlined earlier, however, the above observations apply only to the storm conditions used in the numerical model. A higher rainfall intensity may increase the inflow rate and change the RoE into a RoF, making the outlet discharge less influential on the net flow.

Using a 6mm orifice does reduce runoff by up to 80%, and extends the storm by 25 minutes, under the storm conditions used in the model, giving the sewers more time to convey the runoff. Even so, this setup does not perform optimally as a SuDS device. Orifice diameters of 8, 10, and 12mm were also modelled. However, under the storm conditions used in the model, the RoE effect increased due to larger outlet discharge rates. In general, the proportion of water butt capacity used decreased and high outlet discharge rates produced large net outflows, which in some cases resulted in the water butt draining to outlet level during the storm - increasing discharge to sewers.

Siphon Outlet
Identical tests were completed for a siphon outlet with an upper bend at 80% capacity. For all orifice sizes, the water butts fill to the upper bend of the siphon before outlet discharge commences. Consequently, using the same storm conditions, the time at which outlet discharge commences remains constant (30 minutes) regardless of orifice size. Full capacity is also reached at 30 minutes when peak rainfall occurs, suggesting that even the largest orifice size does not reduce the net inflow enough to delay the time of filling. In reality, smaller orifices would reach full capacity slightly sooner than larger orifices, however due to the time steps used in the model, it remains constant.

The main observable difference between orifice sizes, under the storm conditions used in the numerical model, is with the outlet discharge rates that occur as soon as a net outflow is achieved. As orifice size increases, the difference between outlet discharge and inflow rate increases, causing an increase in the RoE and volume discharged to sewer systems and a decrease in time of drainage after the storm event ends. This is an unfavourable effect, which reduces the effectiveness of the setup as a SuDS device.

Orifice Size Recommendation

Under the storm conditions used in the numerical model, to provide optimum SuDS benefit, orifice diameter should be 2-4mm for both simple and siphon outlets. As a general recommendation, outlet discharge should be restricted significantly to avoid adding runoff volumes to sewer systems and a RoE. An orifice is only one method for restriction and alternatives could be explored.

Simple Outlet: Although for 2mm and 4mm orifices, full capacity is reached before the end of the storm, discharge conveyed to the sewer system is maintained at a low rate, and the full capacity of the water butt is used to remove runoff from sewer systems.

Siphon Outlet: Although all orifice sizes commenced discharge and reached full capacity at the same time, by using a 2-4mm orifice, volumes of runoff conveyed to the sewer system *during the storm* reduced.

Variations in drawdown level

What is drawdown level?

Drawdown level is the point to which water in a water butt drains. The volume stored below the drawdown level is intended for human activity such as gardening.

Theoretical optimum drawdown level

To provide maximum benefit as a SuDS device, in theory, the optimum position of the drawdown level is at the water butt base. This ensures that after every storm event the water butt fully drains, leaving maximum capacity available for the next storm event. This eliminates reliance on the assumption that after every storm event, the volume stored below the drawdown level would be drained by human activity, before the next storm event. However, by installing the orifice at the base of the water butt, gardeners would have no water to use in their garden, eliminating the primary use of a water butt.

Drawdown levels used in modelling

The drawdown levels used in numerical testing were at different proportions of full capacity. Each drawdown level increased by 1/8 times water butt capacity up to 5/8, giving five drawdown levels. Initial predictions suggested that drawdown levels above half capacity would store excessive volumes for human activity, and if not fully drained, would provide less capacity for the next storm event.

Results obtained using the design parameter rainfall intensity (10mm/hr) poorly represented the effects of varying drawdown levels. Therefore, to ease comparison and examine the capability in a more extreme storm event, 20mm/hr was used.

Observations

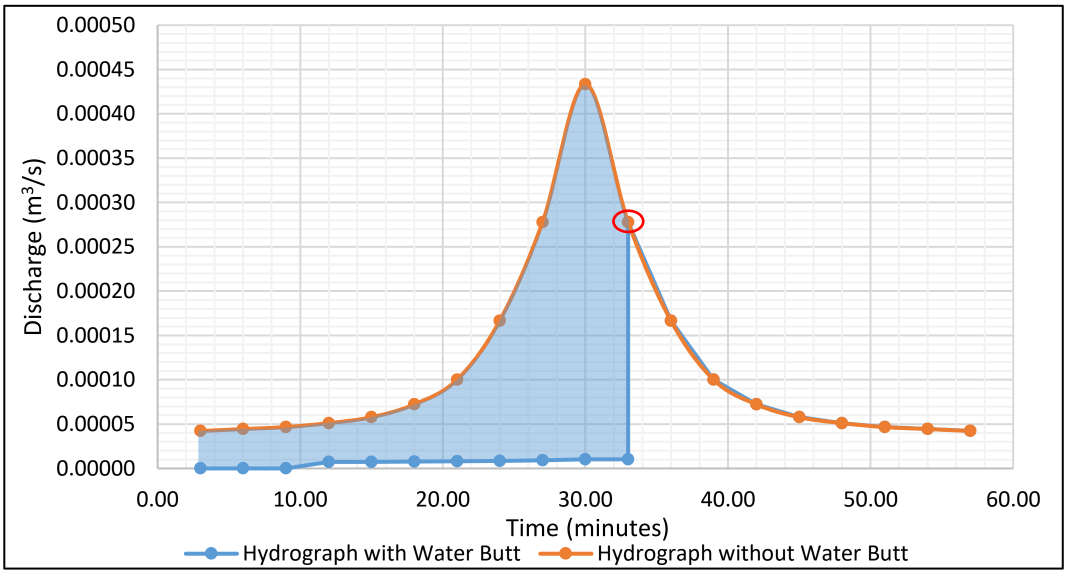

Figure 24: Hydrographs for 1/8 times capacity drawdown level – simple outlet

There are two main impacts of raising drawdown level. Firstly, the time taken for outlet discharge to commence increases, and secondly, the residual volume in the tank after each storm event increases, therefore requiring less volume to be drained after a storm event, taking less time to drain.

Hydrographs for drawdown levels at 1/8, 2/8, 3/8 and 4/8 times full capacity were created, and the hydrographs for 1/8 times capacity are shown in figure 24. *For the storm conditions used within the numerical modelling*, all setups reached full capacity at 33 minutes; however, the time at which discharge commences is delayed as drawdown level is raised. This appears on the hydrographs as a longer time for which the blue line remains at zero discharge. This may be due to the time steps used in the model preventing the exact time at which full capacity is reached from being calculated. Consequently, *for the storm conditions used in the modelling,* increasing the drawdown level increases the effectiveness of a water butt to perform as a SuDS device, as there is a longer time over which zero discharge occurs during the storm and therefore less runoff is conveyed to sewer systems.

A drawdown level of 5/8 times full capacity was also modelled. However, this decreases the time at which full capacity is reached to 30 minutes (3 minutes earlier than all other drawdown levels). Consequently, the water butt provides all of its benefit in the first half of the storm, and cannot provide further benefit in the second half of the storm as it has reached full capacity. This is not necessarily a negative effect, as no outlet discharge, and therefore no runoff volume, is conveyed to sewers until nearly halfway into the storm. This increases the setup's effectiveness as a SuDS device.

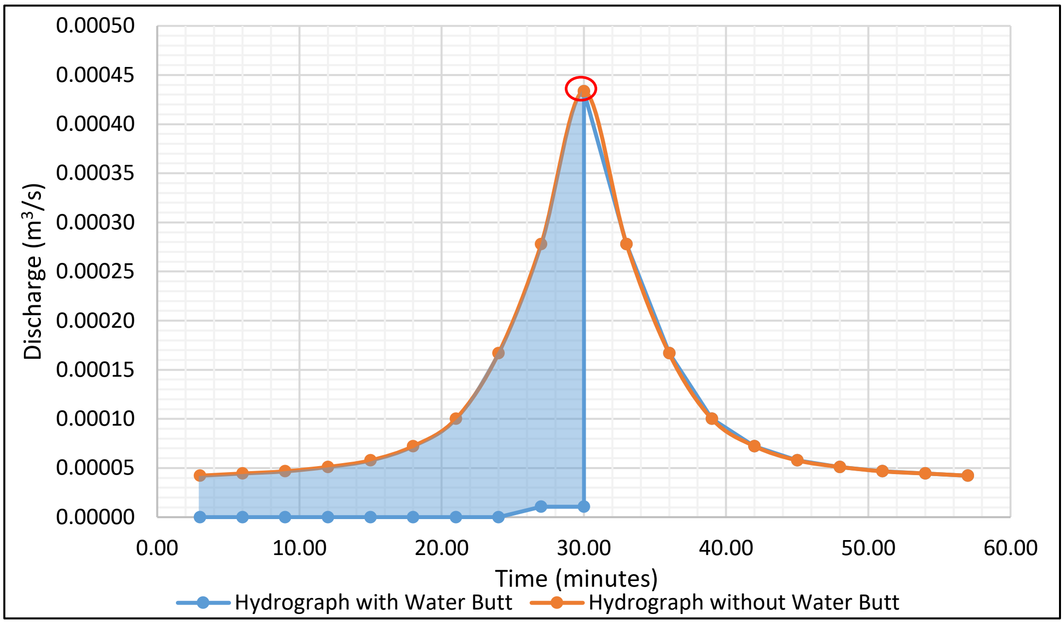

Figure 25: Hydrographs for 5/8 times capacity drawdown level – simple outlet

Drawdown level using a Siphon Outlet

Simple outlets start discharging once water level in the water butt exceeds the outlet; therefore, drawdown level determines when outlet discharge commences. Siphon outlets however, only discharge once the water level in the water butt exceeds the upper bend of the siphon. Consequently, drawdown level has no effect on when outlet discharge commences. Hence, a reduced net inflow or RoF is achieved later in the storm, and full capacity can be reached earlier in the storm. This observation applies not only to the storm conditions used in the numerical model but also to all water butts using siphon outlets.

As a result, the hydrograph *during the storm* is identical for all drawdown levels, where outlet discharge and full capacity both occur at 30 minutes, *under the storm conditions used in the numerical model*. It can therefore be concluded, that no advantage is gained by varying drawdown level with a siphon outlet *during the storm event*. After the storm as drawdown level increases, the time taken to drain reduces. Therefore, a lower drawdown level would be a better SuDS solution, to provide maximum storage space for the following rainfall event and extend the storm duration to give sewer systems extra time to convey runoff.

Distribution of volumes at drawdown levels

Table 7 – Drawdown levels, storage capacity and human activity

Drawdown Level (Proportion of full capacity)	**Storage Capacity if fully drained (m^3)**	**Storage Capacity if not fully drained (m^3)**	**Capacity for human activity (m^3)**	**Number of watering cans (Assume $0.01m^3$ can capacity)**
1/8 (12.5%)	0.200	0.175	0.025	2.5
2/8 (25%)	0.200	0.150	0.050	5.0
3/8 (37.5%)	0.200	1.125	0.075	7.5
4/8 (50%)	0.200	0.100	0.100	10.0
5/8 (62.5%)	0.200	0.075	0.125	12.5

Table 7 above shows the distribution of storage capacity at different drawdown levels. This table emphasises the reliance of the above observations on human activity draining the tank after each storm event. Additional modelling accounting for no human activity should be undertaken.

Evaluation of optimum drawdown levels

The numerical modelling of simple outlets showed that drawdown levels of 1/8-4/8 times capacity produced no variation in the time at which full capacity is reached. A drawdown level of 4/8 times capacity delays the time at which outlet discharge commences the most, which provides the best SuDS benefit. Therefore, *under the storm conditions used in the numerical modelling* and *assuming that the water butt will be fully drained below the drawdown level after each storm event by human activity*, a drawdown level of 4/8 times capacity should be used. Table 7 shows that a 4/8 times capacity drawdown level provides adequate volumes for human activity (100-litres).

This contradicts the statement in '***Theoretical optimum drawdown level'*** that a drawdown level at the base of the butt provides the greatest SuDS benefit. However, this statement does not include provision for human activity and ignores the assumption that human activity drains the water butt below drawdown level after every storm event. An alternative option instead of using a fixed drawdown level for all storm events is to use detachable outlets, which may provide flexibility for seasonal variations. During winter months when storm events are more frequent/extreme and human activity is reduced, lower drawdown levels may be used. In summer months when storm events are less frequent and human activity is greater a higher drawdown level may be used. This accounts for both human and SuDS requirements, managing water quantity without compromising amenity value. Detachable outlets require homeowner participation, which could introduce complications. They may have more potential for example in a school environment where a dedicated caretaker could take responsibility for altering the drawdown levels depending on the season. Further research into the practicalities of detachable drawdown levels is required.

Siphon outlet vs simple outlet

The project set out with two outlet concepts, with the aim of determining which provides a more effective SuDS solution.

Simple outlet

Simple outlets allow outlet discharge as soon as the orifice level is exceeded. This can be seen as an unfavourable effect as it conveys discharge to sewer systems early in the storm, when optimum performance should prevent discharge to sewer systems. Although outlet discharge rates are low, scaling up for 1000 water butts discharging within a larger catchment could generate significant volumes of runoff especially with larger diameter orifices.

In addition, regardless of the magnitude of storm event, the water butt will always drain to the drawdown level. This provides consistency in practice as the proposed storage capacity made vacant for subsequent storm events will always be available.

Finally, simple outlets propose the 'simpler' solution in practicality terms. Complications including priming of pipes, pipe kinking and securing upper bend positions that all exist with siphon outlets, are avoided.

Siphon outlet

Siphon outlets, as explored earlier, delay the time at which outlet discharge commences, compared to simple outlets, to once the upper bend has been exceeded. This is beneficial as outlet discharge and therefore runoff volumes conveyed to sewers are delayed for a longer time during the storm. If a storm event is insignificant enough that water level does not exceed the upper bend of the siphon, the water butt will not drain. If human activity after the storm does not then drain the butt fully, the storage capacity for the next storm is significantly reduced. Therefore, in this case, the setup provides minimal, if any, benefit as a SuDS device.

The numerical modelling showed that generally, siphon outlets are more likely to fill water butts compared to simple outlets, because outlet discharge, which reduces the RoF, commences later in the storm. This effect is more prominent in larger diameter orifices, where larger outlet discharges reduce net inflow/RoF more significantly. This can be seen as a favourable effect because the water butts are using a greater proportion of their capacity, therefore less capacity is unused and wasted.
In the physical modelling, it was observed that a 2mm orifice in a siphon outlet prevents the siphon from fully priming, which limits the outlet discharge. Initially, as the water level increased below the upper bend, the outlet pipe fully filled. However, once the upper bend was exceeded, the restriction from the 2mm orifice was too large to allow adequate discharge to fill the downward section of pipe and prime the siphon. This could cause operational issues in real-life applications and invalidate the numerical modelling conclusions.

Combining Outlets

During extreme storm events (high rainfall intensity or duration), combining both outlet types may provide increased benefit. For example, using a simple outlet with a small orifice allows outlet discharge to commence, once drawdown level is exceeded. This immediately reduces the RoF, increasing the time over which the water butt removes runoff from the sewers. Introducing a siphon outlet with a larger diameter orifice and a high upper bend position (80-90% capacity), allows a larger discharge to commence once the upper bend is exceeded. Although this would increase the discharge from the water butt, it would further decrease the RoF, allowing the water butt to continue to remove runoff from sewer systems, albeit at a slower rate. To quantify the benefits and effectiveness of combining outlets, additional modelling is required.

Outlet Recommendations

As a general recommendation, water butts should utilise simple outlets as the primary outlet solution to provide the greatest and most consistent SuDS benefit. Although outlet discharge occurs earlier in the storm, using a small enough orifice (2-4mm) will mean the discharge rates are almost insignificant. Siphon outlets provide a beneficial solution when storm events consistently guarantee adequate runoff to fill the water butt above the upper bend of the siphon. Otherwise, their performance is inconsistent and uncontrollable. ***These recommendations apply to the results and setups used in this project and will not necessarily apply to all storm events.***

Conclusions and recommendations

This section collates the findings discussed above, to provide conclusions and recommendations in relation to the project aim, stated in section 1.3 of this report. This is followed by a statement regarding the contribution of the conclusions to industry, ending with an explanation of the identified limitations that confine the conclusions and, suggested areas for further research.

Conclusions and recommendations

From the above observations it can be concluded that, *under the storm conditions used in the numerical modelling* a water butt can perform as a SuDS device, reducing runoff rates and volumes conveyed to sewer systems, contributing towards a reduction in urban flooding and its associated risks. In order to achieve this benefit *specifically for the storm conditions used within this project*, a recommended orifice size of between 2-4mm should be used, with a drawdown level at ½ the full capacity of the water butt or lower. As a general recommendation for water butts in other storm conditions, the orifice should provide significant restriction to prevent a rate of emptying occurring, to utilise the full capacity of the water butt and to prevent significant volumes of runoff being conveyed to sewers.

As a general conclusion, water butt capacity should be as large as feasibly possible to store large quantities of runoff without negatively affecting amenity, biodiversity or water quality as outlined by Woods Ballard et al. (2015) in the four pillars of SuDS design. The recommended capacity *for the storm conditions used in this report*, that is readily available for purchase, is 200 litres. Smaller capacity water butts still provide benefit, however the amount of benefit reduces. As a general conclusion from the observations above, simple outlets should be used as the primary outlet solution, to ensure consistent operation and SuDS performance. Siphon outlets should be used where storm events consistently guarantee adequate runoff to fill the water butt above the upper bend of the siphon.

Contributions

This project presents some of the first data in relation to orifice size, capacity and operational capability of a water butt operating as a SuDS device within industry. The conclusions from this project aim to address some of the issues and fill some of the knowledge gaps raised by Woods Ballard et al. (2015), Hamill (2011), Susdrain (2012d), Andoh & Declerk (1999), and Butler & Davies (2011). This research identifies possible setup arrangements that would perform well as a SuDS device in practice and provides a foundation from which further, more detailed, analysis can develop.

With this research, civil/drainage engineers, homeowners and property developers can consider with greater understanding, the possible benefits achieved by introducing a water butt as a SuDS device.

Limitations and further research

It is vital to note that the observations and conclusions presented in this report apply exclusively to the *water butt setups and storm conditions used within this project*. Alternative water butt dimensions, pipe sizes, orifice designs, and design parameters may produce variations in performance resulting in different observations and conclusions. This presents an opportunity for further research of undertaking multifaceted numerical modelling to analyse the performance of water butts in a larger cohort of storm events, with the aim of identifying operational limits and an optimum setup for common storm events.

Furthermore, the large time steps used in the numerical model may have restricted comparisons between water butt setups, compared to a smaller time step. This presents an opportunity for further numerical modelling using smaller time steps to identify, more accurately, the time at which outlet discharge commences, making comparisons between water butt setups more accurate.

Additional opportunities for further research include:

- Analysis into the quantity of water required by humans for gardening, to assist in the design of an optimum SuDS device alongside a functional piece of garden equipment.
- Numerical modelling investigating the use of multiple outlets used in combination to assess whether performance of a water butt as a SuDS device can be improved.
- Additional physical modelling to constantly record discharge with total head, to obtain more accurate loss coefficient values to be used in the numerical model.
- Exploration of alternative orifice designs or outlet options. Using orifices is only one method of restricting flow.
- Exploration of locations to which outlet discharge is directed, such as other SuDS devices, permeable pavements, detention ponds, swales etc. and their effect on reducing runoff rates to sewers.

Acknowledgements

I would like to thank all those who supported me throughout the duration of this project. Notably my dissertation supervisor, Dr John Davies, who helped me find inspiration for this project, guided me through the dissertation process and shared his wealth of knowledge with me. I would also like to thank other members of staff at the University of Plymouth, especially the COAST laboratory technicians, Andrew Oxenham, Gregory Nash, and Hannah Poulson. Special thanks goes to David Butler and John Davies, for allowing me to use their images within this report. Finally, I would like to thank my family and friends who have supported and motivated me to complete this report.

References

Andoh, R.Y.G. and Declerk, C. (1999). *Source control and distributed storage: a cost effective approach to urban drainage for the new millennium?* Sydney: Hydro International plc.

Blockley, D. (2005). *New Dictionary of Civil Engineering*. 1st ed. London: Penguin Books Ltd.

Bray, R. (2001). *Maintenance of sustainable drainage – experience on two EA demonstration sites in England. Proceedings of the 1st National Conference on sustainable drainage.* Coventry University, p93-104.

Butler, D. and Davies, J. (2011). *Urban Drainage*. 3rd ed. Abingdon: Spon Press.

Defra (2008). *Future water. The government's water strategy for England.* [online]. *Available at:* https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69346/pb13562-future-water-080204.pdf

Digman, C., Ashley, R., Balmforth, D., Stovin, V. and Glerum, J. (2012). *C713 - Retrofitting to manage surface water*. London: CIRIA.

Environment Agency (2013). *Rainfall runoff management for developments*. *Flood and Coastal Erosion Risk Management Research and Development Programme*. [online]. Available at: http://evidence.environment-agency.gov.uk/FCERM/Libraries/FCERM_Project_Documents/Rainfall_Runoff_Management_for_Developments_-_Revision_E.sflb.ashx [Accessed 30 Nov. 2017].

Flood and Water Management Act (2010).Chapter 29.Schedule 3 - Sustainable Drainage. The Stationery Office Limited

Hamill, L. (2011). *Understanding hydraulics*. 3rd ed. Basingstoke: Palgrave Macmillan.

Head, P. (2009). *Entering an ecological age: the engineer's role.* Proceedings of the Institution of Civil Engineers - Civil Engineering, [online] 162(2), pp.70-75. Available at: http://www.icevirtuallibrary.com/doi/pdf/10.1680/cien.2009.162.2.70 [Accessed 1 Dec. 2017].

Helmreich, B., Horn, H., (2009). '*Opportunities in rainwater harvesting*', *Proceedings of the Institute of Water Quality Control: Desalination, Vol 248*. [online] Available at https://ac.els-cdn.com/S001191640900575X/1-s2.0-S001191640900575X-main.pdf?_tid=db4db810-cfa0-11e7-aa36-00000aacb35e&acdnat=1511367724_9e65449697769dbd81ae86c8b6940299. [Accessed 22 Nov 2017].

Martin, P., Turner, B., Payne, J., Elliot, C. and Reed, B. (2001). *C523 - Sustainable Urban Drainage Systems - Best Practice manual for England, Scotland, Wales, and Northern Ireland*. 1st ed. London: CIRIA.

Met Office. (2011). *Flooding — Summer 2007*. [online] Available at: https://www.metoffice.gov.uk/about-us/who/how/case-studies/summer-2007 [Accessed 28 Nov. 2017].

Murphy, J., Sexton, D., Jenkins, G., Boorman, P., Booth, B., Brown, K., Clark, R., Collins, M., Harris, G., and Kendon, E. (2009). *Climate Change Projections,* [online]. Version 2, UK Climate Projections. Available at http://ukclimateprojections.defra.gov.uk/content/view/824/517/ [Accessed 25 Nov 2017]

Pennington, K. and Cech, T. (2010). *Introduction to water resources and environmental issues*. Cambridge: Cambridge University Press.

Stewart, D. (2015). '*Urban Drainage'*, Proceedings of the ICE: Flood Risk, ICE Virtual Library [online]. Available at: http://www.icevirtuallibrary.com.plymouth.idm.oclc.org/doi/pdf/10.1680/fr.41561.139 [Accessed: 26 November 2017].

Susdrain (2012a). *Using SUDS – Background - Urban Drainage*. [online]. Available at: http://www.susdrain.org/delivering-SuDS/using-SuDS/background/urban-drainage.html_ [Accessed: 23/11/17].

Susdrain (2012b). *Sustainable drainage*. [online] Available at: http://www.susdrain.org/delivering-SuDS/using-SuDS/background/sustainable-drainage.html [Accessed 2 Dec. 2017].

Susdrain (2012c). *Adoption & Maintenance of SuDS - Adoption*. [online] Available at: http://www.susdrain.org/delivering-SuDS/using-SuDS/adoption-and-maintenance-of-SuDS/adoption/adoption.html [Accessed 7 Dec. 2017].

Susdrain (2012d). *Rainwater harvesting*. [online] Available at: http://www.susdrain.org/delivering-SuDS/using-SuDS/benefits-of-SuDS/rainwater-harvesting [Accessed 4 Dec. 2017].

Thorbeck, D. and Troughton, J. (2016). *Balanced Urban Development: Options and Strategies for Liveable Cities*. 1st ed. Springer Nature, p.45.

Townroe, S. and Callaghan, A. (2014). *British Container Breeding Mosquitoes: The Impact of Urbanisation and Climate Change on Community Composition and Phenology.* PLoS ONE. [online] Available at: http://europepmc.org/backend/ptpmcrender.fcgi?accid=PMC3997353&blobtype=pdf [Accessed 5 Dec. 2017].

Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R. and Kellagher, R. (2015). *The SUDS Manual*. C753. London: CIRIA.

Woods-Ballard, B., Kellagher, P., Martin, P., Jeffries, C., Bray, R. and Shaffer, P. (2007). *Site Handbook for the Construction of SUDS*. *CIRIA C698.* London: CIRIA

Appendices are available as ‘supplementary files’ (please see download area)