Rainwater Harvesting for Drought Mitigation and Flood Management

Submitted by Peter Joseph Melville-Shreeve
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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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Abstract

Rainwater harvesting (RWH) in the UK has seen a low level of uptake relative to similar settings such as Australia and Germany. The relatively low cost of municipal water in the UK limits the financial savings associated with RWH systems, especially in a domestic setting. Although financial benefits can be relatively low (in terms of reduced water bills), academic and practitioner studies have demonstrated the potential for RWH to significantly reduce potable water demands at typical UK houses. Hence, increased uptake of RWH has potential to contribute to mitigating droughts in water scarce regions. Stormwater management in the UK is receiving increasing attention at all levels; from grass-roots sustainable drainage systems (SuDS) such as downpipe disconnections and raingardens; through to implementation of urban realm attenuation schemes and continued development of guidance from UK policy makers. The public realm nature of most SuDS presents a need for partnership approaches to be fostered between infrastructure mangers and the general public. The application of RWH as a technology within the SuDS management train has been limited in the UK as policy makers have taken the view that RWH tanks may be full at the start of a design storm, and thus the potential for attenuation and peak discharge reduction has been largely ignored. However, in the last few years there has been a shift in emphasis; from RWH perceived purely as a water demand management technology to a focus on its wider benefits e.g. mitigating surface water flooding through improved stormwater management. RWH systems examined in this thesis are now available which offer multiple benefits to both end-users and water service providers. The application of RWH in a dual purpose configuration (to displace potable water demands and control stormwater discharges) has seen increasing interest during the development of this thesis. However, the successful design of RWH as a stormwater management tool requires a series of calculations to be completed. To date, practitioners have frequently relied upon low-resolution heuristic methods which lead to a small range of configurations being deployed, with minimal demonstrable stormwater control benefits. In this thesis, full details of novel and traditional RWH technologies were identified and described. Empirical data was collected, both in laboratory conditions and at field sites, to identify the real world operating characteristics of a range of RWH configurations. Additionally a new time series evaluation methodology was developed to enable RWH systems to be designed and analysed. This method quantifies water demand benefits and also focusses on stormwater management metrics (i.e. largest annual discharge and total discharge volume per year). The method was developed to enable a range of RWH configurations to be evaluated at a given site. In addition, a decision support tool (RainWET) was developed and tested which enabled the methods to be deployed in real world settings. The application of the RainWET software allowed a UK-wide, time series analysis of RWH configurations to be completed and the holistic benefits of a range of dual purpose RWH systems to be analysed and described. Evidence from the UK study suggests that a traditional RWH installation (3000l storage, 300l/day demand and 60m^2 roof) installed at a house in a water scarce region (London, SAAR 597mm) was able to fully mitigate stormwater overflows over a 20 year analysis whilst providing a mean water saving of 31,255l/annum. An equivalent system located in the wettest region studied (Truro, SAAR 1099mm) saw mean reductions in the largest annual storm of 62% (range 35-86%) whilst satisfying a mean rainwater demand of 50,912l/annum. The study concluded that suitably designed dual purpose RWH systems offered better stormwater management benefits than those designed without a stormwater control device. In addition, the integration of smart RWH controls were shown to maximise stormwater control benefits with little or no reduction in a system's ability to satisfy non-potable water demands.

Acknowledgments

Firstly, I would like to thank my academic supervisors, Professor David Butler and Dr. Sarah Ward for their support and constant encouragement to make the most of the opportunity afforded by the STREAM Engineering Doctorate programme. In turn, I must thank all the administrators and technical staff involved in Challenge Weeks and Technical Skills Modules. Paul Jeffrey and Ewan McAdam and Tania Rice at Cranfield, your support and mentoring has been most welcome. I owe a lot to my fellow STREAMERS (Cohort Quattro) for their day to day support. Shenan, Hossein and Sarah, you have all engaged with my unquenchable desire to "*talk research*" and consequently, you have notably influenced the outcomes of my project. I would also like to thank the EPSRC for funding the programme, and must thank all those in the Centre for Water Systems who have guided this work over the years. To the Innovation Team at Severn Trent, you included me as one of your own, and provided essential advice and assistance over the programme. Bernadette Ryan, Bob Stear, Doug Clarke, Jo Claronino, and John Brewington, you have both been truly supportive of this project, I will always be grateful for you attitudes, time and input. To those who have engaged with me from water companies, rainwater companies and consultancies, thank you for giving me your data, guidance and time. Finally, I wish to thank my family, friends and especially, my wonderful wife Antonia. I am quite certain she still wishes we never started on this journey. To my parents, thanks for being there whenever we have needed. To my son and daughter, thanks for helping with the core research. I have enjoyed reading much of the key literature in your company; Flooding (Doctor Foster); Drought (Rain in Spain) and Rainwater Management Systems (Itsy Bitsy Spider).

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List of Abbreviations

A – Collection area

ARV – Attenuated Release Volume

ARVDt – Active Release Volume of Discharge

AWR – Alternative Water Resources

AWSS – Alternative Water Supply Systems

DN – Non-potable Water Demand

Dt – Demand During Time Interval

Ft – First Flush Losses

Ht – Hydraulic Filter Loss Coefficient

Mt – Mains Water Top-up During Time Interval

Ot – Overflow Volume During Time Interval

PRVt – Maximum Release Volume

Qt – Rainwater Inflow During Time Interval

RainWET – Rainwater Harvesting Evaluation Toolkit

RMS – Rainwater Management System

RPO – Reduction in Peak Overflow

RVDt – Passive Release Volume of Discharge During Time Interval

RWH – Rainwater Harvesting

S – Store Capacity

SC – Stormwater Control Capacity

SuDS – Sustainable Drainage Systems

Vt – Volume in Store During Time Interval

WSP – Water Service Provider

WSUD – Water Sensitive Urban Design

YAS – Yield After Spillage

YBS – Yield Before Spillage

YR – Rainwater Yield

Yt – Yield From Store During Time Interval

Chapter 1: Introduction to Rainwater Harvesting (RWH) Systems

1.1 Background

Rainwater harvesting (RWH) has been a staple of water provision around the world for millennia (Crasta, 1982, Radharkrishna, 2003). The technology involves the interception, capture, storage and use of rainwater falling on roofed areas (Herrmann and Schmida, 1999). In parts of the globe with low levels of economic development, the practice of harvesting rainwater still represents a key water resource (Islam *et al.*, 2010, Ishaku *et al.*, 2012, Al-Salaymeh *et al.*, 2011). More recently, RWH is becoming a key element in the water infrastructure of developed nations as it has a proven ability to displace potable water requirements within dwellings and commercial premises (Texas Water Development Board, 2005, Thomas *et al.*, 2014, Coombes *et al.*, 2000, Ward *et al.*, 2012c). To date, the majority of research on RWH has been as an alternative water resource (AWR) (Roebuck *et al.*, 2011, Fewkes and Butler, 2000, Campisano and Modica, 2012a). However, in the past few years increasing progress towards the deployment of RWH as a stormwater management technique and as a low carbon water resource have been made (DeBusk *et al.*, 2013, Campisano *et al.*, 2014, Gerolin *et al.*, 2010, Vieira *et al.*, 2014). This thesis approaches the use of RWH with the dual objective of drought mitigation (i.e. provision of an AWR) whilst controlling stormwater discharges. A spectrum of scenarios are evaluated from RWH systems that are designed solely for AWR through to RWH systems that focus on the stormwater control objectives as a primary design criteria.

In order to investigate the benefits of RWH on a holistic basis, the focus of this thesis is to quantify the ability of RWH systems to act as water demand management and stormwater management assets, whilst recognising that secondary benefits such as; greater resilience to droughts and floods; and the development of low-carbon water resources can also play an important role. As the research was delivered as part of an

Engineering Doctorate guided by Severn Trent Water’s strategic innovation requirements, the work focuses on RWH for UK houses whilst recognising that many aspects of the research are wholly applicable to residential or commercial premises on a global-scale.

Chapter 2 investigates the application of, and research into, RWH within industrial and academic literature. RWH systems can be deployed in a wide range of localities in both rural and urban settings. Although detailed RWH definitions are discussed in Chapters 2 and 3, Figure 1.1 describes traditional RWH in the context of a UK property. This thesis uses the term traditional RWH to reference configurations in the form set out in Figure 1.1 (whilst noting that a header tank may also be incorporated). Traditional RWH systems use the following key elements (Fewkes and Butler, 2000); 1) A roof area feeding rainwater into a gutter system; 2) Conveyance pipework feeding rainwater to a storage tank; 3) A filter and calmed inlet structure to maximise water quality; 4) A tank to store rainwater; 5) A pump to feed rainwater via pipework to non-potable applications (WC, laundry and garden); 6) A mains water top up to ensure a minimum volume of water is available within the tank to feed applications during periods when rainwater supplies have been exhausted.

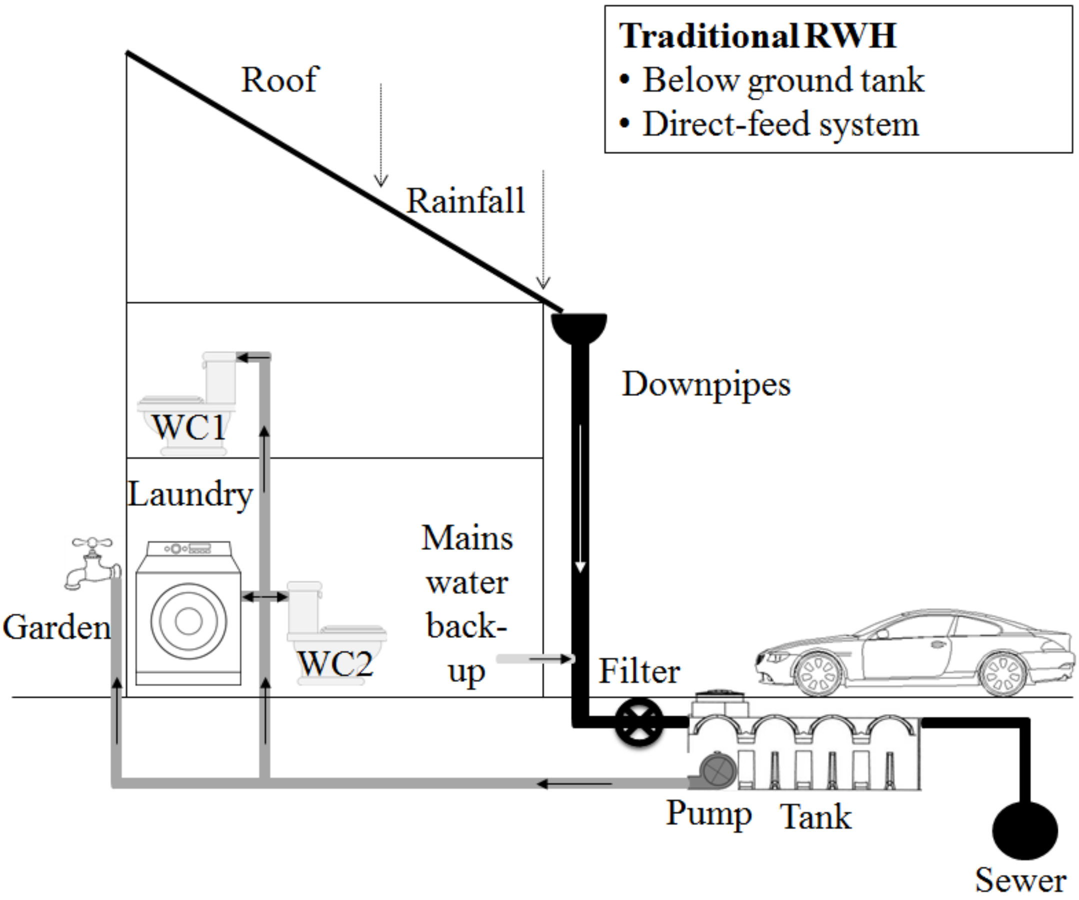


Figure 1.1 – Traditional Rainwater Harvesting Configuration

1.2 Aims and Objectives of Research

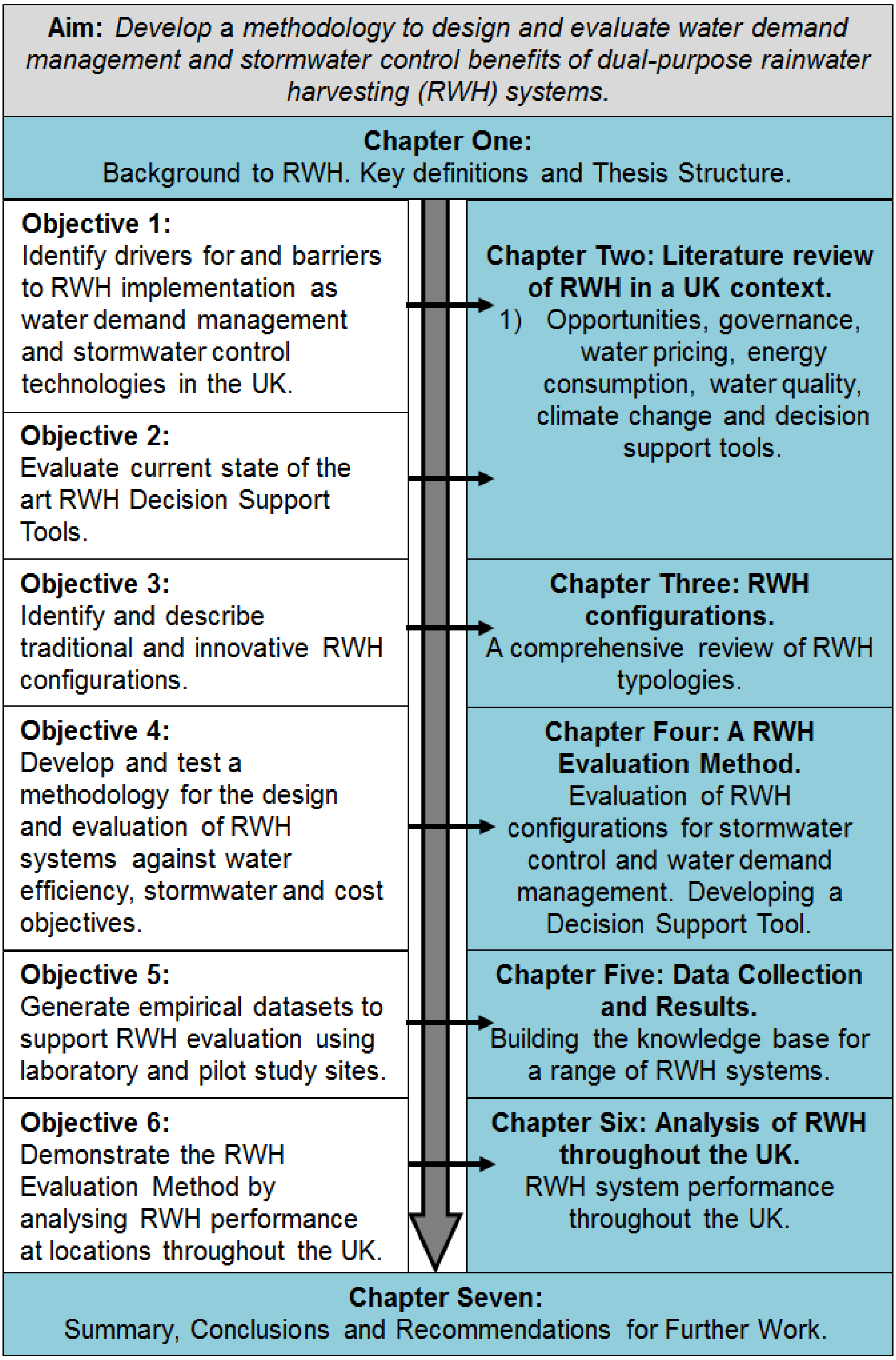
The discussion presented in Chapter 2 highlighted a number of gaps in knowledge relating to the use of RWH as a dual objective technology. Consequently, to undertake research to address some of these gaps, the following aim was defined:

Aim: *Develop* a *methodology to design and evaluate water demand management and stormwater control benefits of dual purpose rainwater harvesting (RWH) systems.*

To facilitate delivery of the Aim, this Engineering Doctorate Project investigates the ability of RWH systems to be deployed as a dual purpose technology that can displace potable water whilst reducing the total volume and peak discharge rates associated with storm events. With a focus on water demand and stormwater management, the study also investigates RWH in the context of new-build and retrofit scenarios; low-carbon water resources; and its potential role in climate change adaptation. Best practice examples and literature are reviewed from scenarios at a range of scales, however, the contribution to knowledge centres around design and evaluation of RWH in a domestic setting in the UK. The contents, aims and objectives of the thesis are summarised in Section 4, 1.4 Thesis Overview and described in Thesis Structure (Figure 1.2).

1.3 Objectives

1. Identify drivers and barriers to RWH implementation as water demand management and stormwater control technologies in the UK.
2. Evaluate current state of the art RWH Decision Support Tools.
3. Identify and describe traditional and innovative RWH configurations.
4. Develop and test a methodology (the RWH Evaluation Method) for the design and evaluation of RWH systems against water efficiency, stormwater and cost objectives.
5. Generate empirical datasets to support RWH evaluation using laboratory and pilot study sites.
6. Demonstrate the RWH Evaluation Method by calculating RWH performance at locations throughout the UK.



Aim: *Develop a methodology to design and evaluate water demand management and stormwater control benefits of dual-purpose rainwater harvesting (RWH) systems.*

Chapter One:
Background to RWH. Key definitions and Thesis Structure.

Objective 1:
Identify drivers for and barriers to RWH implementation as water demand management and stormwater control technologies in the UK.

Objective 2:
Evaluate current state of the art RWH Decision Support Tools.

Chapter Two: Literature review of RWH in a UK context.
1) Opportunities, governance, water pricing, energy consumption, water quality, climate change and decision support tools.

Objective 3:
Identify and describe traditional and innovative RWH configurations.

Chapter Three: RWH configurations.
A comprehensive review of RWH typologies.

Objective 4:
Develop and test a methodology for the design and evaluation of RWH systems against water efficiency, stormwater and cost objectives.

Chapter Four: A RWH Evaluation Method.
Evaluation of RWH configurations for stormwater control and water demand management. Developing a Decision Support Tool.

Objective 5:
Generate empirical datasets to support RWH evaluation using laboratory and pilot study sites.

Chapter Five: Data Collection and Results.
Building the knowledge base for a range of RWH systems.

Objective 6:
Demonstrate the RWH Evaluation Method by analysing RWH performance at locations throughout the UK.

Chapter Six: Analysis of RWH throughout the UK.
RWH system performance throughout the UK.

Chapter Seven:
Summary, Conclusions and Recommendations for Further Work.

Figure 1.2 – Thesis Structure

1.4 Thesis Overview

Chapter 2: Literature Review of RWH in a UK context

This thesis starts with a broad review of RWH in a UK context whilst drawing on knowledge from international research. The chapter focuses on the technical barriers and opportunities associated with RWH deployment. It closes with a review of current best practice for design and evaluation of RWH systems to fulfil Objective 2.

Chapter 3: RWH Configurations

Chapter 3 investigates the current best practice for RWH technologies. A wide set of configurations is identified from industry, academia and patent searches to enable a detailed description of existing and innovative technologies to be set out. Through deconstruction and recombination of the various components included in the RWH systems identified, a set of 72 technically viable RWH configurations are described.

Chapter 4: Developing a Rainwater Harvesting Evaluation Methodology

Chapter 4 builds on literature from Chapter 2 to enable the development of a time-series analysis methodology for RWH design and evaluation which focuses on water saving efficiency and stormwater management. The methods are described and implemented within a new decision support tool, the Rainwater harvesting Evaluation Tool (RainWET).

Chapter 5: Data Collection and Results

Chapter 5 describes a series of studies which generate empirical data relating to the performance of RWH systems. Furthermore, investigations at field study sites monitored throughout the research project are also reported. Analysis of the performance of the RWH systems investigated in these studies is used to support a contribution to knowledge alongside the development of the RainWET.

Chapter 6: Analysis of traditional and novel RWH systems throughout the UK

Chapter 6 analyses the simulated performance of a range of RWH systems at ten UK locations. The Rainwater Evaluation Method described in Chapter 4 is deployed to establish the performance of a range of RWH systems in terms of yield, peak stormwater overflow reductions and annual stormwater discharge volumes. This chapter synthesises the studies conducted in the thesis to demonstrate the performance of a range of traditional and novel RWH systems enabling cost-benefit trade-offs to be completed.

Chapter 7: Conclusions and Recommendations for Further Work

This chapter summarises key conclusions from the thesis, describes original contributions and investigates opportunities for further work.

1.5 Guidance from Engineering Doctorate Industrial Partner

In addition to those mentioned in the Acknowledgments, the research conducted in this study was initially steered by Severn Trent Water's Strategy Manager, David Essex. Severn Trent Water's sponsorship for the research was made based on a notion that RWH is poorly understood within UK water service providers, and that innovation can be driven through knowledge transfer. To paraphrase David Essex's view (2014): *"No longer do we concur with previous generations who believed having a WC at the bottom of the garden was a social norm. In the years ahead, we need to stop flushing potable water down the toilet in anticipation that our grandchildren will one day marvel at our generation's wasteful use of such a precious resource".*

Chapter 2: Literature Review of Rainwater Harvesting in the UK

2.1 Rainwater Harvesting – Background, Drivers, Barriers and Opportunities

This literature review investigates the drivers and changing socio-economic environment in which household RWH technology sits within a UK context and goes on to investigate factors affecting water quality and RWH modelling methods. In this chapter the following objectives are addressed:

1) Identify drivers for and barriers to RWH implementation as water demand management and stormwater control technologies in the UK; and

2) Evaluate current state of the art RWH Decision Support Tools.

Rainwater harvesting (RWH) has been practiced in semi-arid regions for many hundreds of years (Radharkrishna, 2003). For example, water storage structures in India were constructed to collect water from manmade rain catchments as illustrated in Figure 2.1a. Some Indian water infrastructure still in use dates back over 1000 years (Figure 2.1b) (Mishra, 2009). These ancient structures clearly illustrate the viability of utilising RWH as a water resource, and exemplify the benefits of high quality construction and the value of taking a long-term view when evaluating RWH benefits. Moreover the existence of these structures and their ongoing use illustrate that simple RWH systems are not a novel idea. These ancient RWH systems stand as a testament to the benefits that well implemented rainwater management systems can provide. Their longevity demonstrates the need to evaluate RWH systems over long time frames as both financial and environmental benefits may not be realised when short term financial goals are applied.

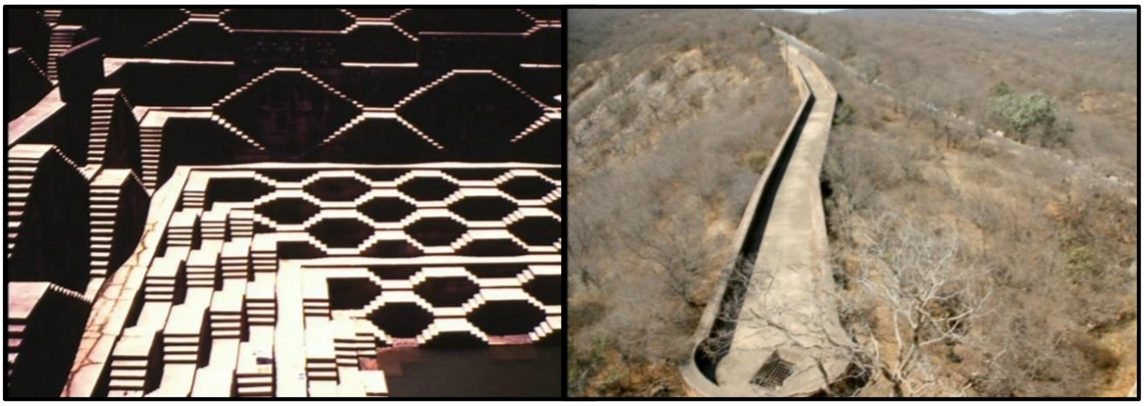


Figure 2.1 – a) Stone access well C1100; b) Water catchment canal C1600, India (Mishra, 2009)

Towards the latter half of the 20th century RWH uptake increased in Europe, USA and Australia as an alternative water supply option, (Herrmann and Schmida (1999), Ashley *et al.*, 2013, Wang and Blackmore, 2012). Parsons *et al.* (2010), MTW (2010) and Ward *et al.* (2013) observed that the UK has seen a relatively slow uptake of RWH when compared against other post-industrialised economies. Despite this, there are many RWH suppliers and thus design variations in use in the UK (UKRHA, 2014).

In the academic literature the first clear definition of a broad set of RWH design configurations was identified by Herrmann and Schmida (1999). Their research sets a baseline on which many other RWH studies and installations have been completed. It is evident from the four design configurations described by Herrmann and Schmida (1999) that residential RWH systems in the UK are typically designed to match configurations used in Germany, where the market for RWH has grown rapidly since the 1990's. The scale of the success of the German market is identified by Partzsch (2009) as representing 80,000 installations per annum at a value of 340 million Euros. With successful growth in the German market, UK based providers offer similar configurations to those available in Europe (Stormsaver, 2014, Rainwater Harvesting Rainwater Harvesting Ltd., 2014, Graf, 2014). Work has been ongoing over the last decade to evaluate and improve upon these design concepts, both within the RWH providers themselves and within academic research (Diaper *et al.*, 2001, Lazarova *et al.*, 2003, Ward *et al.*, 2009, Gerolin *et al.*, 2010, Parsons *et al.*, 2010, UK Rainwater Harvesting Association, 2014).

2.2 Rainwater Harvesting in the UK

Rainwater harvesting (RWH) in the UK is an under-utilised technology that can provide a simple, relatively low cost solution to a wide number of pressures associated with our water resources (Ward *et al.*, 2009, Roebuck, 2008, Environment Agency, 2011b, Woods-Ballard *et al.*, 2007). Academic studies, industrial guidance and commercial literature focus on offering RWH under a paradigm whereby the primary reason to install the technology is to provide an AWR to displace mains water in non-potable applications (Ward *et al.*, 2012a, Dixon *et al.*, 1999, (BSI), 2013b, Rainwater Harvesting Ltd., 2014). Until recently a key market driver for RWH installation at new build premises was the nationwide application of the Code for Sustainable Homes (CSH) (DCLG, 2010). However, this guide is no longer used at the planning application stage and the industry has seen a drop off in demand for RWH systems since the CSH was withdrawn. In contrast to the CSH’s focus on RWH as a water demand management opportunity, Kellagher (2011) set out a range of benefits that could potentially align to support RWH to become a technology that will support increased resilience to a broad range of potential threats such as reduced water availability or increased rainfall intensity associated with climate change. Defining and quantifying these wider benefits will become increasingly important as the magnitude and frequency of these threats increases as a result of population increases and climate change in the years ahead (Murphy et al, 2009). The UK RWH market remains relatively immature and is focussed on new build installations, although some retro-fitting has taken place, (MTW, 2010). Commercial RWH systems are typically more financially viable than those at a household scale as the cash savings generated by the reduction in water bills are more likely to outweigh the overall system costs (Stormsaver, 2014, Ward *et al.*, 2012c).

Watts (2003) describes: *“Connected, distributed systems… as both more fragile and more robust than isolated entities.”* As a decentralised tool that can supplement existing water supplies, RWH installations can be classed as a distributed system. However, RWH systems are not typically proposed as a standalone feature as, in a UK context, backup water supply is always available ((BSI), 2013b). Consequently, RWH systems represent an opportunity that can increase robustness without the undesirable increase in fragility of the overall water supply system (Lash *et al.*, 2014). If wider benefits such as stormwater control, lower energy demand, lower whole life costs and lower carbon footprints can be aligned then, from a technological perspective at least, the implementation of RWH in the UK could grow in a manner akin to the recent photo-voltaic installation boom (Dominiczak, 2015). Of course governance, policy, business frameworks and social interactions all have a significant part to play in defining the success or failure of any innovation, even those that have been in use by early-adopters for thousands of years (Ward, 2016). Ward (2010) developed a framework to better understand how RWH technologies could be improved to better satisfy the demand of the UK’s “water management market” and represented the first step in the process to overcome the barriers between the opportunity and it’s market (Bond and Houston, 2003). Building on this concept, Ward (2010) called for technological development which, if achieved could see disruptive innovations change the face of the UK RWH sector over the coming decade (Matheson, 2013).

2.3 Alternative Water Resources

Although often well utilised in developing nations (Taffere, *et al.* 2016), alternative water resources (AWR) are under exploited in the UK (Ward *et al.*, 2013). They represent a group of non-municipal water supply opportunities defined on a catchment scale by the Australian National Water Commission (2005) as including; “*seawater, saline* *groundwater, urban stormwater, and wastewater (e.g. treated sewage effluent).”* Frequently, they are also referred to as Alternative Water Supply Systems (AWSS) (Memon and Ward, 2014). In addition to these, plot scale AWR can include boreholes, RWH and greywater recycling (Environment Agency, 2011b, Environment Agency, 2011a, Venhuizen *et al.*, 2013, Zhang *et al.*, 2010). The Organisation for Economic Co-operation and Development (OECD, 2009) use the term “alternative water systems” defining them as differing *“from prevailing ones in at least one of two dimensions; i) they recycle and reuse water for a variety of uses; ii) they can be based on decentralized infrastructures, producing water where it is consumed.”* This definition captures a potential driver for growth of AWR as decentralised systems can offer greater resilience to climate threats (Schuetze and Chelleri, 2013). AWR are frequently associated with off-grid, decentralised water resources (Mankad, 2012, Mankad et al, 2011, Zhang *et al.*, 2009). In addition, at a regional scale, the practice of coordinating or developing catchment based strategies using decentralised water assets can also be termed decentralised water management (Schuetze and Chelleri, 2013).

In the UK, the development of more flexibility for WSPs in the form of market reform will permit WSPs to provide water as a wholesaler whilst they or a third party provide the retail services to non-domestic customers from 2017 onwards (HM Government, 2014). Separating the retail and wholesale businesses has been set out as a potential driver to see wider implementation of AWR as retailers will be increasingly incentivised to support their customers to reduce water consumption and wastewater discharges (Defra, 2013). Within this, RWH is being promoted as a potential technology to provide non-potable water within commercial developments. RWH at non-commercial developments typically has longer payback periods than commercial development sites (Roebuck *et al.*, 2012). The tools and methods described in Roebuck’s research include a whole life cost method for evaluating RWH designs. However, to date the focus of RWH design as an AWR is limited to traditional RWH configurations. Further work is warranted in this sphere to appraise alternative RWH technologies building on the methods described by Roebuck *et al.* (2012). Chapter 4 describes the development of a new methodology that satisfies this knowledge gap. In contrast Kellagher (2011) and (Gerolin *et al.*, 2010) demonstrated that many other benefits can be identified which could be integrated into the assessment of RWH benefits as a tool for supporting the delivery of AWR in the UK. In summary it is evident that AWR uptake in the UK could be further supported by suitable design and evaluation tools. The design of such tools must enable users to understand the benefits associated with stormwater management alongside those traditionally associated with AWR (Kellagher, 2011).

2.4 Rainwater Harvesting Definitions

Literature from across the globe often uses the term “rainwater harvesting” and consequently it has been used in a wide range of contexts. A review of the term has been undertaken using a spectrum to contextualise it’s meaning in a UK setting as described in Figure 2.2.

The two extreme ends of the RWH definition spectrum can be identified as:

No Rainwater Use: *“Rain which is harvested and returned immediately to the ground.”*

This context is referred to in some Chinese case studies (Jianbing *et al.*, 2010), although it must also be recognised that China also has case studies of highly sophisticated development-scale stormwater harvesting systems such as the Spring Dew Mansion Area in Shanghai (Lu *et al.*, 2013). In UK terminology, the above definition would be referred to as a “soakaway” or “raingarden” as water is not being harvested for use, but is arguably available for groundwater recharge (Bray *et al.*, 2012, Woods-Ballard *et al.*, 2015).

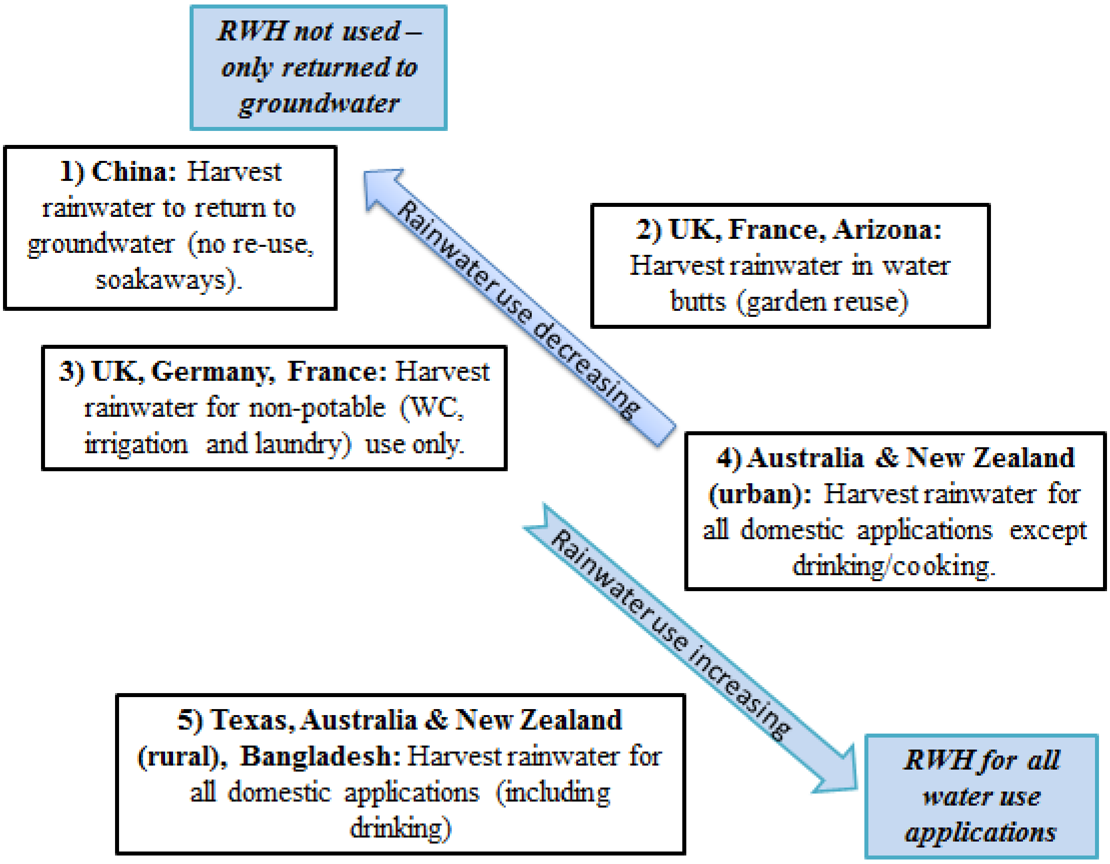
The opposite end of the RWH definition spectrum can be described as:

Total Rainwater Use: *“Rain which is harvested, stored and used for all potable requirements, including human consumption.”*

In Texas, water from RWH systems is frequently deemed to be appropriate for all potable uses and thus the local design documentation refers to RWH systems as providing water for all household water requirements (Texas Water Development Board, 2005). Additionally, in developing countries, harvested rainwater is often considered to be the safest source of water available and will therefore be used for all applications typically after boiling if it is being consumed (Ishaku *et al.*, 2012, Al-Salaymeh *et al.*, 2011, Islam *et al.*, 2010).

In an Australian context, RWH systems are frequently used for applications that a UK water user would perceive to be inappropriate (Ward *et al.*, 2012a). An excellent nationwide infrastructure combined with strong UK governance surrounding water management gives water users a perception that only municipal supplies should be used for washing, drinking and cooking. Contrasting this, in Australia, rainwater is harvested and used for a wide range of household applications. Many RWH systems in Australia will see rainwater used for WC, laundry, showering and bathing facilities, with potable water supplies used for cooking and drinking alone (Coombes *et al.*, 2000). In rural areas, large RWH systems (household tanks can often hold >30,000 litres of storage (Burns *et al.*, 2014)) can represent the only water available and will be used for all water requirements (Ahmed *et al.*, 2010). This definition of RWH sits towards the “Total Rainwater Use” end of the spectrum, akin to the definition of RWH in the Texan context.

In the UK, RWH will often refer to water butts (also referred to as rain barrels in the USA) which provide water solely for garden usage. The second meaning in a UK context is for RWH systems that provide water for WC’s and laundry applications. These concepts sit in the centre of the RWH definition spectrum, as the water is being harvested for use (with minimal treatment) on a fit-for-purpose basis, but not for potable or bathing applications. With RWH systems being used across the globe ranging from routing downpipes to soakaways through to; a precious resource; the only water available for drinking, it can be argued that the UK values rainwater more greatly than those regions where it is used for groundwater recharge, but less than water stressed regions such as Texas and parts of Australia. Figure 2.2 describes the spectrum of definitions to demonstrate the broad use the phrase "rainwater harvesting" in the literature reviewed.



Sources: 1) (Jianbing *et al.*, 2010), 2) (Ward *et al.*, 2009, Lansey *et al.*, 2013) 3) (Roebuck *et al.*, 2011, Herrmann and Schmida, 1999, Saint-Cast *et al.*, 2013) 4) (Coombes *et al.*, 2000, Umapathi *et al.*, 2013) 5) (Simmons *et al.*, 2001) 5) (Venhuizen *et al.*, 2013, Islam *et al.*, 2010, EnHealth, 2010)

Figure 2.2 – A spectrum of RWH definitions from the literature

With the focus of this thesis investigating RWH in a UK context, the definition of RWH as a system that collects rainwater for use in garden, WC and laundry applications as illustrated in the configuration described in Figure 1.1 is applied throughout this study. A key aspect of the benefit of RWH installations in a UK setting is the ability for users to reduce their water and sewerage bills and thus generate a financial benefit. The unit cost of water in the UK varies regionally. Furthermore, the true price of water (and the infrastructure required to treat, deliver and remove it) is not necessarily fully encompassed within householder's water bills.

2.5 Putting a Price on Water: An Under-valued Commodity?

Hubbert (1956) set out the concept of “peak oil” by illustrating that the global reserves of economically available oil would rise to a peak and fall away as increased costs drove societies to seek alternative energy resources such as nuclear power. Due to the nature of the water cycle, direct application of the peak oil concept to water resources is only appropriate where fossil aquifers are being utilised as a water resource (Berger and Finkbeiner, 2010). However, Gleick and Palaniappan (2010) set out a framework to define “peak water” under a range of sub-categories, taking into account the cost/benefit setting. Their concept of “peak ecological water” is the point at which the value of water obtained from a catchment is equal to the value of the ecological services provided by water as illustrated in Figure 2.3. Beyond this point, further water abstraction has a higher cost on the ecosystem than the benefit derived from abstracting the water. Their application of a holistic assessment of the true value of water differs from the UK’s current water abstraction policies which currently attribute a low value to the water resource itself (Fenn, 2012).

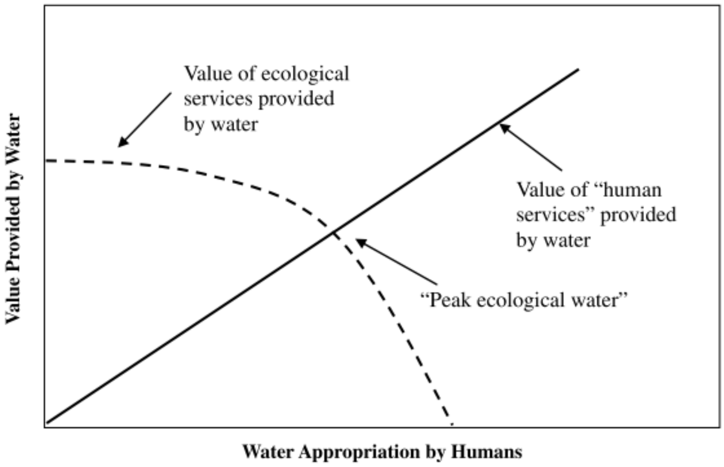


Figure 2.3 – Defining “peak ecological water” (Gleick and Palaniappan, 2010)

With global population projected to reach 8.97 billion by 2050 (United Nations, 2004) pressure on our water resources will continue to increase. In the UK, the population is projected to reach 73.3 million in 2037, an increase of 9.6 million over 25 years (ONS, 2014). The use of RWH technologies represents an opportunity within the UK (and elsewhere) to provide an AWR to address the pressures on peak ecological water posed by population growth and resource depletion (Ahmed *et al.*, 2011). The increasing importance of achieving more sustainable water management practices represents a potential driver for RWH applications. Wider benefits of RWH are mentioned in the literature, but infrequently investigated in detail ((BSI), 2013b, Herrmann and Schmida, 1999, Liuzzo *et al.*, 2016, Amos *et al.*, 2016). Further investigation is therefore warranted into the potential for RWH to provide multiple benefits that reach beyond its role as an AWR. The literature associated with using RWH for stormwater control and associated flood mitigation benefits is investigated in Section 0 2.8 Rainwater Harvesting for .

The potential for RWH systems to generate a satisfactory yield and thus provide water demand management benefits is investigated in the following Section.

2.6 The Traditional Rainwater Harvesting Motive: Drought Mitigation

The UK is portrayed in national press as a country with ample rainfall (Daily Express, 2014, Daily Telegraph, 2014). However, it is inappropriate to view the UK as a homogenous unit in terms of rainfall patterns, water consumption and water availability. The Environment Agency (2012) report on RWH for farm usage described rainfall variability for England and Wales as illustrated in Figure 2.4.

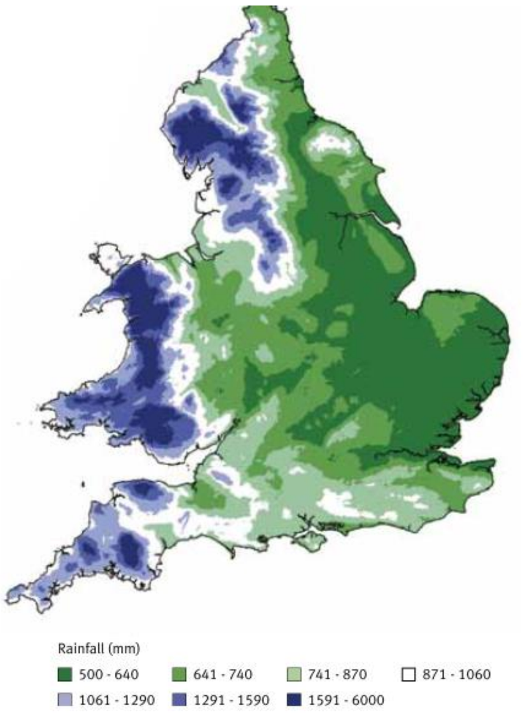


Figure 2.4 – Annual rainfall variability in England and Wales, (Environment Agency, 2012)

The marked variability in annual average rainfall (from 500mm to 1500mm+), poses significant challenges to the stakeholders responsible for water management in the UK. The low rainfall availability in the south east of the UK is compounded by the high population density in this region. Figure 2.5 illustrates water availability/capita as defined by Royal Geographical Society (2012) with the south-east's dense population and high water demand coinciding with the UK's driest region.

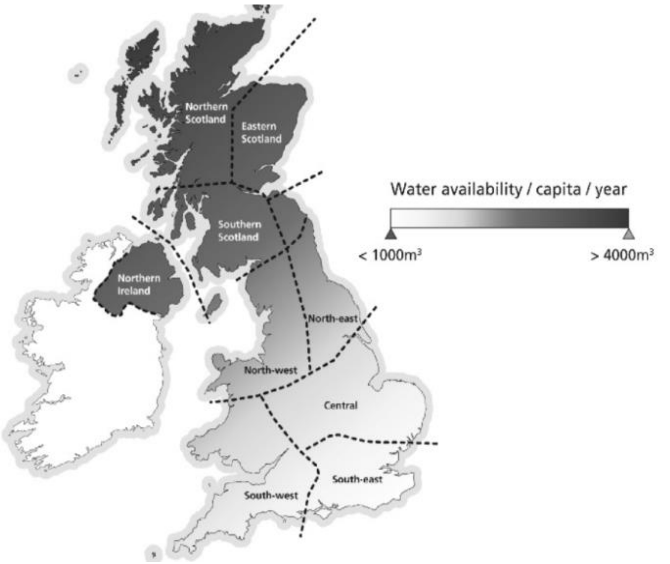


Figure 2.5 – Water availability per capita (Royal Geographical Society, 2012)

The developed nature of the UK means that centralised water infrastructure is available nationwide, though private water supplies are also common in some areas (DWI, 2016). As a consequence of historic oversized reservoir schemes such as the Kielder Reservoir, some researchers argue that there is no longer a need for construction of large scale capital projects to satisfy our water demands (Mcculloch, 2006). The developed nature of the UK along with the comprehensive regulatory framework applied to the water industry and planning process has ensured that the water service providers (WSPs) and other key stakeholders continue to improve their water infrastructure in small steps to ensure the supply-demand balance does not pose a risk to society (Severn Trent Water, 2009). A recent threat to the UK’s water infrastructure, the 2010-12 drought, was one of the worst on record in parts of the UK (Met Office, 2013b). A hydrological drought caused by a prolonged period of lower than average rainfall left WSPs with limited resources as reservoir levels were depleted due to lack of rainfall as illustrated in Figures 2.6-2.8. For some WSPs, their ability to supply water was stretched to its limit and large-scale advertising campaigns were rolled out to encourage increased water efficiency (Waterwise, 2013). These campaigns were continued through the summer of 2012 which lead to some confusion with customers as the summer period was wetter than average. The rains in late 2012 were of such magnitude that despite the dry start to the year, many locations experienced flooding and ultimately the year was the second wettest (across the UK) since records began in 1910 (Met Met Office, 2013a). The high variability of rainfall in the UK was demonstrated during 2012 with Thames Water having to cope with extremes of drought and flooding in a single year as illustrated in Figure 2.6.

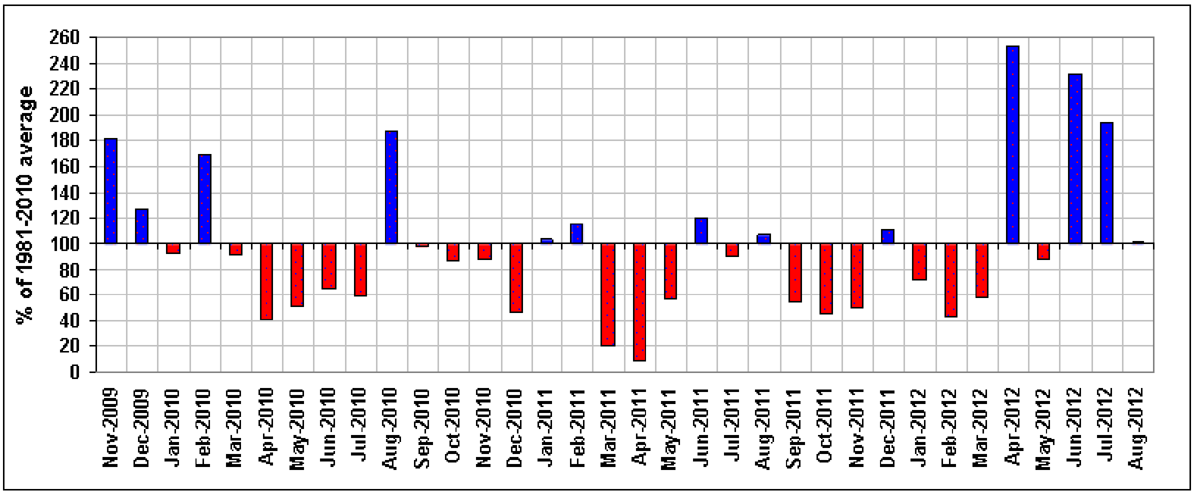


Figure 2.6 – Monthly rainfall (% of 1981-2010 average) for Lowland England 2010-12 (Met Office, 2013b)

Figure 2.7 – Thames Water's 2012 drought campaign poster (Waterwise, 2013)

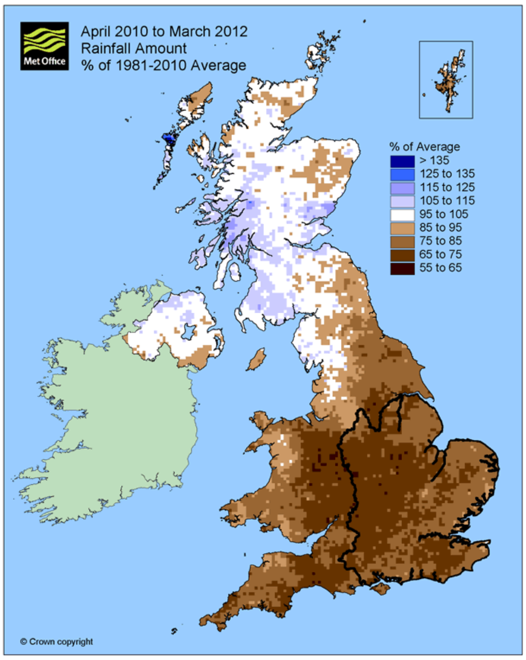


Figure 2.8 – Map illustrating spatial distribution of low rainfall during 2010-12 drought (Met Office, 2013b)

Following the end of the 2010-12 drought there were calls for a re-think of the UK's water management practices to ensure our water infrastructure will be able to cope with such drought events in the future (Fenn, 2012). Fenn (2012) undertook work on abstraction licensing on behalf of Ofwat to build and test a decision support tool to enable an incentive mechanism to be put in place. This was intended to encourage WSPs to maximise water abstraction when there is least impact on the resource. This mechanism, "The Abstraction Incentive Mechanism (AIM)" (Fenn, 2012), was designed to allow WSPs to abstract more water when river levels were high, to increase their ability to cope when flow rates were lower than average. Supply-side tuning of water abstraction practices can play a role in ensuring water availability in times of drought in the decades ahead. However, demand-side measures such as RWH have been shown to reduce household water usage by between 30-50% at a household scale, an order of magnitude greater than the AIM proposal (Roebuck *et al.*, 2011, Rainwater Harvesting Ltd., 2014, Stormsaver, 2014, Burns *et al.*, 2014). Water savings are typically even greater still at commercial RWH systems (Ward *et al.*, 2012c). Internationally, some best practice exemplars have claimed RWH can provide development-wide water savings in the region of 60% (Coombes *et al.*, 2000). The literature illustrates that widespread uptake of RWH at UK houses could see significant reductions in the total water required for supply (Ward, 2010).

RWH is widely cited as a potential solution to the pressures on water infrastructure (Partzsch, 2009, Ward *et al.*, 2012b, Ashley *et al.*, 2013, Diaper *et al.*, 2001, Garcia-Montoya *et al.*, 2016), yet evidence of uptake remains low. Conte *et al.* (2012) observed that excessive water use is “damaging European groundwater and rivers” which the EU Water Framework Directive 2000/60 requires to be classed as having “good status” before 2015. Taking forward the idea that ecosystem management can be achieved on a local scale by appropriate RWH uptake, a review of global scale drivers is also appropriate. The impacts and consequences associated with extreme rainfall/dayroughts are likely to be exacerbated by climate change (Murphy et al 2009). These threats and their consequences are increasingly evident within European policy. A 2009 EU white paper (Commission of the European Communities, 2009, p8) called for EU wide action; *“To promote strategies which increase the resilience to climate change of health, property and the productive functions of land, inter alia by improving the management of water resources and ecosystems.”*

The UK’s response to this includes the National Adaptation Programme: Making the country resilient to a changing climate (HM Government, 2013). This document and programme describes water efficiency measures as low-regret actions, which have the ability to provide benefits under virtually any future climate scenario. The paper goes on to state that: *“By the 2050s, the number of people in the UK living in areas affected by water supply-demand deficits could be between 27 million and 59 million”* (HM Government 2013, p16). It should be noted that the upper estimate of this range would represent 80-90% of the UK’s current population. The document concludes by allocating actions to address priority risks, including for WSPs to *“continue to deliver water efficiency campaigns to households and businesses”* (HM Government 2013, p28).

Within the water industry both drought and flood risks are widely recognised to require ongoing investment in order to maintain resilient water systems that are able to cope in a range of future scenarios (Environment Agency, 2009). The delivery of sustainable investment strategies is underpinned the economic strategies associated with the UK's WSPs.

2.7 Water Economics: Water Service Provider (WSP) Structures, Governance and Pricing

Water pricing in the UK is fixed by the WSPs under an annual pricing regime which is set out on a five yearly business plan, described as the Asset Management Plan (AMP) (Ofwat, 2013a). Each company holds a regional monopoly to provide water and sewerage services, although a number of the smaller companies only provide water supply services. Ofwat's role as financial regulator ensures the WSPs have robust business plans to support their charging schemes. As a result of these arrangements, the WSPs set out a range of different pricing structures which see domestic customers charged for water used and wastewater discharged on a flat rate or on a volumetric basis from water meter readings. Meter coverage varies by region, with only 40% of domestic customers charged by metered water supply (Ofwat, 2013b). In water stressed regions, Ofwat has permitted WSPs to provide compulsory water meter installations as part of a water demand management strategy (Ofwat, 2013b). The remaining 60% of properties (which are unmetered) typically pay quarterly water and sewerage rates based on the rateable value of their house. Consequently, the majority of UK water users have no financial incentive to save or reduce their water usage, unless they opt to have a meter installed. In order to review the variability of water charging practices throughout the UK a thorough search for WSP charging schemes was conducted. Table 2.1 collates this information.

Table 2.1 – typical annual water and sewerage charges for UK (England and Wales) houses (adapted from (Water UK, 2016))

Water & sewerage companies	Average Water Bill (£)	Average Sewerage Bill (£)	Average Combined Bill (£)
Anglian	182	229	411
Dŵr Cymru	181	257	438
Northumbrian (excluding Essex & Suffolk)	174	203	378
Severn Trent	172	157	329
South West	219	319	488
Southern	147	264	422
Thames	198	176	374
United Utilities	201	214	425
Wessex	234	226	460
Yorkshire	162	204	366
Water only companies			
Affinity Water Central region	174	-	-
Affinity Water East region	174	-	-
Affinity Water Southeast region	206	-	-
Bournemouth	136	-	-
Bristol	175	-	-
Dee Valley	145	-	-
Portsmouth	98	-	-
South East	198	-	-
South Staffordshire	142	-	-
Sutton & East Surrey	186	-	-
Essex & Suffolk	236	-	-
Cambridge	127	-	-
National average Bill	**183**	**206**	**389**

Although the data reported above is of interest to consider an average user in each region, a calculation of annual volumetric charges for a nominal 3 person family (assuming demand of 150 l/c/d (Butler and Memon, 2006)) demonstrates that water costs vary significantly throughout the UK. A family in South West Water's region (£5.52/m^3) (South West Water, 2016) would be charged £906/annum (plus standing charge). In contrast the same household in the Thames Water region (£2.10/m^3) (Thames Water, 2016) would pay £344/annum (plus standing charge). It is apparent from the rates that there is potentially 250% greater incentive to install water demand management devices in the South West Water region when compared against the

Thames Water region. It follows that installation of household RWH generates 2.5 times greater cash benefit to a householder in Devon when compared to a similar house in London. However, this assessment is too simplistic. The statement is only valid when assessing water demand management measures such as dual flush toilets and low flow showers. A further review of the terms and conditions set out in each WSP's charging scheme identified that, since 2014, South West Water and Severn Trent Water have required customers using rainwater for non-potable applications to monitor and declare their rainwater usage. They must subsequently pay relevant wastewater charges on the rainwater used (South West Water, 2014a, Severn Trent Water, 2014). Consequently, the financial benefit of installing RWH in these two regions is significantly reduced leading to increased payback periods. The practicalities associated with WSP's installing metering, reading the meters and policing the use of harvested rainwater are not clear, as it is seemingly unrealistic to rely on customers to actively report their rainwater use and effectively request their bills are increased. Research conducted by WRc (2012) was commissioned by Thames Water and Severn Trent Water to investigate the desirability and viability of charging for greywater and (used) harvested rainwater discharges to sewers. This study states (WRc, 2012, p56):

"The Walker review wants to incentivise rainwater systems that remove surface water run-off from sewers and asks water companies and Ofwat to identify how this might be achieved. Ofwat accept the position of the Walker Review i.e. not to charge and to review this in the long run. Thus currently there is little potential to charge household customers for increased wastewater costs."

In contrast to this statement some departments in WSPs see RWH systems as a risk to the company's revenue as they can enable customers to reduce their wastewater charges without necessarily reducing the wastewater volumes / loads discharged to the sewers. On the one hand, research is ongoing into the opportunities to shift the balance towards widespread uptake of RWH, meanwhile some WSPs have adjusted pricing policies to dis-incentivise RWH uptake.

Where RWH systems are installed at metered properties, the savings in water (and if applicable wastewater) costs can give customers a direct financial benefit in the form of reduced water bills. This financial benefit is frequently identified in both UK and international RWH literature to be the main (and sometimes the sole) driver for RWH uptake (Roebuck *et al.*, 2011, Burns *et al.*, 2014, Ward *et al.*, 2012b, Wang and Zimmerman, 2014, DeBusk *et al.*, 2013). RWH research has increasingly recognised that RWH installations in the UK tend to have low financial benefits, as a consequence of the low water prices set out in the WSP's charging schemes (Roebuck *et al.*, 2012, Roebuck *et al.*, 2011). Even in the south west of the UK where water and sewerage unit charges are highest at £5.52/m^3, a householder would need to utilise 18,120 litres of harvested rainwater to save £100. This equates to over 3,000 toilet flushes (for a 6 litre toilet cistern) or 360 loads of washing (with a 50 litre cycle). However, the recent shift in South West Water's policy to charge for rainwater disposed to sewerage networks makes this assessment invalid as the legitimate saving would now be reduced to £2.05/m^3. The shifting nature and consequent uncertainties of future WSP charging policies relating to RWH represents an area of potential error in existing RWH evaluation studies. Long-term financial savings estimated for RWH systems in existing studies (Roebuck *et al.*, 2011) could be further penalised by financial policies within WSPs. As revenue generating departments seek to penalise rainwater use, it is necessary to investigate broader benefits such as stomwater control and flood mitigation. The potential for RWH to perform as a source control technique is reviewed in the next Section.

2.8 Rainwater Harvesting for Stormwater Control

RWH systems have the potential to mitigate flooding by reducing stormwater discharges and controlling peak stormwater runoff rates (Sample and Liu, 2014, Petrucci *et al.*, 2012). However, with the low level of uptake in the UK to date, the first scale where RWH could potentially have an impact on flooding is at a plot / local sewer network scale. Consequently the opportunity to mitigate flood risk may be centred around urban flood risk reduction by using RWH as a source control device (Woods-Ballard *et al.*, 2015) as part of a stormwater management strategy (Ward, 2010).

2.8.1 Rainwater Harvesting as a Stormwater Management Tool

Stormwater management is a growing field of interest in relation to RWH systems in the UK ((BSI), 2013b, UKRMA, 2016). RWH is cited as a source control technology in the updated Ciria SuDS Manual (Woods-Ballard *et al.*, 2015) and is now referred to in policy documents such as the London Plan (Greater London Authority, 2015). Designers of sustainable drainage systems (SuDS) are thus increasingly supported and encouraged to identify and incorporate the source control benefits of RWH systems for new build and retrofit stormwater management schemes (Stovin and Swan, 2007, Raja Segaran *et al.*, 2014).

Terminology varies internationally and SuDS are also referred to as a component of; green infrastructure (GI), stormwater management (SWM), best management practice (BMP) approaches, low impact development (LID), water sensitive urban design (WSUD) and integrated water management (IWM). Fletcher *et al.* (2014) undertook a global review of terminology in the sphere of integrated water management which highlights the complexities of the many phrases used to describe products, processes and approaches associated with sustainable water management. Figure 2.9 charts the evolution of the use of a number of these phrases to illustrate the growing research trends in these fields.

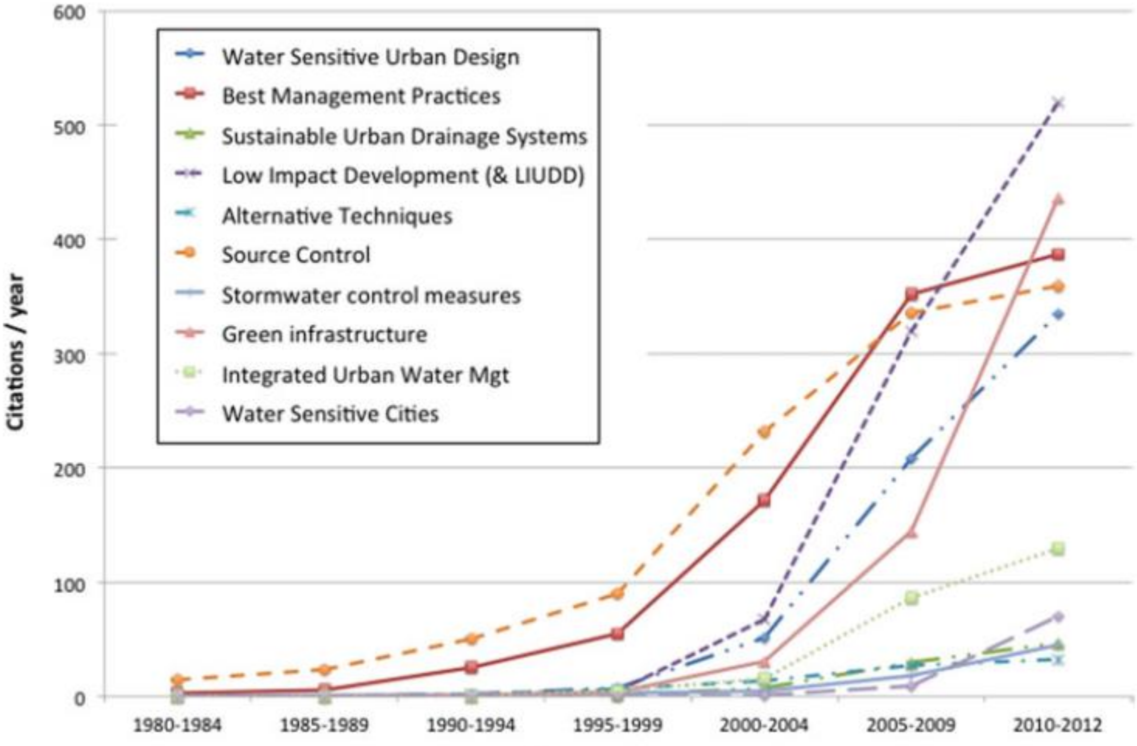


Figure 2.9 – Charting progress and use of sustainable water management terminology in the literature (Fletcher et al. 2014)

Regardless of terminology, the emphasis of research into these fields has been on increasing the sustainability of our water infrastructure. Elkington (2004) described sustainability in terms of The Triple Bottom Line (TBL) referring to the three pillars of sustainability; economic, social and environmental values. In industry literature, these are sometimes referred to as the 3 P's; People; Planet and Profit (International Water Association, 2016). Although methods vary, the balance of these three factors is frequently assessed in the planning stages of water infrastructure projects. Capital expenditure for these projects must be delivered; on budget (economic); to satisfy society's water/wastewater demands (social); whilst minimising damage to the environment. In addition to minimising damage to the environment, technologies that can be deployed that improve the environment (or at least reduce the harm), whilst having social benefits at lower whole life costs, can give a resulting outcome that is more sustainable than the status quo. Hence, the deployment of RWH in appropriate locations has the potential to increase the sustainability of water infrastructure under all 3 P's. This represents an under-valued aspect of RWH deployment, as there is potential for RWH systems to provide financial, environmental and social benefits (Ward *et al.*, 2012a). A key aspect identified here is for RWH systems to be utilised as source control tools, to minimise impacts and consequences associated with intense rainfall events in urban settings and hence reduce the costs, social harm and damage to the environment associated with sewer flooding (DeBusk *et al.*, 2013, Gee & Hunt, 2016).

In order to investigate RWH as a source control technology within existing developments and their SuDS systems in the UK, a comprehensive search was conducted of industry documentation, via UK web-searches, through a review of case studies identified in the academic literature and through discussions with industry professionals (Rainwater Harvesting Ltd, 2013b, Hyett, 2016). Outside of projects associated with the research presented in this thesis, no examples were identified whereby RWH has been installed with the specific objective of managing roof-runoff in a manner which fully complies with UK drainage regulations. All case studies that were identified describe the RWH systems as a sustainable technology that is able to provide an AWR. In order to fully frame the opportunity RWH poses for source control in the UK, a wider review of the policy surrounding surface water management in England and Wales is warranted.

2.8.2 Source Control in the UK: The Regulatory Framework and Design Process

SuDS are implemented to mimic the natural hydrological processes within a developed catchment. In order to support the successful implementation of this approach in England and Wales, the SuDS Management Train was defined. This seeks to minimise surface water runoff and pollution using the following hierarchy; 1) Prevention, 2) Source Control, 3) Site Control, 4) Regional Control (Woods-Ballard *et al.*, 2015). Practitioners designing surface water management systems in England and Wales are thus encouraged to maximise source control opportunities before considering site wide or regional stormwater control strategies. Despite this, there remains a prevalence of end-of-pipe solutions (e.g. geocellular storage and ponds) as these are frequently deemed to be the easiest way of complying with the legislation (Hughes, 2009). A more sustainable option could include drainage strategies which allow surface water to be managed at its source whenever viable in line with SuDS principles. Woods-Ballard *et al.* (2015), identifies solutions such as; green roofs; infiltration chambers; water butts; and RWH as potential technologies that can contribute to a source control strategy. Where calculations show the design rainfall event cannot be wholly addressed through local source control solutions, green infrastructure or below ground pipework is used to route surface water to regional control structures such as infiltration basins and attenuation ponds. Finally, where no other solution can be identified, below ground storage tanks with throttled outlets and regional control ponds are utilised (Woods-Ballard *et al.*, 2015). With the above hierarchy in mind designers are encouraged to maximise the benefits of a given source control technique (in this case RWH), to minimise additional downstream storage volumes within a site-wide drainage design to achieve a best practice SuDS. Figure 2.10 illustrates a high amenity value SuDS system.

Figure 2.10 – Best practice SuDS at The Triangle, Swindon (Ciria, 2015)

In England and Wales, drainage design for new developments must comply with a set of stringent design standards (Kellagher, 2012, DCLG, 2012). To oversee this process, hydraulic calculations must be submitted to the Environment Agency (EA), Internal Drainage Board or Lead Local Flood Authority who, in their regulatory role, ensure compliance of new drainage systems. In the context of drainage design, RWH can reduce storm runoff volumes and rates (Leggett and Shaffer, 2002, DeBusk *et al.*, 2013, Burns *et al.*, 2014). However, the magnitude of such benefits cannot be generalised as a large number of site specific parameters must be evaluated. These will typically be associated with antecedent rainfall, yield and non-potable water demand. Each of these factors must be considered when appraising a RWH system's ability to function as a source control technology. The EA's current position on RWH as a surface water management technique is that it can contribute as part of a SuDS, and that each site should be appraised and modelled in detail to ensure these benefits are appropriately assessed in the site-wide drainage design (Parkes et al, 2010).

The pressures of population growth and climate change are likely to be further exacerbated by user behaviour associated with urban creep (Grant, 2011). The 'do nothing' scenario leads to increased CSO spills and sewer flooding as permeable surfaces continue to be paved over. Throughout the UK urban creep is increasingly recognised as a problem whereby contributing areas continue to increase even after developments have been constructed. One study (UKWIR, 2010) reported an increase in CSO spills of 10%, 22% and 41% for three case study sites modelled with the measured urban creep areas added to the hydraulic models. Changes in impermeable surfaces since construction are illustrated for one of the case study catchments in Figure 2.11.

Figure 2.11 – Change in impermeable surfaces since construction (orange=paving, blue=roofs) (UKWIR, 2010)

2.8.3 Rainwater Harvesting for Source Control: Existing Approaches in a UK Context

Practitioners and researchers have suggested that a deeper understanding of source control benefits associated with RWH is warranted (Kellagher, 2011, Gerolin *et al.*, 2010). Debusk and Hunt (2012) reached the following conclusion in a broad literature review on RWH; *“There is very little research on the stormwater management benefits of RWH”.* The research made the following recommendations; “*Modelling of stormwater benefits should be further investigated… Installation, monitoring and calibration and verification of RWH linked stormwater models* [should be developed].”

The earliest UK text identified which seeks to appraise the source control benefits of RWH systems on a household scale in England and Wales dates back to 2007. Kellagher and Maneiro Franco (2007) undertook a hydraulic modelling study to assess the overall reduction in stormwater runoff volumes and peak flow rates from a housing development where a single large RWH tank was proposed. Another study by Memon *et al.* (2009)

modelled a development of 200 properties and also concluded that RWH can reduce peak flows in downstream sewers. Gerolin *et al.* (2010) set out a methodology based on demand for water from a RWH system freeing storage capacity for the next storm. This study again concluded that RWH systems can positively manage stormwater successfully when the non-potable demand exceeds the yield. The work was extended by Kellagher (2011) whereby a number of RWH systems in a residential housing development were monitored. The research is viewed as best practice as it has now been incorporated into the British Standard for Rainwater Harvesting and the SuDS manual ((BSI), 2013b, Woods-Ballard *et al.*, 2015). Further work is described in Kellagher and Gutieriez-Andres, 2014. A detailed review of the current application of this methodology is completed in the next Section.

2.8.3.1 The British Standard for Rainwater Harvesting

The first version of the UK's British Standard for RWH, BS8515:2009; Rainwater harvesting systems – Code of practice, (BSI, 2009) provided a holistic design guide and sets out simple; intermediate; and detailed approaches that support the implementation of RWH systems in England and Wales. BS8515's design methods are applicable to commercial and residential premises. The main focus of the document was to support the delivery of suitably designed RWH systems as AWR. Its key design criteria seek to enable a designer to select a suitable tank size whilst minimising the potential risks associated with poor water quality. This framework was set around the concept that oversized tanks result in poor water quality, whereas installation of small tanks provides inadequate storage during dry periods. Application of the British Standard has coincided with a steady growth of RWH installations in the last few years (MTW, 2010). However, the document failed to focus on the opportunity for RWH to manage stormwater discharges as a source control method. The implementation of RWH as a source control technique was covered as a normative annex rather than integrated within the calculation steps. The normative annex in BS8515:2009 (BSI, 2009) offers simple source control design options and sets out a design method for application by practitioners. In summary, the methods result in designers specifying (intentionally) oversized storage tanks to increase the likelihood that storage is available at the beginning of a storm event. As with the design of a standard RWH system, three design approaches (simple, intermediate and detailed) are set out in the annex. For the source control design to be applicable one critical design requirement must be met; the demand must be greater than yield. Where this is not the case, then the tank is unlikely to have a useful volume of storage available when a large storm occurs. Consequently, the RWH system is unable to reduce the volume of the forthcoming storm event. For the simplified approach, the standard provides a chart to allow an oversized storage tank to be specified as set out in Figure 2.12.

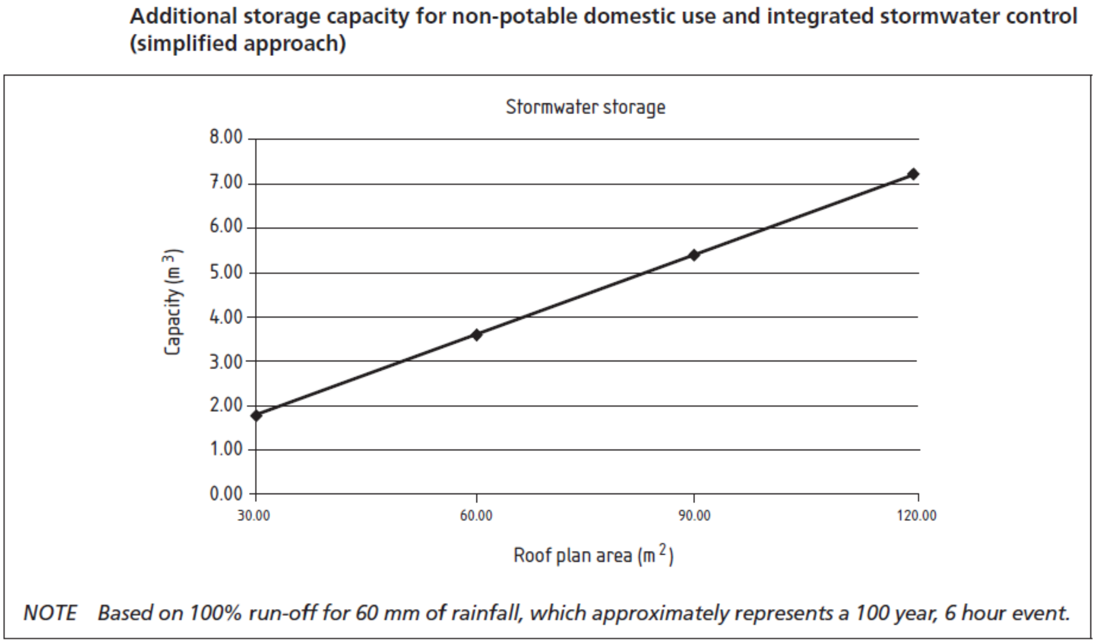


Figure 2.12 – BS8515:2009's simple source control sizing method (BSI, 2009)

Building upon this method, an intermediate approach is described in Equation 2.1 (BSI, 2009) by using a nominal coefficient of spare storage fixed at 0.5 times the volume of the design rainfall event.

(Equation 2.1)

$Where\ D_N > Y_R$

$SC = R_d \times A - (D_N - Y_R) \times 0.5$

$However, where\ D_N < Y_R$

$SC = 0$

$D_N\ is\ the\ non-potable\ water\ demand\ (l)$

$Y_R\ is\ the\ annual\ rainwater\ yield\ (l)$

$SC\ is\ the\ stormwater\ control\ capacity\ (l)$

$R_d\ is\ the\ design\ storm\ event\ depth\ (mm)$

$A\ is\ the\ collecting\ area\ (m^2) - potable\ water\ demand\ (l)$

$0.5\ is\ the\ coefficient\ for\ allowance\ of\ spare\ storage$

This approach offers the user a low level of confidence that the design will achieve the intended outcome. For example a designer might wish to control the 1 in 100 year storm event with a R_d value of 50mm/hour for a roof area of 100m^2. Having oversized the RWH tank, the designer cannot be certain that; 1) the demand pattern will successfully reduce the tank level prior to the storm (i.e. SC could = 0 at the start of the storm); and 2) the designer may not have confidence that the filter and conveyance system can capture and convey 100% of the rainwater into the storage tank.

BS8515:2009 ((BSI), 2009) sets out a detailed calculation approach based on application of one of the following three analyses; a) analysis of 20+ extreme events; b) 100+ year extreme stochastic series; or c) probability analysis with a five-year time series.

As with the simple approach described in Equation 2.1, these approaches are limited in their applicability as the demand must be greater than the yield. Where this requirement cannot be achieved, regardless of the tank’s total storage volume, it is unlikely to have a useful amount of spare storage volume. With low demand, it is likely that tanks are filled to capacity by relatively small rainfall events. Even where demand is greater than yield, it cannot be guaranteed that the designed storage will be available as a number of other factors affect the demand and the data used will always be an estimate built upon a wide number of assumptions. The major limitation of this approach is its reliance upon user behaviour to be consistent with the core assumptions. Willis *et al.* (2013) described shifts in household water usage patterns as a result of an increased uptake in social and technological adaptation measures. Taking a short term perspective, the tank may remain full when the house is out of use (e.g. being sold, renovated, or during a vacation). When this scenario occurs, no source control benefits are offered by the RWH system, and downstream surface water systems may be overwhelmed if an extreme rainfall event occurs. Over a medium term horizon, the demand on a RWH system may vary as homeowners change their water usage habits or water-using micro-components for more efficient versions. In the long term, suitable institutional frameworks must be in place to prevent homeowners removing or adapting RWH systems. This might take the form of an agreement written into the deeds of the property to maintain the RWH system in perpetuity (South West Water, 2014b). Alternatively ownership of the RWH system might vest with a management company, the Lead Local Flood Authority (LLFA) or the WSP in order to ensure the ongoing functionality of the RWH systems as a SuDS device (Woods-Ballard *et al.*, 2007). An additional strategy that may be of value would be to adjust the technology to allow tanks to automatically empty based on pre-defined criteria, e.g. where RWH systems remain unused for several days (Han and Mun, 2011) . Building on the methods in BS8515, further research into the benefits of RWH as stormwater control systems were investigated in an academic/industry collaboration project - Water Cycle Management for New Developments (WaND) (Butler, 2010). Research conducted on the Water Cycle Management for New Developments (WaND) (Butler, 2010) project included modelling assessments to investigate the benefits of the integration of RWH systems within new developments as part of a stormwater management strategy. The project focussed on two potential metrics; 1) reducing annual stormwater runoff; and 2) minimising peak discharge rates, as detailed in the following sections.

2.8.3.2 Modelling RWH to Reduce Annual Stormwater Runoff

As part of the WaND project, a study conducted by Kellagher and Maneiro Franco (2007) utilised hydraulic models to assess the overall reduction in stormwater runoff volumes and peak flow rates from a development where RWH was evaluated. Infoworks CS (Innovyze, 2011) was used and a stochastic rainfall series was produced using TSRsim (Spiers, 2007) to generate a hundred year time series. The study assumed each household's roof runoff is routed to a single communal RWH tank. Additionally, the study used a scenario based analysis of two tank sizes; 0.75 m^3/ person and 1.5m^3/person. A range of daily water demand scenarios was also tested. A roof area of 20m^2/person was implemented and the model assessed a development with 100 occupants in Greenwich (low annual average rainfall = 555mm/year). The study noted that the findings are built on a number of fixed parameters that may not be representative throughout the UK. Further work in this field to generate a tool to assess the feasibility of RWH installations (to function in a SuDS capacity) at a given site would potentially represent a valuable extension to this study. This has been identified as a key research gap to be addressed in this thesis. Furthermore, integration of such an approach within proprietary drainage design software may also be of value to stimulate wider use of the concepts.

Table 2.2 illustrates the notable reductions in stormwater runoff modelled in the Kellagher and Maneiro Franco (2007) study.

Table 2.2 – Annual Rainfall Volume Results (Adapted from Kellagher and Maneiro Franco, 2007)

	Year 1		Year 2		Year 3	
Daily demand (l/c/d)	**Tank sizes (m^3/person)**					
	0.75	**1.5**	**0.75**	**1.5**	**0.75**	**1.5**
-	*Total Annual Reduction in runoff from roofs (%)*					
25	70	80	82	84	80	88
50	85	98	99	100	88	95
100	92	100	100	100	90	97

The study's conclusions based on the above findings are offered as follows (Kellagher and Maneiro Franco, 2007, piii); *"Tank sizing for stormwater control of extreme events need to be between 1.5 and 2.5 times larger than requirements for the benefits of use in the property, though considerable stormwater benefits are achieved with standard sized systems."*

The three non-potable water demand scenarios tested represent a wide range of potential water demand from 25 – 100 l/c/d. Butler and Memon (2006) demonstrated that approximately 30% of UK household water demand is used for WC flushing with a further 20% used in laundry applications. Taking the widely used daily water usage figures applied by Kellagher and Maneiro Franco (2007) as 150l/c/d, daily non-potable demand for UK residential developments can be identified as set out in Table 2.3.

Table 2.3 – Indicative daily non-potable water usage for households with RWH systems after Butler and Memon (2006)

RWH water usage applications	Average daily usage (l/c/d)
WC only	50
Laundry only	25
WC and Laundry	75

Assuming a daily rainwater demand of 50l/c/d, the annual reduction in discharges from the model used in the study ranged from 85% - 100%. This study thus suggests that RWH can provide highly beneficial reductions in annual storm water flows (and thus reductions in treatment volumes, costs and combined sewer overflow [CSO] spills).

Where Yield/Demand (Y/D) <0.95 and oversized tanks are installed, traditional RWH systems were shown in the study to successfully function as a source control tool as part of the SuDS hierarchy. Two observations are important in qualifying this finding. Firstly, the research relies upon a desktop assessment. Empirical data from a project exemplar would be beneficial to further demonstrate the findings. Secondly, the study illustrates that oversized communal RWH systems can have benefits to local drainage networks. Individual or more broadly dispersed RWH systems within a given catchment would potentially have different discharge characteristics and individual catchment specific hydraulic modelling would need to be undertaken to further assess the benefits of dispersed RWH systems.

2.8.3.4 Modelling RWH to Reduce Extreme Stormwater Runoff

The second phase of the WaND study (Kellagher and Maneiro Franco, 2007) appraised the extreme rainfall events identified from a 100 year time series data set. The extreme events were selected by identifying the 10 largest storm events from the hundred year series. The study's results are illustrated in Table 2.4.

Table 2.4 – Illustration of RWH system's source control during extreme rainfall events (20m^2 roof per capita) adapted from Kellagher and Maneiro Franco (2007)

	10 Largest Storm Events over 100 years (E1-10)									
RWH tank = 1.5m^3/c	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**	**E9**	**E10**
total rainfall (mm)	105	98	98	183	64	90	61	63	54	53
effective rainfall (m^3)	390	362	363	1116	237	334	224	795	199	198
Reduction in peak flow (%)										
no RWH	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
RWH and demand 50l/c/d	39	54	**0	3	*54	0	53	53	51	51
Total run-off volume (m^3)										
no RWH	*393*	*372*	*381*	*723*	*232*	*329*	*235*	*226*	*199*	*207*
RWH and demand 50l/c/d	238	229	232	**555	105	214	109	104	*92	97
Reduction in run-off volume (%)										
no RWH	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
RWH and demand 50l/c/d	39	38	39	**23	*55	35	54	54	54	53

*Greatest Source control; **Least source control

Table 2.4 shows that even in the 10 most extreme events over a 100 year dataset, the RWH system modelled offered notable reductions in runoff volumes ranging between

23-55%. Peak flow reductions during the extreme rainfall events at the outfall from the site ranged between 0 and 54% in the scenario assessed. However, the outputs showed one event (E3) during which the peak runoff rates were not reduced as a result of the RWH being incorporated within the model. This illustrates that traditional RWH configurations do not necessarily lead to peak runoff reduction from all storm events. These findings support the author's conclusions (Kellagher and Maneiro France, 2007, p49 and piii):

1) *"Retro-fitting of urban areas with rainwater use systems, which suffer from relatively frequent flooding, could significantly reduce the flooding frequency and flooding volumes."*

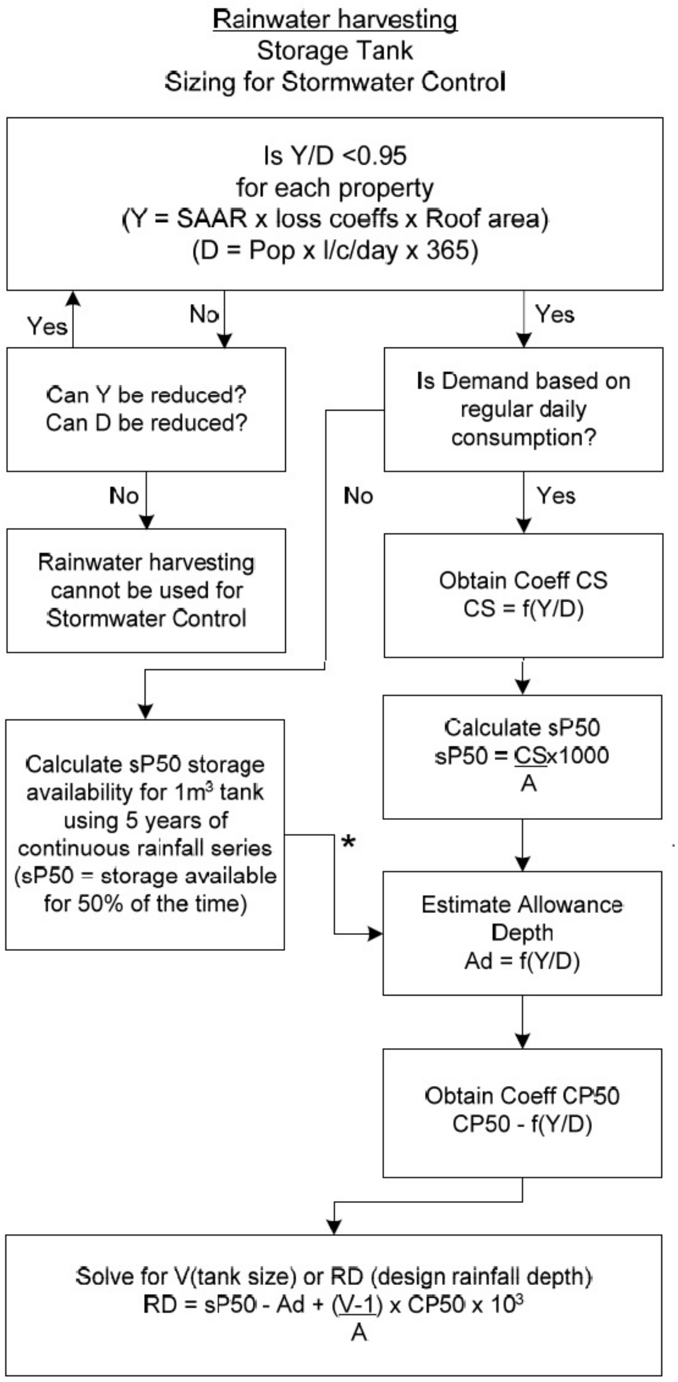
2) "The stormwater control benefits for managing extreme rainfall events are significant, both in terms of peak flow or volume control. Rainwater use systems should be considered (if they are being used in the development) in the design of stormwater storage of the main drainage systems and performance compliance assessment of the drainage system with discharge consent criteria."

2.8.3.5 The Kellagher / Gerolin Method for Rainwater Harvesting Tank Upsizing

Leading on from the initial approaches documented in BS8515:2009 (BSI, 2009) and adding to the WaND research, a study into the benefit of RWH systems for source control in England and Wales was described in Gerolin *et al.* (2010). This method again focusses on demand for water from a RWH system freeing storage capacity for the next storm. The work was extended further by Kellagher (2011) whereby a number of RWH systems in a residential housing development were monitored. In the study, each RWH system was designed to comply with the Kellagher / Gerolin Methodology (i.e. the tanks were oversized through implementation of their design method). Furthermore, the approaches are now featured in the updated British Standard and the SuDS Manual C753 ((BSI), 2013b, Woods-Ballard *et al.*, 2015).

This design methodology can be undertaken through application of the flowchart shown in Figure 2.13. It relies upon the user appraising the predicted non-potable demand (D) at each property at the proposed development. The yield (Y) is then calculated from the contributing roof area and average rainfall for the site. In summary, where the Y/D ratio is identified as less than 0.95 then there it is a good statistical likelihood that storage will be available in the RWH tank at the commencement of an extreme storm event. Where Y/D is <0.7 "*there is usually considerable storage available"* (Kellagher, 2011, pv). It follows that this available storage volume can reduce the total volume of runoff during the next storm and thus provide source control. The study concludes that stormwater can successfully be managed through implementation of the Kellagher / Gerolin Methodology.

Although the British Standard for RWH (BS8515:2009+A1:2013) (BSI, 2013b) guidance now further promotes opportunities for using RWH as stormwater control devices in a UK context, it should be recognised that the calculation method is not simple to implement in a timely manner and is described by 12 pages of guidance. Consequently, the method is not straightforward to deliver on a bespoke basis for individual RWH systems in a cost effective fashion. The time taken to undertake the calculations (which can be iterative in nature to allow an optimal solution to be identified), can be considerable. Figure 2.13 sets out the flowchart used for storage sizing for RWH systems that are intended to control runoff as well as provide rainwater as a resource. A key drawback of the approach is that it relies on consistent user behaviour over the design life of a development. Further work to provide a robust and easily used design tool for undertaking multiple RWH scenario calculations would be valuable to support the wider implementation of RWH as a SuDS tool. This thesis addresses this need by further advancing the projects and methods described.



*Note application of the procedure for irregular demand resulting in greater variability in storage availability has not been tested. Proceed with caution

Key

AAR	Annual average rainfall (mm)
e2	Run-off coefficient
ds	Depression storage (mm)
ns	Estimate of the number of rainfall events per year ~ 150
h	Is the filter efficiency
A	Roof area (m²)
Rd	Design storm rainfall depth (mm)
CS	Coefficient which is a function of Y/D
AD	Additional rainfall depth allowance to cater for the random nature of rainfall (mm)
CP50	Effective proportion of additional storage available for increasing the tank size from 1m³
sP50	Rainfall depth for 1m³ of storage (mm)

Figure 2.13 – Complex design flowchart for appraising source control benefits of RWH systems (Kellagher, 2011)

2.8.4 Alternative Configurations for Rainwater Harvesting and Source Control

The literature reviewed above focussed on approaches which seek to enable traditional RWH to be included within a SuDS strategy simply by undertaking calculations. In addition to this, an initial review of alternative (i.e. yet to be widely deployed) RWH configurations was carried out to establish options for revised designs to achieve increased source control benefits. Further research into novel RWH configurations is undertaken to support this gap in the academic literature in Chapter 3. Herrmann and Schmida (1999) set out a range of RWH designs and identified a RWH system that achieves source control through addition of a throttle and retention volume in the upper region of the storage tank as illustrated in Figure 2.14.

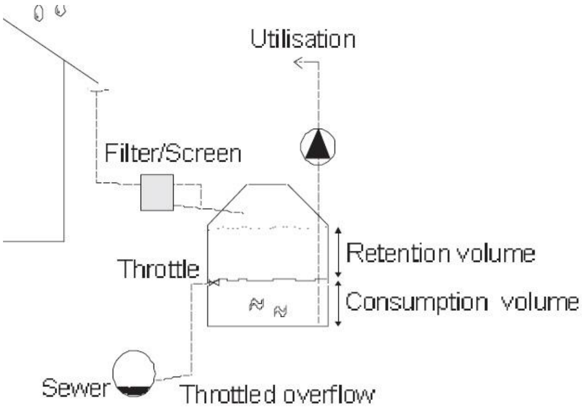


Figure 2.14 – A RWH system configured for rainwater use and source control the "retention and throttle typology" (Herrmann and Schmida, 1999)

Residential RWH systems in England and Wales are typically purchased from a specialist RWH supplier as a package for installation on site as part of a new build or renovation project. As a consequence, except for the work reported in this thesis, no examples of the throttle and retention technology have been identified in the UK. Internationally, research into its use has been undertaken by DeBusk *et al.* (2013) in the USA. Furthermore, a study undertaken by Huang and Shaaban (2009) included RWH tanks designed with a 5m^3 tank capacity at each house. The top third of the tank was able to overflow via a 50mm outlet orifice. A series of scenarios were modelled using a proprietary hydraulic model assuming RWH tanks were installed at a development of 242 houses in Kuala Lumpur. Peak rainwater discharge for the 30 minute rainfall event was reduced by 21%, 24%, and 22% for the 10, 50 and 100 year events. Notably, Huang and Shaaban (2009) did not consider the optimisation of either the tank storage volumes, the level of the overflow in the tank or the size of the flow control orifice.

The original British Standard BS8515:2009 (BSI, 2009), includes no mention of RWH systems which integrate a flow control device in order to provide greater storm control benefits. However, the annex to the updated document now refers to an active RWH system (BSI, 2013, p13):

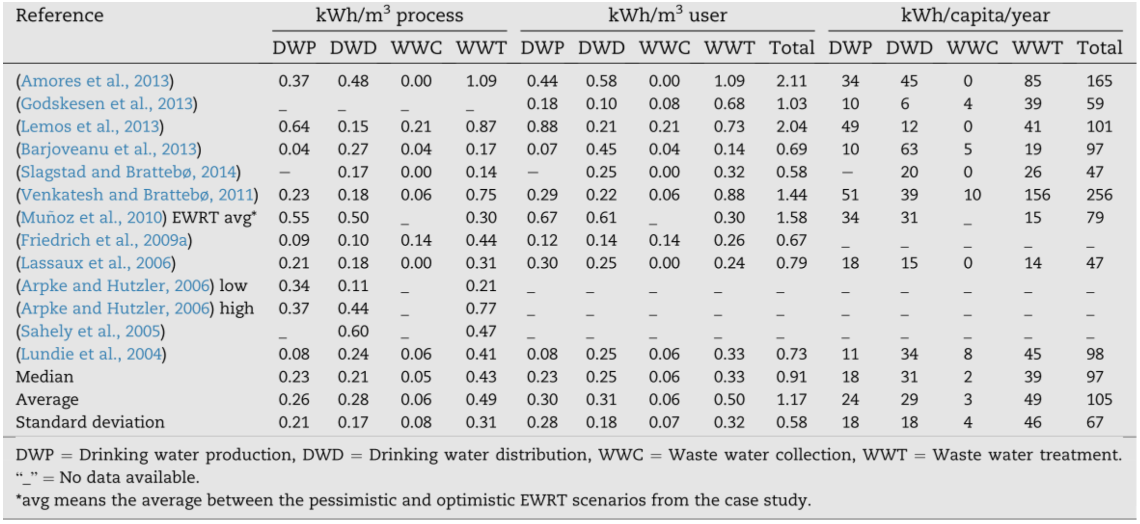
“An active [RWH] system is one where the stored water volume is managed to maintain spare storage at all times for the eventuality of a large storm to insure the runoff is stored.”

Under this framework, a throttle and retention system (Herrmann and Schmida, 1999) could be classed as an active RWH system. However, given that no “active” intervention (i.e. pump activating) (Quigley and Brown, 2014) is required to allow a throttle and retention RWH tank to partially drain down, this design concept might better be referred to as a “passive RWH system”, or a “RWH system with passive source control”. This configuration certainly satisfies the overarching aim to enable multiple benefits of RWH to be achieved. Regardless of preferred terminology, these configurations can be described as “dual purpose” RWH (Mugume *et al.*, 2015), i.e. systems which are designed to provide stormwater control and water demand management benefits.

Active RWH systems are described in a handful of texts, with a day-to-day operational target to provide rainwater for local use, whilst draining the tanks prior to a storm to reduce the impact of intense rainfall (Quigley and Brown, 2014, Han and Mun, 2011, iota, 2014). With appropriate use of time-series or stochastic rainfall data, actively controlled RWH systems can be designed and implemented which provide source control using a real time control philosophy to maximise the source control potential of RWH systems (Quigley and Brown, 2014). Alongside the concept of “actively pumped discharges”, increasing the complexity of communications and electronics systems can lead to a greater energy demand. The need for RWH systems to operate efficiently in terms of energy use is investigated in the following Section.

2.9. Energy Costs of Water and Wastewater Production, Delivery and Treatment

A comprehensive, global study of water energy costs was conducted in Loubet *et al.* (2014). This study identified 117 journal papers that incorporated lifecycle analysis of energy costs of water and wastewater systems. Figure 2.15 has been adapted from the supplementary data provided with the study. The data collected compares the holistic energy costs for the delivery and treatment of water and wastewater. The results illustrate that operational energy (and thus carbon) footprints for provision of drinking water and treatment of wastewater can vary significantly. This is of significant relevance to the deployment of RWH systems, as there are potentially locations in highly energy efficient water networks where RWH will provide an AWR at a higher energy cost than the existing system. In contrast, these results illustrate the opportunity to install RWH as an energy saving device in locations where the unit energy costs are higher than those of a given RWH system. The results presented by Loubet *et al.* (2014) show a range of total energy costs for water provision and wastewater treatment between 0.58-2.11 kWh/m^3. Presented in terms of costs per capita, the data ranges between 47-256 kWh/capita/year.

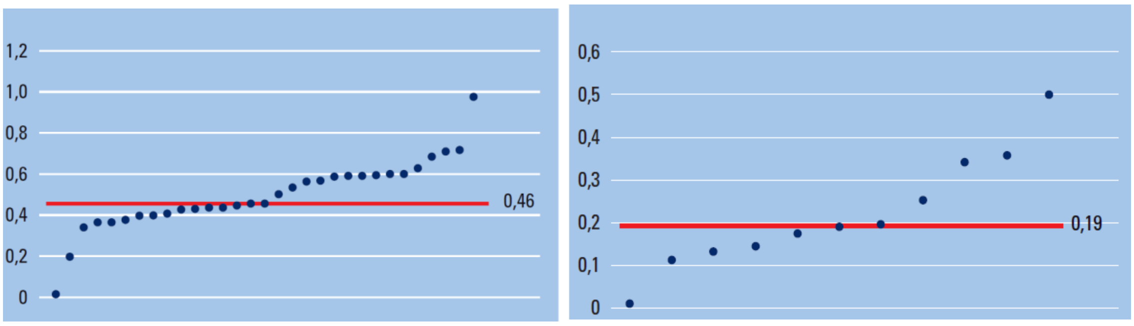


Reference	kWh/m^3 process				kWh/m^3 user					kWh/capita/year				
	DWP	DWD	WWC	WWT	DWP	DWD	WWC	WWT	Total	DWP	DWD	WWC	WWT	Total
(Amores et al., 2013)	0.37	0.48	0.00	1.09	0.44	0.58	0.00	1.09	2.11	34	45	0	85	165
(Godskesen et al., 2013)	_	_	_	_	0.18	0.10	0.08	0.68	1.03	10	6	4	39	59
(Lemos et al., 2013)	0.64	0.15	0.21	0.87	0.88	0.21	0.21	0.73	2.04	49	12	0	41	101
(Barjoveanu et al., 2013)	0.04	0.27	0.04	0.17	0.07	0.45	0.04	0.14	0.69	10	63	5	19	97
(Slagstad and Brattebø, 2014)	–	0.17	0.00	0.14	–	0.25	0.00	0.32	0.58	–	20	0	26	47
(Venkatesh and Brattebø, 2011)	0.23	0.18	0.06	0.75	0.29	0.22	0.06	0.88	1.44	51	39	10	156	256
(Muñoz et al., 2010) EWRT avg*	0.55	0.50	_	0.30	0.67	0.61	_	0.30	1.58	34	31	_	15	79
(Friedrich et al., 2009a)	0.09	0.10	0.14	0.44	0.12	0.14	0.14	0.26	0.67	_	_	_	_	_
(Lassaux et al., 2006)	0.21	0.18	0.00	0.31	0.30	0.25	0.00	0.24	0.79	18	15	0	14	47
(Arpke and Hutzler, 2006) low	0.34	0.11	_	0.21	_	_	_	_	_	_	_	_	_	_
(Arpke and Hutzler, 2006) high	0.37	0.44	_	0.77	_	_	_	_	_	_	_	_	_	_
(Sahely et al., 2005)	_	0.60	_	0.47	_	_	_	_	_	_	_	_	_	_
(Lundie et al., 2004)	0.08	0.24	0.06	0.41	0.08	0.25	0.06	0.33	0.73	11	34	8	45	98
Median	0.23	0.21	0.05	0.43	0.23	0.25	0.06	0.33	0.91	18	31	2	39	97
Average	0.26	0.28	0.06	0.49	0.30	0.31	0.06	0.50	1.17	24	29	3	49	105
Standard deviation	0.21	0.17	0.08	0.31	0.28	0.18	0.07	0.32	0.58	18	18	4	46	67

DWP = Drinking water production, DWD = Drinking water distribution, WWC = Waste water collection, WWT = Waste water treatment.
"_" = No data available.
*avg means the average between the pessimistic and optimistic EWRT scenarios from the case study.

Figure 2.15 – Operational energy usage at a number of global water and wastewater networks (Loubet et al. (2014)

In the UK, energy and carbon costs associated with provision of potable water delivery are reported to Ofwat on a company-wide basis. The broad collection of greenhouse gases are reported under the catchall of a CO_2 equivalent (CO_2e). One pan-European study conducted by The European Benchmarking Co-operation (2013) collated average energy costs of municipal water supplies to find a European mean value of 0.46 kWh/m^3 (supplied to the tap) as illustrated in Figure 2.16a.



a) b)

Figure 2.16 – a) Electricity consumption (x-axis = supplier, y-axis = energy cost in kWh/m^3); and b) Carbon footprint (x-axis = water service provider, y-axis = footprint in kgCo$_2$e/m^3) for a number of European municipal water supplies (European Benchmarking Co-operation, 2013) (X-axis =

Figure 2.16b also shows a smaller sample of carbon footprints for water provision from the same study. The average carbon footprint of water provision is identified as 0.19

$kgCO_2e/m^3$. This value is lower than some UK based utilities with Anglian Water (2014) reporting their energy consumption as $0.452kgCO_2e$ (year 2011). It is likely that a range of different reporting methods were used and consequently, caution must be applied when utilising these figures. The EBC (2010) report also assessed wastewater treatment costs on a per capita basis, identifying that 36kWh/capita is the average from the European stakeholders involved in their research as illustrated in Figure 2.17. The report does not clarify the time frame associated with the 36kWh/capita figure, e.g. if it represents the annual consumption.

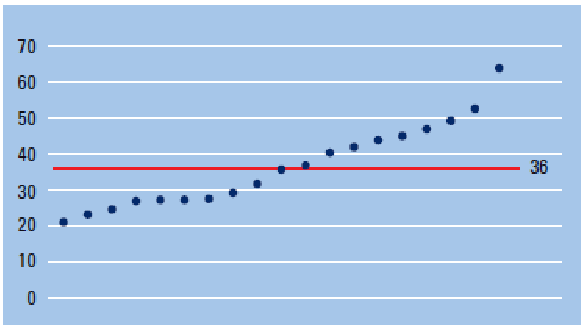


Figure 2.17 – Wastewater treatment energy (kWh/capita) for European water service providers (x-axis) (European Benchmarking Co-operation, 2013)

Given the spatial variability and heterogeneous nature of the UK, any appraisal of mean energy usage data for plot or even catchment scale assessments is of limited value. In simple terms, distance from treatment works could be used as a proxy to better assess this factor although literature assessing energy costs, RWH and site specific locations was not identified through this literature review. This observation is reinforced by a study of RWH benefits undertaken by Wang and Zimmerman (2014). This study identified energy costs within a life cycle assessment of 14 hypothetical RWH systems across the USA. Although average energy costs for municipal water supplies of 2.93 kWh/m^3 and 0.86 kWh/m^3 were identified in San Diego and Phoenix respectively, the remaining 12 RWH case studies were modelled against municipal water supplies with an energy consumption based on the USA average of 0.396 kWh/m^3. As the energy usage value is a key input parameter within the study, the use of this continent-wide average value will have significantly influenced the study's outcomes. The complexities involved when setting boundaries for modelling studies associated with RWH evaluation make it difficult to make accurate assessments on a plot-scale, unless accurate site or catchment specific data can be obtained. Work in this thesis will focus on using site specific data where possible to drive simulation and calculation approaches.

2.10 Energy Consumption of Existing Rainwater Harvesting Systems

RWH system suppliers in the UK offer configurations that aim to reduce user's water bills by displacing their potable water demand with rainwater. However, a review of documents from these suppliers illustrates that only one out of five undertook power consumption analysis and reported their system's energy consumption data. Table 2.5 describes the marketing claims (and associated methods where applicable) for five RWH systems. In summary, the only available figure for power consumption at UK RWH installations available from industry literature is 0.682kWh/m^3. However, the StormSaver system uses a pump with significantly lower power output and could in principle enable harvested rainwater delivery at a lower energy cost.

Table 2.5 – Reported energy consumption for UK RWH suppliers

Supplier / System	Reported Values	Comments on reported data and methods
Rainwater Harvesting, Ltd. RainDirector[1]	Water costs *"1p/person/day"* Equating to "*0.682kWh/m*^{3}"	Detailed methodology provided to support claims and study overseen by Portsmouth University. 800W submersible pumps used with AC supply. Laboratory-based data (not collected on system over long term in domestic setting).
StormSaver. Monsoon Eco 14 Control Panels[2]	*"system uses 75 per cent less energy than other domestic rainwater harvesting systems… and could be powered by solar panels of wind turbine… (achieved using a) technologically advanced membrane pump which operate on a mere 90 Watts"*	Lower wattage pump (90W) than other suppliers using 24V DC supply. No specific values reported to support claims.
Freerain[3]	*"As the pump is starting and stopping less frequently than direct systems and indeed other header tank systems, power consumption and the life of the pump will be better."*	No pump or control specification details provided. No specific values reported to support claims.
Rainman™ Smartfit[4]	*"Pump control switches submersible pump on and off, on demand"*	No pump or control specification details provided. No specific energy consumption claims reported.
Kingspan[5]	*"It's a system that pays for itself"*	No pump or control specification details provided. No specific energy consumption claims reported.

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[1] http://www.rainwater-harvesting.co.uk/downloads/pdf/rainwater-harvesting/rwh-white-paper-raindirector-electricity-use.pdf

[2] http://www.stormsaver.com/write/Monsoon_Domestic_Brochure.pdf

[3] http://www.freerain.co.uk/shop/domestic-rainwater-harvesting-systems

[4] http://www.freewateruk.co.uk/rainwater-recycling-smartfit.htm

[5] https://www.kingspanenviro.com/klargester/envireau-rainwater-harvesting

Energy consumption for RWH systems was investigated in a number of international studies (Vieira *et al.*, 2014, Siems and Sahin, 2016, Chang *et al.*, 2017). Vieira *et al.* (2014) illustrated the gap between hypothetical studies, which typically under report the total energy consumption required to operate a RWH system, and empirical evidence. Their review of empirical studies gives a mean value of 1.40kWh/m^3 for RWH systems across a range of global settings. Siems and Sahin (2016) described the nuanced performance of RWH systems in terms of energy demand by illustrating that different end uses can see a range of performance values. Furthermore, this work illustrated that values in kWh/m^3 are also affected by occupancy rates. Ward *et al.* (2012c) also exemplified how the scale of a RWH installation can have an effect on energy consumption. Their empirical study reports a value of 0.54kWh/m^3 at a UK-based commercial premises designed for 300 occupants. With a high level of uncertainty over the performance of RWH systems in terms of energy consumption, laboratory and pilot-study data collection is still needed to better build the evidence base supporting claims that RWH can provide a low-carbon water supply.

2.11 Summarising Drivers for Multiple Benefit Rainwater Harvesting from a Water Service Provider Perspective

Kellagher (2011) provided an illustration of the potentially wide reaching benefits of RWH in England and Wales. Other than financial benefits associated with water demand management, each of the aspects identified in Figure 2.18, remain largely unrecognised (and consequently unassessed and un-incentivised). This poses a research opportunity to develop RWH evaluation methods that enable metrics to be incorporated to evaluate the benefits highlighted in Figure 2.18.

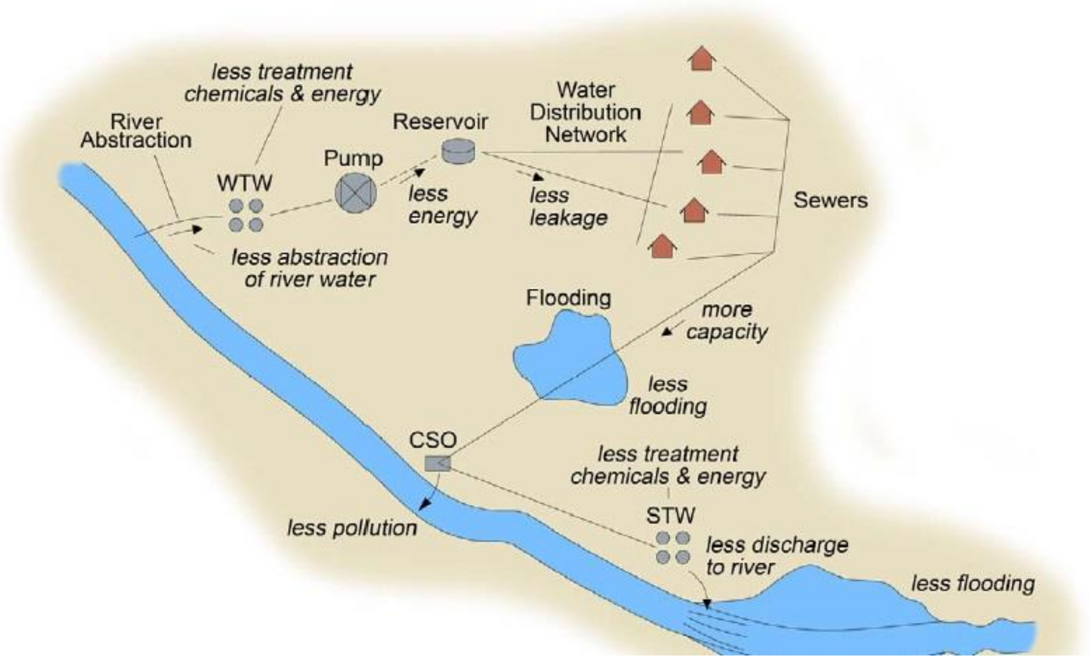


Figure 2.18 – Catchment-scale benefits of RWH uptake, from Kellagher (2011).

A summary of the potential opportunities for RWH to offer holistic catchment scale benefits was set out is described in Table 2.6.

Table 2.6 – Potential energy savings and environmental benefits resulting from residential water use reductions via large-scale RWH adoption (Melville-Shreeve, 2014a)

Process	Potential benefits of wide-scale RWH uptake
Raw water abstraction	• Reduced annual abstraction, increased river flow during summer low-flow periods, reduction in negative environmental impacts such as fish kills. • Higher summer low-flows may permit increased sewage discharge rates lower in the catchment.
Raw water pumping	• Reduced pumping may offer lower carbon and energy footprints.
Water treatment	• Reduced pumping, mixing and chemical use may offer lower carbon and energy footprints.
Water pumping station	• Reduced pumping may result in lower carbon and energy footprints.
Water distribution	• Reduced water demand within a network may reduce peak demand leading to extended design lives for existing assets, potentially delaying capital upgrades.
Wastewater collection	• Reduced sewage flows may reduce the risk of pollution events caused by flooding or spills from combined sewer overflows.
Wastewater pumping	• Reduced wastewater flows may lead to reduced pumping volumes giving lower carbon and energy footprints.
Wastewater treatment	• Reduced wastewater treatment flows may reduce chemical use and pumping/treatment energy requirements giving lower carbon and energy footprints.

Whilst overseeing all facets of economic regulation in the water sector, Ofwat have a secondary duty to contribute towards the achievement of sustainable development and resilience. Over the last decade Ofwat has increased the flexibility of its regulatory regime to allow WSPs to define their own key business performance incentives termed outcome delivery incentives (ODIs) (Ofwat, 2016). In principle this enables a broader range of solutions to be adopted which could enable innovative solutions such as RWH to be used as source control devices. Whilst some WSP departments see a potential opportunity, others see a potential reduction in revenue and reduce the financial savings associated with RWH installations (South West Water, 2014a). The overlapping drivers and incentive mechanisms associated with the opportunity posed by dual purpose RWH systems are therefore poorly understood by existing supply chains. With a lack of clear understanding as to the performance of RWH systems, further empirical studies and knowledge sharing is now required to enable these opportunities to be realised. WSPs have significant investment programmes in place to reduce CSO spills. These projects seek to minimise impacts on downstream shellfish and bathing waters (South West Water, 2015, Department for Environment Food and Rural Affairs, 2016). With data available to demonstrate reductions in rainwater discharges associated with RWH systems, schemes to retrofit plot-scale RWH could continue in the coming decade (South West Water, 2014b).

2.12 Rainwater Harvesting as a Climate Change Adaptation Measure

The UK has an estimated surplus water availability of 2,000ML/day however, by 2050s deficits are projected to be widespread (Wallingford, 2015). UKCP09 climate change projections describe the impacts of climate change on the UK under a range emissions scenarios (Adaptation Sub-Committee (ASC), 2012). Future improvements to these projections will be made available in the UKCP18 projections (UK Climate Projections, 2016). Figure 2.19 describes the high emissions scenario (p90) in which a continued increase in global carbon dioxide concentration leads to a reduction in overall rainfall availability. The map illustrates that most parts of the UK are likely to have a deficit in water availability by the year 2080, assuming that no adaptation beyond current plans is delivered.

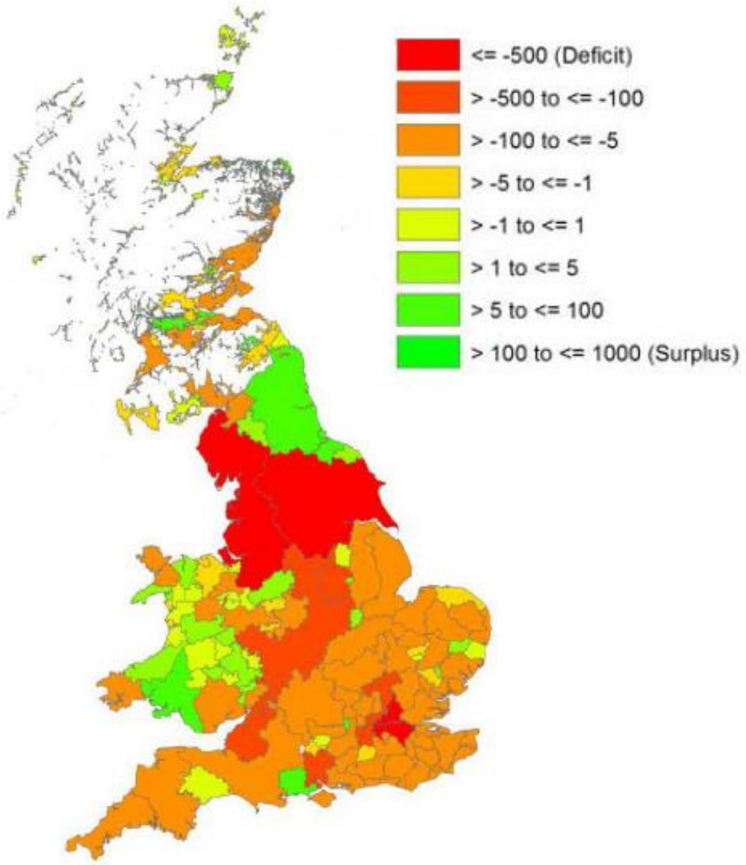


Figure 2.19 – Deficits in water availability for p90 climate change scenario for 2080 (Dawson, 2015).

A UNFCC (2006) technical paper noted that coping with climate change through mitigation (i.e. reducing anthropogenic greenhouse gas (GHG) inputs) was a concept considered at the highest level by governmental bodies such as the Intergovernmental Panel on Climate Change (IPCC). The paper provides a broad overview of technological adaptation to climate change and asserts that adaptation must be included in governmental strategies rather than leaving this task to individual agents (UNFCC, 2006 p7). The report goes on to state that; *“mitigation is essential and adaptation is inevitable”* UNFCC, 2006 p7). “A*daptation will demand that institutions… plan their strategies and take action in advance.”* (UNFCC, 2006 p8). Technologies are classified as either soft (e.g. insurance schemes or implementing crop rotation) or hard (e.g. improved drip-irrigation technology). Planned adaptation to climate change is described by Klein *et al.* (1999) as illustrated in Figure 2.20.

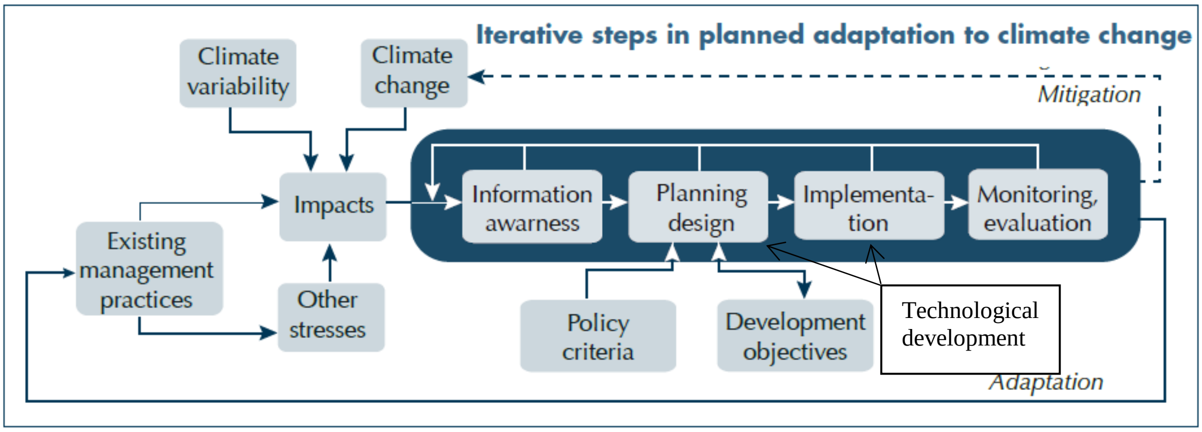
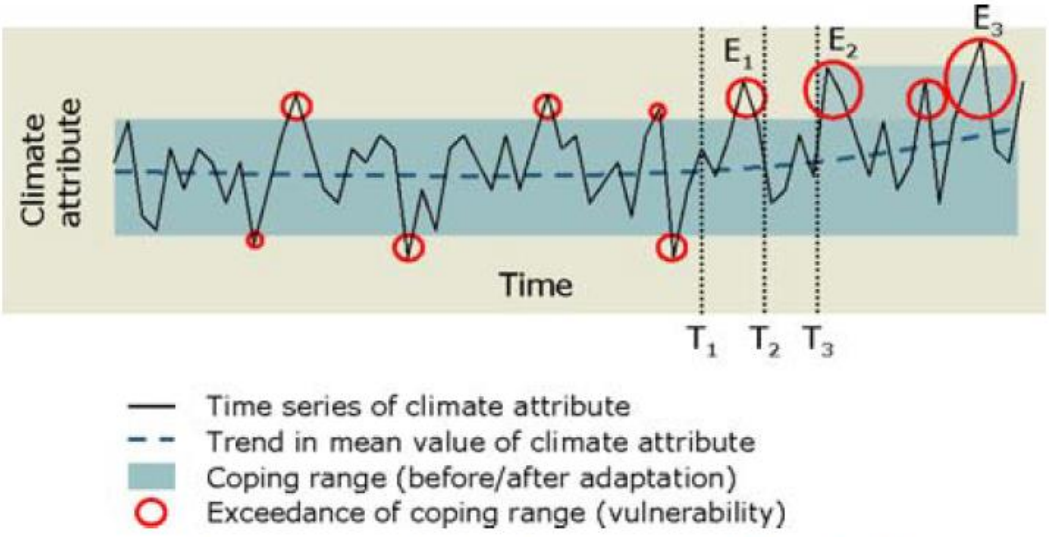


Figure 2.20 – Applying technological development to a conceptual cycle for planned adaptation to climate change, adapted from Klein et al. (1999)

The processes described in Figure 2.20 illustrate how technological advancements feed into the cycle at the planning and implementation stage. The report identifies four potential water demand management technologies that will support climate change adaptation:

1. “*Use “grey” water [sic]*
2. *Reduce leakage*
3. *Use non-water-based sanitation*
4. *Enforce water standards*” (UNFCC, 2006, p18).

Füssel (2007) set out some key concepts associated with climate change adaptation. The study investigated how hypothetical interventions (e.g. the deployment of new technologies) can increase our ability to cope with new climate extremes. The need for adaptation is elegantly described in Figure 2.21.



Hypothetical example for the timing of planned adaptation

Figure 2.21 – Coping with climate change (Füssel, 2007, p4)

Describing Fussel's planned adaptation chart, at T_1 the frequency and magnitude of extreme events has begun to slowly increase. At T_3, an adaptation intervention has been implemented that increases the coping range. In turn future extreme events become more likely to be within the tolerable range.

The wide-scale uptake of RWH as a climate change adaptation strategy is described using a Japanese case study (Fukuoka) in Conte *et al.* (2012). The study describes RWH uptake in the context of a water demand management measure, which contributed to the city's water demand being reduced to approximately 20% less than other comparably sized cities. Applying Fussel's (2007) model, the widespread deployment of RWH could reduce the risk of drought and flooding (i.e. too little AND too much water) by increasing the coping range to these climate attributes. Such a model implies RWH is a valuable climate change adaptation measure. However, the latest Climate Change Risk

Assessment Synthesis Report (Committee on Climate Change, 2017) does not mention RWH, AWR or AWSS although it does acknowledge that water demand management will be necessary to maintain the ecological health of lakes and rivers. The lack of investigation of RWH as an adaptation option in the UK illustrates the continued need for performance data to be collected. Recent evidence from research abroad has shown that RWH can play a role as a climate change adaptation measure in a range of settings (Ayele, 2014) (Boelee *et al.*, 2013) (Pandey, 2003).

The literature illustrates the deployment of RWH as a climate change adaptation measure (in the UK) shows potential to reduce drought and stormwater flooding. In addition, increased RWH deployment warrants a deeper understanding of the benefits of a wide range of RWH designs. The design of RWH systems can be achieved using a range of decision support tools and an investigation of existing best practice is undertaken in the following Section.

2.13 Rainwater Harvesting Decision Support Tools

Modelling tools and methodologies have been developed by international researchers over the last 20 years to facilitate the basic evaluation (and design) of RWH systems. Key studies have focussed on objectives associated with matching water availability (e.g. rainfall) with water demand (Dixon *et al.*, 1999, Roebuck *et al.*, 2011, Campisano and Modica, 2012a, DeBusk, 2012, Ward *et al.*, 2012c). As both rainfall and water demand are temporally variable, RWH evaluation models are frequently used as a design tool to calculate the volume of storage required to balance these inflows and outflows, such that the water demand is adequately met for a specific building or location. Evaluation tools are commonly based on mass balance models which enable design or analysis to be conducted on a variety of spatial and temporal scales (Fewkes and Butler, 2000, Roebuck *et al.*, 2012, Campisano, 2013, Melville-Shreeve *et al.*, 2016b, Ward *et al.*, 2010). Typically RWH models combine a set of interrelated modules which include the following;

1) A behavioural model, to represent rainwater demand (D). Demand can be taken from historic meter data, real-time metering data, or literature derived estimates of rainwater demands.

2) A rainwater yield (Y) model to represent available water. These are based on synthetic rainfall series or rain gauge data. Temporal datasets range from minutes to months with spatial proximity ranging from on-site rain gauges to regional averages;

3) A calculation module which enables mass balance calculations to be performed whilst accounting for losses at each time step (such as roof runoff losses, first flush losses, filter losses, tank overflows, and planned discharges/drain-downs);

4) An output module which logs, summarises and presents data from each simulation.

The demand model represents user behaviour and this aspect is arguably the hardest aspect to accurately quantify as other parameters can be designed (e.g. roof area / tank size) whereas demand profiles are user specific. Demand profiles can vary between seemingly identical households in similar locations due to various socio-technical factors including varying work patterns, household demographics and deployment of different water fittings (e.g. low-flush WCs). Empirical datasets illustrate water demands to be highly variable however, RWH evaluators will frequently fix the demand as an average value to enable simulations to be completed (Parker and Wilby, 2012, Ward *et al.*, 2012a, Melville-Shreeve *et al.*, 2016b). Sensitivity analyses are warranted where behavioural models are based on a low level of evidence. In contrast, reflective evaluations which analyse the historical use of water demand based on (for example) daily water use data can give accurate estimates of water saving efficiencies. Studies that use high resolution demand data from empirical studies can provide highly accurate outputs (Campisano and Modica, 2014). The yield model must also account for significant input variability, although this can be simplified by using low resolution (spatially and temporally) regional averages. Model output accuracy can be improved by running simulations at higher frequencies (daily or sub-daily time steps), especially where site specific rainfall datasets are available (Ward *et al.*, 2012c).

Figure 2.22 illustrates a RWH system and the interaction of typical model components. Parameters for the design, evaluation and installation of RWH systems have been defined in design guidance across the globe (Texas Water Development Board, 2005, Standards Australia, 2008, (BSI), 2013b). Typical modelling of RWH systems adopt the size parameters illustrated ni Figure 2.22. In addition to the parameters described in Figure 2.22, evaluation tools require a time step to be selected to enable realistic representations to be developed.

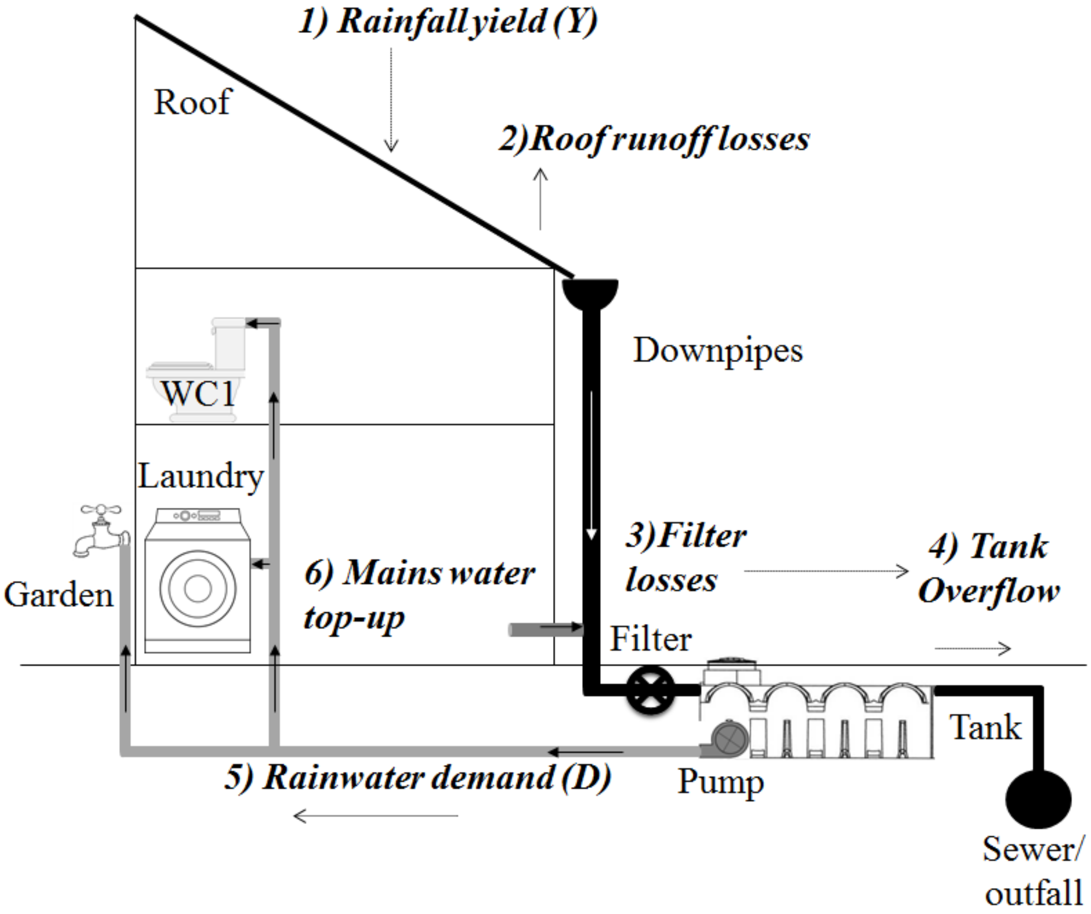


Figure 2.22 – Components and parameters of typical RWH evaluation models

Fewkes and Butler (2000) first defined the basic modelling approaches of “yield after spillage” (YAS) and “yield before spillage” (YBS) in the context of RWH and these have been used in many models since:

(Equation 2.2)

$$Y_t = \min\begin{cases} D_t \\ V_t - 1 \end{cases} \qquad V_t = \min\begin{cases} V_t - 1 + Q_t - Y_t \\ S - Y_t \end{cases}$$

$$Y_t = \min\begin{cases} D_t \\ V_t - 1 + Q_t \end{cases} \qquad V_t = \min\begin{cases} V_t - 1 + Q_t - Y_t \\ S \end{cases}$$

$Where\ Dt\ =\ Demand\ during\ time\ interval\ t$

$Vt\ =\ Volume\ in\ store\ during\ time\ interval\ t$

$Qt\ =\ Rainwater\ inflow\ during\ time\ interval\ t$

$Yt\ =\ Yield\ from\ store\ during\ time\ interval\ t$

$S\ =\ Store\ capacity$

The YAS operating rule defines the yield at a given time interval as the smallest of either the demand or the volume of rainwater available in the storage tank from the preceding interval. Rainwater inflow is then added to the volume within the store with any excess spilling via the overflow before the yield is subtracted. The YBS operating rule defines the yield at a given time interval as the smallest of either the present demand or the storage volume from the preceding time interval plus the rainwater inflow from the current time interval. Fewkes and Butler (2000) undertook an assessment that defined water saving efficiency by modelling a RWH system at a range of time intervals (hourly, daily and monthly) with the YAS and YBS operating rules tested. Their conclusions support the use of the YAS operating algorithm for design purposes as it results in a more conservative estimate of water saving efficiency. Water efficiency modelling approaches within RWH tools have been widely shown to give accurate representations when daily time step intervals are used (Fewkes and Butler, 2000, Fewkes, 2007). However, RWH tools can be manipulated to use a wide range of time steps with selection based on the resolution of data available. Recent work by Campisano and Modica (2014) has further exemplified the opportunity for high resolution data to drive accurate simulations, including an emphasis on stormwater retention. A range of studies which provide further details of existing RWH evaluation tools is summarised in Table 2.7. Research identifying RWH water saving efficiencies in a wide range of international settings is ongoing (Kim and Yoo, 2009, Ghisi and Schondermark, 2013, Karim *et al.*, 2015, Unami *et al.*, 2015).

Table 2.7 – Details of RWH evaluation tools

		Main focus of tool		
Author	Tool	Water efficiency	Stormwater control	Details
Basinger *et al.* (2010)	SARET (Storage and Reliability Estimation Tool)	Yes	No	Behavioural simulation with stochastic precipitation generator based on historical data. Focus on developing reliable RWH sizing tool.
Briggs and Reidy (2010)	Advanced Water Budget Analysis	Yes	Partial	Behavioural simulation with historical precipitation. Focus on USA applications.
Guo and Baetz (2007)	NA	Yes	Partial	Analytical probability distributions
Jones and Hunt (2010)	Rainwater Harvester	Yes	Partial	Behavioural simulation with historical precipitation. Focus on USA case study.
Palla *et al.* (2011)	NA	Yes	No	Behavioural simulation with historical precipitation. Focus on Italian case study.
Roebuck and Ashley (2008)	RainCycle	Yes	Partial	Behavioural simulation with historical precipitation. Focus on UK use.
Vieritz *et al.* (2007)	TANK	Yes	No	Behavioural simulation with historical precipitation. Focus on Australian location.
Zhang et al (2010)	AquaCycle	Yes	Yes	Behavioural simulation with historical precipitation. Focus on Australian location.

Researchers have further developed these methods and integrated facilities to analyse whole life costs within evaluation tools (Roebuck, 2008, Ward *et al.*, 2012b). Furthermore, methods have been extended to enable life cycle analysis of RWH systems to be conducted (Neto *et al.*, 2012, Loubet *et al.*, 2014, Morales-Pinzón *et al.*, 2015, Devkota *et al.*, 2015). Such studies enable the benefits of RWH technologies to be holistically assessed against alternative water supply strategies.

As asserted in Figure 2.2, RWH is increasingly being considered as an option for satisfying both local water demand and for contributing to stormwater management. These are typically larger-sized tanks, some with two compartments or zones, one designed to stay as full as possible to satisfy water demand and one designed to stay as empty as possible to allow capture and attenuation of rainfall-runoff. Conseqeuently, RWH evaluation tools have been further extended to enable stormwater management metrics to be evaluated (Kellagher and Maneiro Franco, 2007, Memon *et al.*, 2009, Gerolin *et al.*, 2010, Campisano, 2013, Campisano & Modica 2016, Campisano & Lupica 2016, DeBusk *et al.*, 2013). Mugume *et al.* (2015) used a hydraulic model to demonstrate the benefits of dual purpose RWH systems when deployed at a city scale to meet both stormwater and water efficiency objectives.

In summary, modelling methods which simulate RWH performance have been widely shown to give accurate representations when daily time step intervals are evaluated within a model. Further work is required to develop RWH modelling tools to evaluate stormwater discharges under a range of settings and configurations. A new methodology for evaluating RWH for source control and water demand management will be developed (Chapter 4) and tested (Chapter 6). To support this research further studies were necessary to generate empirical data from laboratory and pilot projects as described in Chapter 5 of this thesis.

A broad review of RWH literature has been completed to investigate academic and industrial literature relating to the drivers and barriers pertinent to UK RWH systems. Reflecting on; 1) the current state of the art evaluation tools; 2) the need for dual purpose RWH systems and; 3) the opportunity to adapt the UK’s water and wastewater infrastructure to face a changing climate; a conceptual model has been described to illustrate the potential benefits which were targeted throughout the thesis.

2.13.1 Defining a conceptual model for benefits of dual purpose RWH systems

Füssel's (2007) model of planned adaptation captures the opportunity for a technology (in this case RWH) to be used as an adaptation measure. It described the ability of a system to cope with variation associated with climate attributes. As identified in this chapter, RWH can provide sustainable water management benefits such as stormwater control and water demand management. Hence for a single adaptation technology, dual benefits associated with RWH deployment are potentially achievable as coping is increased in relation to reduced stormwater discharges and lower water demand. In contrast to Füssel's (2007) model, where the planned adaptation provides an ability to cope with the gradual increase in magnitude of a single climate attribute, RWH's ability to control stormwater and provide alternative non-potable water allows the red lines on Figure 2.23 to be extended to show an increased coping range for *both* rainfall increase and decrease.

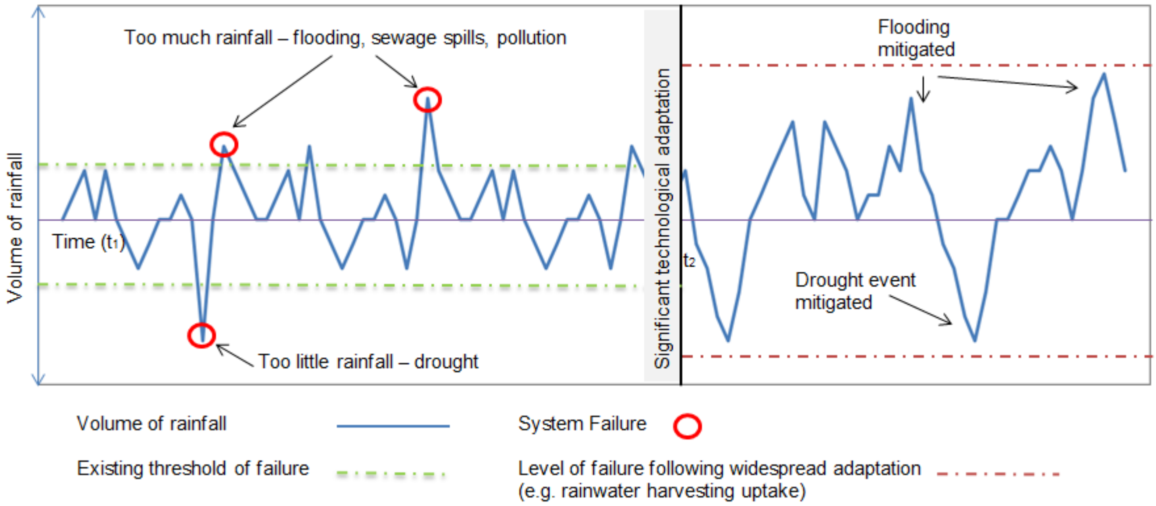


Figure 2.23 – A conceptual model for reduced system failure through implementation of dual purpose RWH as a technological adaptation tool

This conceptual model connects the resilience framework set out in Butler *et al.* (2014) with Füssel (2007) to show that there can be multiple benefits of RWH for water infrastructure stakeholders. Linking these benefits directly to the decision makers who choose to install RWH systems would potentially support growth of UK RWH uptake. Subject to the overall benefits of installing RWH systems being greater than the negative impacts, alternative financial arrangements could be developed to incentivise and support the growth of RWH in the UK. As described in Conte *et al.* (2012) adaptation to climate change in the water management sector will become increasingly important in the decades ahead. Consequently, the increased understanding of benefits associated with RWH deployment could see continued sector growth in the coming decade (Ward, 2010). In addition, the development of design tools and RWH configurations which can satisfy the UK's SuDS industry could play an important role in the applicability of RWH to new-build and retrofit scenarios as a dual purpose technology. Work conducted in the development of this thesis has focussed on this opportunity as summarised in the Chapter Summary.

2.14 Chapter Summary and Scope for Further Work

This literature review was conducted to satisfy Objective 1, to investigate the drivers and barriers associated with dual purpose RWH implementation in the UK. In addition the review satisfies Objective 2, to evaluate state of the art RWH decision support tools. The literature review investigated a broad range of themes including; AWR, RWH definitions, drought mitigation, UK water sector governance, flood mitigation, SuDS, RWH design standards, energy consumption, RWH design methods, RWH decision support tools and climate change adaptation.

Reflecting on the literature evaluated in this review, key research gaps were defined which enabled the formulation of the wider research objectives:

- Identify and comprehensively describe traditional and novel RWH configurations that may have holistic benefits when evaluated as dual purpose technologies.
- Build upon existing RWH modelling approaches to develop an evaluation methodology and decision support tool that can support investigation of a wide range of RWH configurations in terms of stormwater control and water demand management.
- Install, monitor and model laboratory-scale and real world RWH systems to obtain empirical evidence demonstrating their performance against a range of metrics such as water demand management, energy demand, water quality and stormwater management / source control.
- Analyse traditional and novel RWH systems throughout the UK to evaluate their performance as water demand management and stormwater control technologies.

Chapter 3: RWH Typologies: A framework for describing RWH configurations

3.1 Chapter Overview

This chapter describes a detailed investigation of RWH configurations identified from the literature as having the potential to satisfy multiple design objectives. The chapter sets out the wide variety of configurations that could potentially be deployed to satisfy a range of criteria such as water demand management, stormwater control, and the provision of low-energy water resources. Hence this chapter makes a contribution to knowledge by collating a range of resources which have the potential to support the design and implementation of multi-purpose RWH systems. The chapter describes 72 RWH configurations that could be adopted in the UK (and potentially elsewhere) and sets out a high-level selection methodology the “RWH design toolkit” to enable RWH designers to combine available RWH components to select the most suitable configuration for a given site. The research presented in this chapter was published in Melville-Shreeve *et al.* (2016b).

3.2 Introduction

As illustrated in Chapter 2, RWH systems in the UK have traditionally been installed at domestic residences for the single objective of providing a non-potable water supply for use in toilets, laundry facilities and for garden irrigation (Environment Agency, 2011b, (BSI), 2013b). Unlike some fully off-grid configurations implemented elsewhere (Ahmed *et al.*, 2010, Texas Water Development Board, 2005), system configurations in the UK are supplemented by mains water supplies for potable water applications such as drinking, bathing and dishwashing. Germany has seen strong uptake of RWH technologies as reported by Partzsch (2009) with 80,000 installations per annum and a total industry value of 340 million Euros. With successful growth in that market driven by policies that seek to (financially) support green technologies, one in three houses constructed in 2005 installed a rainwater tank. However, the nascent UK RWH installation market has developed with early-adopters purchasing well-established technologies that directly derive from installations found in countries where RWH is now mainstream, such as Germany (Herrmann and Schmida, 1999) and Australia (Burns *et al.*, 2014). The design of these products seeks to satisfy a single objective, to reduce water demand by utilising rainwater as a cost effective alternative water resource.

A review of configurations from three leading RWH system providers in the UK illustrates that they either license products from European manufacturers or have mimicked such configurations (Stormsaver, 2014, Rainwater Harvesting Ltd., 2014, Graf, 2014). Whilst suitable for some sites, the direct transplantation of these off-the-shelf, traditional RWH system configurations into the UK marketplace could prevent optimal RWH solutions from being installed, as the current market-place only offers a limited range of technologies to potential purchasers (Ward *et al.*, 2009). Additionally, these traditional RWH systems are best suited to new build houses with large gardens or driveways (under which tanks can be placed) with high non-potable water consumption. They can be difficult and costly to retrofit and may have high maintenance requirements (Ward *et al.*, 2012a). House building trends in the UK are for smaller properties with low-flush toilets and less garden space. Recent research on water using practices revealed that 62% of the sample had some garden applications for which rainwater could be used (plants, flowers, lawn). However, 26% of this subset did not irrigate or water their gardens, but simply waited for rain (Pullinger, 2013). In combination, this means that there is a growing need for retrofittable RWH systems (Ward *et al.*, 2009) which utilise smaller rainwater tanks. However, there are few commercially-available systems to address this opportunity. Furthermore, optimal RWH systems might be designed to respond to a wider set of drivers than simply achieving (non-potable) water supply, such as reducing total water related energy consumption and improving stormwater control.

Minimal government incentives, subsidy or support for RWH means the UK market remains nascent. At the residential property scale, installation rates remain low with the market reportedly worth just £8 million in 2009 (MTW, 2010). This is no doubt due to the whole life cost benefits of traditional configurations resulting in long payback periods to individual purchasers (Roebuck *et al.*, 2011). There is therefore a need to identify and develop a range of affordable, retrofittable and multi-benefit RWH system configurations and options to respond to these property and regime level drivers.

In this chapter, traditional and innovative RWH systems have been identified and their configurations described. Secondly, components have been categorised to enable innovations from existing configurations to be combined in novel ways to generate new designs. The chapter demonstrates the ability of RWH systems to satisfy a number of objectives and the methods identified are intended to support designers, householders, water companies and installers in understanding the broader opportunities presented by emerging innovative RWH technologies.

3.3 Existing Cost-Benefit Approaches to RWH Assessment

A straightforward method of financial appraisal can be achieved by evaluating the payback period for a RWH system. This sets the capital cost against the long-term savings generated from the reduced water supply and associated sewerage costs. Contemporary RWH studies and modelling tools also integrate the operational costs and planned maintenance costs (for example pump replacement and tank cleaning) (Neto *et al.*, 2012). Such an approach was demonstrated by Roebuck *et al.* (2011) who concluded that a whole life cost (WLC) approach is most appropriate for undertaking financial appraisal of RWH systems in the UK. This research advocated the need to include capital, maintenance, operational and decommissioning costs while attributing financial benefits to the savings linked to water and sewerage tariff reductions. Ward *et al.* (2012a) agree that WLC approaches represent best practice and propose that daily rainfall datasets should be deployed to enable more accurate modelling of RWH systems (Ward *et al.*, 2010). Roebuck *et al.* (2012) extended their earlier research to illustrate that use of simplified tools (for example those that do not account for WLC) can result in designs that have hypothetically viable payback periods but cost more to maintain and operate than they save when whole lifecycle costs are included.

A wider review of literature and RWH system design tools illustrates that appraisal beyond financial benefit is lacking (Steffen *et al.*, 2013, Jones and Hunt, 2010, Friedrich, 2007). An appraisal under a single objective to “maximise whole-life financial benefit of rainwater use” omits many of the additional benefits offered by RWH systems. Consequently, examination of novel RWH system configurations benchmarked against a wider set of criteria is warranted.

3.4 A Framework for RWH Evaluation under a Range of Criteria

Taking forward research initiated by Coombes (2002), this chapter develops a conceptual decision space that trades off whole life benefits and whole life costs. This concept frames the need for innovation in the context of the UK’s RWH industry through visualizing system configurations using a Pareto front as illustrated in Figure 3.1. The delivery of optimal rainwater management is currently constrained by the size and variety of the original set of RWH solutions at the designer’s disposal. For example, if the designer of a new housing development is aiming to install an alternative water resource, they might reasonably investigate the relevant British Standards: BS8595:2013 Code of practice for the selection of water reuse systems ((BSI), 2013a); BS8525-2:2011 Greywater systems. Domestic greywater treatment equipment requirements and test methods (BSI, 2011); and BS8515:2009+A1:2013 Rainwater Harvesting Systems – Code of practice ((BSI), 2013b). The components and configurations included within these standards might be extracted and evaluated on a case-by-case basis using a handful of cost benefit metrics. These designs represent the total set of potential design solutions. The designer may conclude that RWH is not a cost effective option, as no solutions evaluated met the designer's budgetary constraints. Consequently, the initial target to incorporate rainwater management into the development remains unmet. In graphical form, this is conceptualised in Figure 3.1. It is evident from this graphic that expanding the original set of solutions may increase the likelihood that suitable RWH system configurations can be identified. In this example, Figure 3.1 identifies that two previously "unseen" solutions are available to the designer that are within budget but were not considered in the previously limited decision space (located to the left of the dashed line).

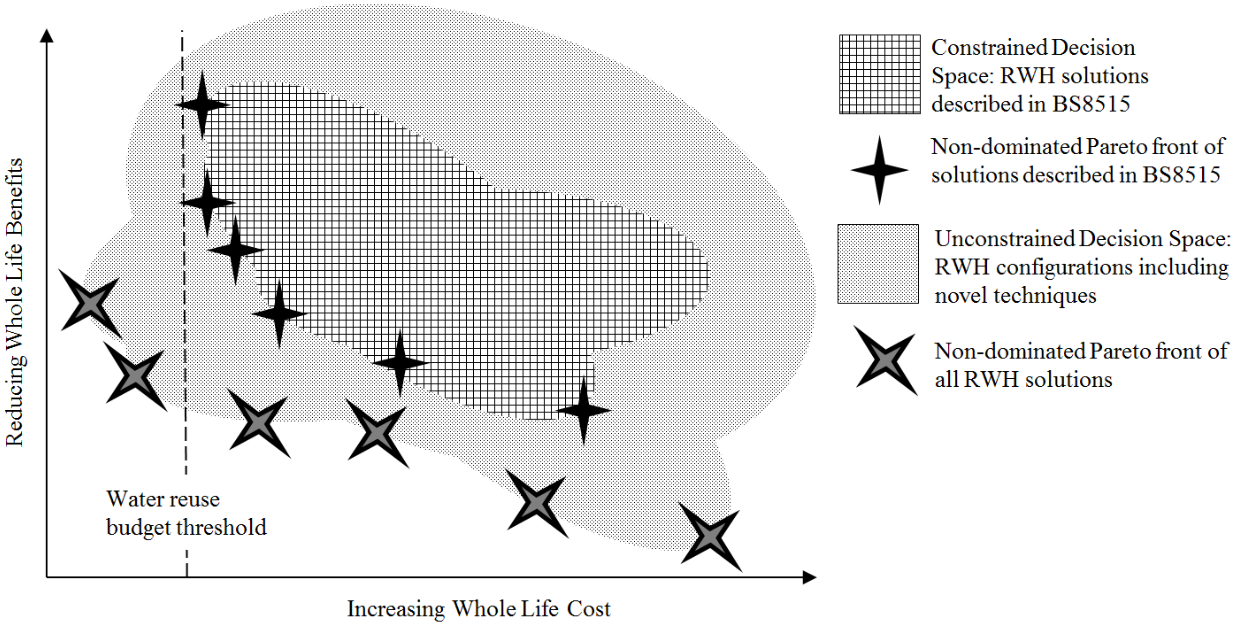


Figure 3.1 – Conceptualising the benefits of novel RWH system configurations (adapted from Coombes, 2002)

It is proposed that the development of a quantitative RWH assessment tool that incorporates a range of criteria will enable practitioners to widen the decision space and implement RWH systems in locations where single objective benefit appraisals fail to satisfy cost benefit criteria.

3.5 A Method for Identifying RWH System Configurations and Drivers

Continued innovation in RWH design has been ongoing within the RWH industry and the academic research community (Diaper *et al.*, 2001, Lazarova *et al.*, 2003, Gerolin *et al.*, 2010). The method set out in this chapter seeks to answer the following problem statement: "Identify a range of traditional and novel multi-purpose RWH technologies that could be deployed at a given location."

A two-step process was defined in order to enable RWH configurations to be defined and compared when deployed at a typical UK house.

3.5.1 Step 1 – Define a typical UK house

A set of fixed parameters were generated to enable comparison of RWH configurations to be undertaken at a domestic property. Parameters for a typical UK house are described in Table 3.1. The property is assumed to be located in Exeter, UK and have: a pitched roof with a plan area of 60m^2, four occupants utilising 150l/person/day (with a usage ratio based on existing literature (Butler and Memon, 2006)), space and structural capacity for up to 2 no. 0.25m^3 loft or wall mounted header tanks, and can accommodate up to 5m^3 of above ground or below ground storage.

Table 3.1 – Defining the characteristics for a typical UK house.

Model Parameter	**Reference**	**Value**
Roof Area (m^2)	User Selected	60
Roof Runoff Coefficient	User Selected	0.9
First-Flush Losses (l/day)	User Selected	5
Usage Ratio (WC:Laundry:Potable:Other)	(Butler and Memon, 2006)	30:20:5:45
Tank storage size	User Selected	• 0.5m^3 if located in loft • 0.5m^3 if located externally for gravity feed • 5m^3 if located at or below ground level. (Storage volume reduced to 4.5m^3 where mains top up also enters storage tank)
Time-series rainfall data	Exeter, UK	Daily rainfall (mm) records for Exeter, UK

With parameters for a house defined a range of RWH configurations were identified to enable comparisons to be completed.

3.5.2 Step 2 – Identifying Alternative Options: RWH System Configurations

RWH systems comprise a number of components, which typically include: gutter systems, downpipes, filters, storage tanks, tank overflows, pumps, pressure vessels, pipework, valves, backup supply systems, sensors / float switches and electronic controllers. Details of these components can be identified through grey-literature available from RWH providers (Stormsaver, 2014, Graf, 2014, Rainwater Harvesting Ltd., 2014) and are described in BS8515:2009+ A1:2013 ((BSI), 2013b). Detailed descriptions of well-defined components are not included here as they are already described in existing texts (Roebuck, 2008). Existing literature describing RWH typologies chiefly focuses on a small number of potential configurations (Herrmann and Schmida, 1999). Furthermore, some terminology used does not match terms used by current UK RWH suppliers. The following typologies aim to extend and clarify these terminologies.

3.6 Best Practice in the UK: Traditional RWH System Configurations

In the UK, residential RWH systems typically utilise buried tanks although above ground tanks are also sometimes installed. Pumped flows of stored harvested rainwater are delivered via direct-feed or header tank systems. Consequently, four traditional RWH system configurations were identified as representing current best practice for household installations as described in Figure 3.2 Stormsaver, 2014, Graf, 2014, Rainwater Harvesting Ltd., 2014). The systems illustrated in Figure 3.2 each capture rainfall from the roof and store the filtered rainwater in below ground (3.2.1 & 3.2.3) or above ground (Fig 3.2.2 & 3.2.4) tanks. Harvested rainwater is then delivered by a submersible pump to non-potable applications either by direct-feed (Fig 3.2.1 & 3.2.2) or via a header tank (Fig 3.2.3 & 3.2.4). For the purposes of clarity, the overflow outlet from the system is described as a sewer (for example a combined sewer network) although RWH systems can also discharge to an infiltration device, surface water sewer or watercourse, depending on the site setting.

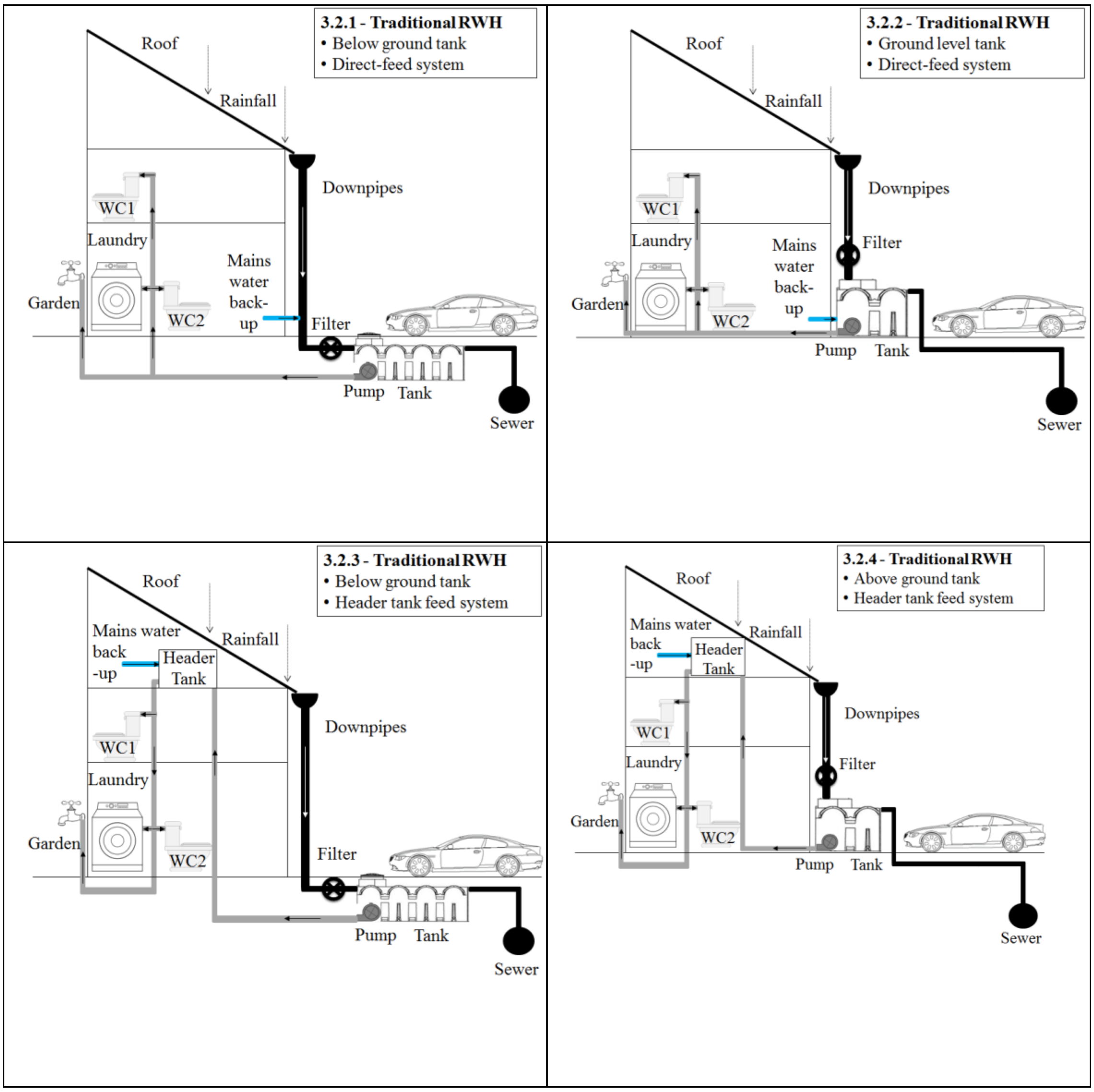


Figure 3.2 – Conceptual schematics for four traditional RWH configurations used in the UK

In addition to the traditional RWH configurations described in Figure 3.2, emerging designs were identified from website and patent searches.

3.7 Emerging Practice in the UK: Innovative RWH System Configurations

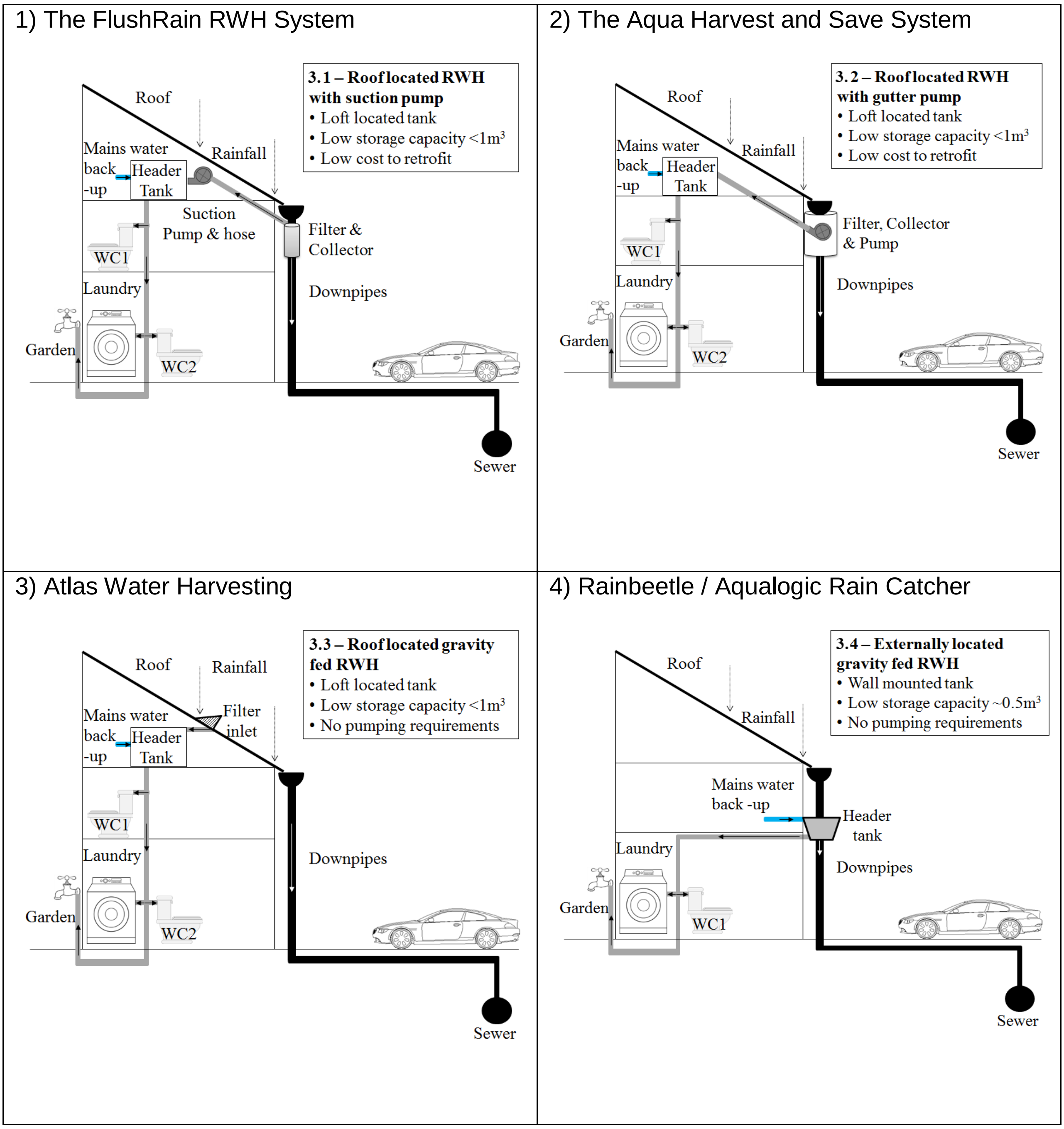
A series of RWH innovations were identified through discussions with industry professionals, web searches and patent reviews. Through the collection of evidence, as described in Table 3.2 it is apparent that stormwater control potentially represents an additional key driver for innovation of RWH configurations. A summary of the innovations identified is set out in Table 3.2 and the configurations are diagrammatically illustrated in Figure 3.3.

A first common theme with the first five of these innovative RWH system configurations is a high-level roof-runoff inlet, which facilitates the replacement of the large ground-level tank with wall-mounted or internal header tanks. This enables rainwater to be propelled by low energy pumps or flow under gravity into header tanks, which in turn feed end uses by gravity. A second common theme with the next three innovative RWH system configurations (Figure 3.3.6-3.3.8) is the inclusion of a ‘sacrificial’ amount of storage that is utilised for stormwater control. These dual purpose RWH systems enable flow to be released from storage either passively, using an orifice at a specifically designed height in the tank, or actively through a release valve. Taking this a step further, Figure 3.3.8 describes a system that includes functionality to enable a central authority (for example the water service provider (WSP)) to control tank levels based on predicted rainfall, to enable real-time control of rainwater discharges to a sewer network. The final innovative RWH system is a treatment train consisting of filtration, UV and ozonation, which is designed to enable harvested rainwater to be treated to potable standards.

Table 3.2 – Innovative RWH system configurations identified by this research

System Provider & Patent No.	Description	Country	References (see footer)
FlushRain Ltd. Patent: GB2449534	A patented suction pump system that captures rainwater from downpipes and stores rainwater in large header tanks. Easily retrofitted, with no external tanks.	UK	[1,2]
Aqua Harvest & Save Patent: GB2480834	A patented gutter-located pump system lifts rainwater into large header tanks. Easily retrofitted, with no external tanks.	UK	[2,3]
Atlas Water Harvesting Patent: GB2496729 & Rooftop Rain Patent:GB2475924 & GB2228521	A gravity-fed inlet is installed within the roof to enable ~50% of the roof to flow under gravity into large header tanks within the loft.	UK	[4,5,6,7]
Aqualogic (ARC); Rainbeetle GB2501313-B	An externally mounted tank, located near the roofline is installed to store rainwater and deliver flows by gravity.	UK	[8]
Hydromentum, Water Powered Technologies ltd.	An externally mounted header tank, drives a passively powered (zero electricity) pump to lift flows to a header tank.	UK	[9]
RainActiv, Rainwater Harvesting Ltd.	A passive rainwater discharge control (flow attenuation system) for inclusion within RWH tanks to ensure some storage is always maintained to attenuate extreme storm events.	Germany, USA, UK	[10,11,12]
KloudKeeper Ltd.	An active rainwater discharge control (flow attenuation system) for inclusion within RWH tanks to ensure some storage is always maintained to attenuate extreme storm events.	UK	[13]
IOTA, South East Water (Aus) & Geosyntec (USA)	A real-time control system that enables weather forecast data to support a decision maker to empty a RWH tank in a controlled way before a storm, thus ensuring capacity is available to capture extreme storm events.	Australia S. Korea, USA	[14,15,16]
RainSafe	Rainwater treatment system that enables harvested rainwater to meet potable water standards.	UK	[17]

***References**: 1)Patent Number GB2449534; 2) Melville-Shreeve (2014a); 3) Patent Number GB2480834; 4) Patent Application Number GB2496729; 5) Atlas Water Harvesting (2015); 6) Patent Number: GB2475924; 7) Patent Application Number: GB2228521; 8) Patent Application Number: GB2501313; 9) Hydromentum (2015); 10) Rainwater Harvesting Ltd. (2014); 11) Melville-Shreeve (2014b); 12) DeBusk et al. (2013); 13) (BSI) (2013b); 14)iota (2014); 15)Reidy (2011); 16) (Han and Mun, 2011) 17) (RainSafe, 2015)*


1) The FlushRain RWH System

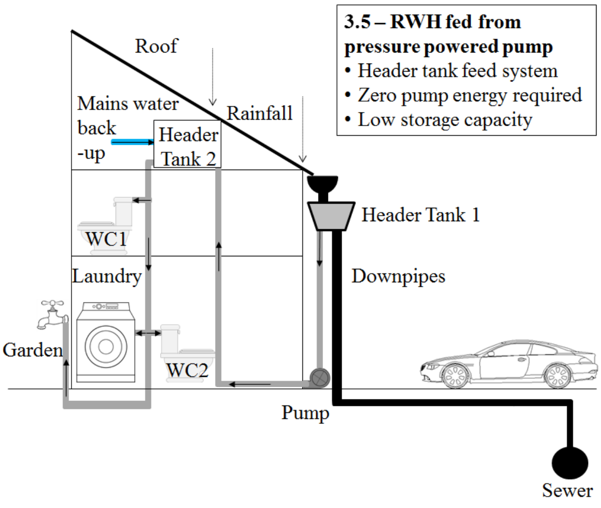
2) The Aqua Harvest and Save System

3) Atlas Water Harvesting

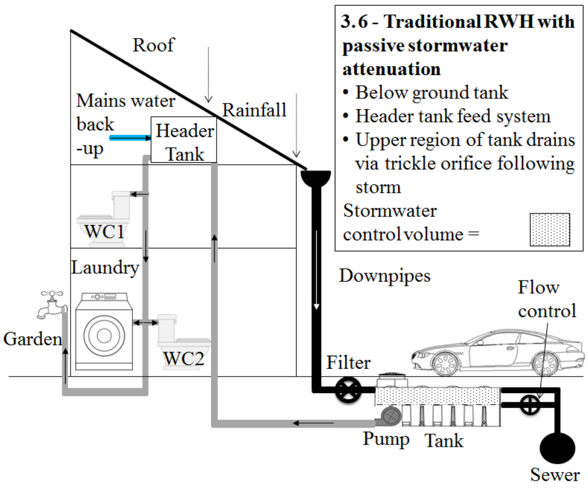
4) Rainbeetle / Aqualogic Rain Catcher

Figure 3.3 – Innovative RWH system configurations emerging in the UK

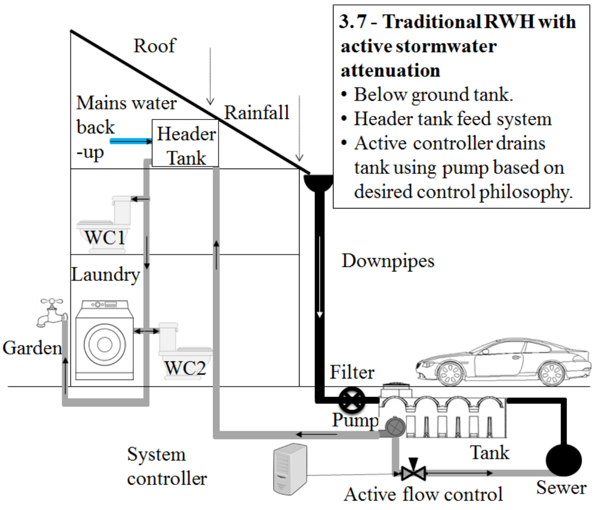
5) Hydromentum, Passively Powered RWH



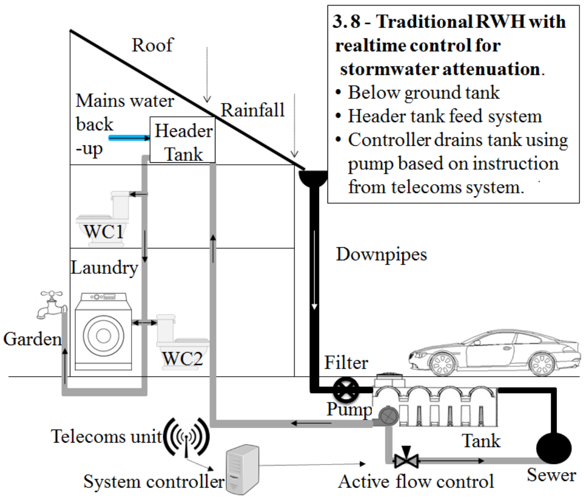
6) Passive Stormwater Attenuation RWH



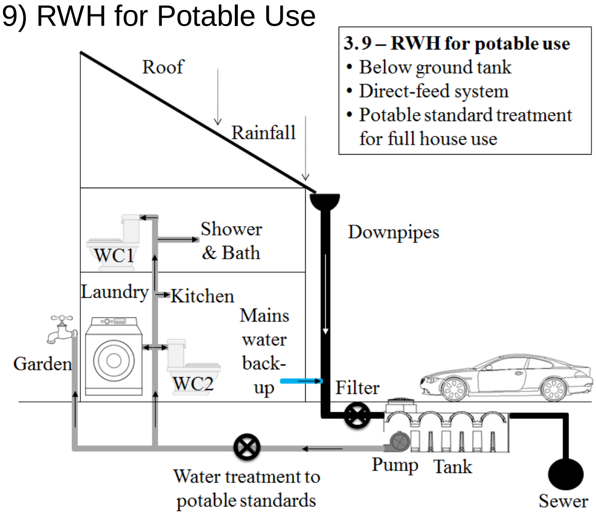
7) Active Stormwater Attenuation RWH



8) Real-time Control Stormwater Attenuation RWH



9) RWH for Potable Use



Having defined a set of novel RWH configurations, the following section sets out an approach to break the systems down into their component parts and categorise each configuration.

3.7.1 Categorising RWH components

A review of industry and academic literature has enabled conceptual descriptions to be provided for a wide range of previously unrecognised RWH configurations. However, engineers designing AWR/AWSS or SuDS systems at new developments are frequently presented with design problems that cannot be solved by off-the-shelf solutions. This is increasingly true when considering opportunities for retrofitting SuDS to existing sites (Stovin and Swan, 2007). Viewing the problem through the designer's lens, it is undesirable for RWH configurations to be limited to a set that can be bought off-the-shelf. Conversely, the majority of industry literature describes off-the-shelf systems, therefore this thesis increases opportunities for designers to consider a broader range of solutions. Through deconstructing the design of RWH systems into a subset of component categories, it is possible to generate a broader set of configurations.

A set of five component categories were defined to enable all of the innovations identified in this chapter to be combined in a manner previously undescribed. This approach enabled the combination of novel technologies to be considered for a single domestic installation. The five categories are described in Figure 3.4 and include; Tank Locations; Delivery System; Pump Location; Stormwater Control Measures; and Water Treatment Measures. Through selection of a component from each category (C_1-C_5), a designer is able to develop novel solutions that have the potential to outperform (in the broadest sense) the traditional configurations described in existing patents and literature.

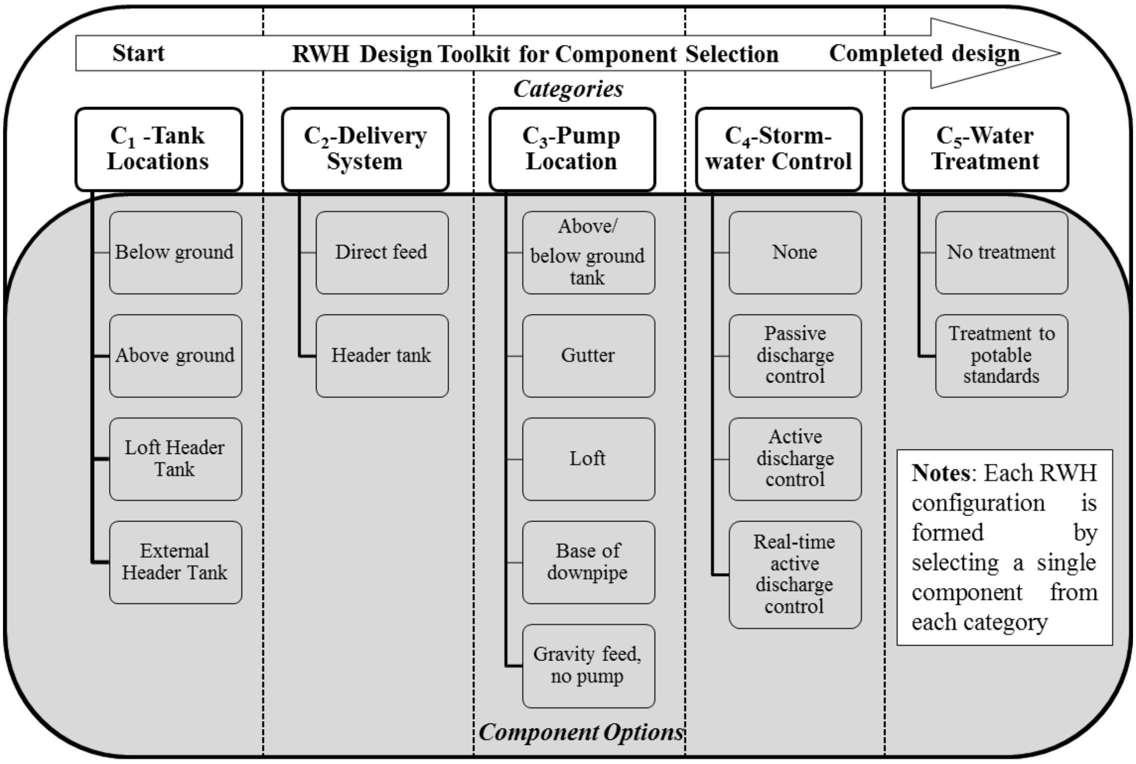


Figure 3.4 – Design toolkit for selection of RWH components

The RWH Design Toolkit was used to investigate how a range of components can be combined to generate a wider set of RWH configurations than those currently described in existing texts.

3.8 Defining a Complete Set of Configurations

A complete set of configurations was developed by grouping every possible combination of RWH components described in Figure 3.4 to generate 320 hypothetical design configurations. However, not all of these solutions were identified as technically feasible (for example it is not viable to install a RWH system with a below ground tank that utilizes a pump located in the gutter). Consequently, a reduced set of 72 technically feasible RWH system configurations was derived, each of which could potentially be installed at the UK house characterised in Table 3.1. The 72 viable RWH configurations identified by this approach are described in Table 3.3.

Table 3.3 – 72 technically viable RWH configurations identified by this research

Traditional RWH with large below ground or above ground tanks	1-BG-DF-TK-NS-NT	*Pump in gutter, tanks in loft*	33-LH-HT-G-NS-NT	*External wall-mounted tank*	65-EH-HT-NP-NS-NT
	2-BG-DF-TK-NS-TT		34-LH-HT-G-NS-TT		66-EH-HT-NP-NS-TT
	3-BG-DF-TK-PD-NT		35-LH-HT-G-PD-NT		67-EH-HT-NP-PD-NT
	4-BG-DF-TK-PD-TT		36-LH-HT-G-PD-TT		68-EH-HT-NP-PD-TT
	5-BG-DF-TK-AD-NT		37-LH-HT-G-AD-NT		69-EH-HT-NP-AD-NT
	6-BG-DF-TK-AD-TT		38-LH-HT-G-AD-TT		70-EH-HT-NP-AD-TT
	7-BG-DF-TK-RTAD-NT		39-LH-HT-G-RTAD-NT		71-EH-HT-NP-RTAD-NT
	8-BG-DF-TK-RTAD-TT		40-LH-HT-G-RTAD-TT		72-EH-HT-NP-RTAD-TT
	9-BG-HT-TK-NS-NT	*Pump and tanks in loft*	41-LH-HT-L-NS-NT	**KEY** BG=Below Ground AG=Above Ground LH=Loft Header Tank EH=External Header Tank DF=Direct-Feed HT=Header Tank TK=Pump in AG/BG Tank G=Pump in Gutter L=Pump in Loft DP=Passive Powered Pump at Base of Downpipe NP=No Pump NS=No Stormwater Control PD=Passive Stormwater Control AD=Active Stormwater Control RTAD= Real-Time Active Stormwater Control NT=No Water Treatment TT = Potable Water Treatment	
	10-BG-HT-TK-NS-TT		42-LH-HT-L-NS-TT		
	11-BG-HT-TK-PD-NT		43-LH-HT-L-PD-NT		
	12-BG-HT-TK-PD-TT		44-LH-HT-L-PD-TT		
	13-BG-HT-TK-AD-NT		45-LH-HT-L-AD-NT		
	14-BG-HT-TK-AD-TT		46-LH-HT-L-AD-TT		
	15-BG-HT-TK-RTAD-NT		47-LH-HT-L-RTAD-NT		
	16-BG-HT-TK-RTAD-TT		48-LH-HT-L-RTAD-TT		
	17-AG-DF-TK-NS-NT	*Passively activated ram pump*	49-LH-HT-DP-NS-NT		
	18-AG-DF-TK-NS-TT		50-LH-HT-DP-NS-TT		
	19-AG-DF-TK-PD-NT		51-LH-HT-DP-PD-NT		
	20-AG-DF-TK-PD-TT		52-LH-HT-DP-PD-TT		
	21-AG-DF-TK-AD-NT		53-LH-HT-DP-AD-NT		
	22-AG-DF-TK-AD-TT		54-LH-HT-DP-AD-TT		
	23-AG-DF-TK-RTAD-NT		55-LH-HT-DP-RTAD-NT		
	24-AG-DF-TK-RTAD-TT		56-LH-HT-DP-RTAD-TT		
	25-AG-HT-TK-NS-NT	*Gravity inlet feeds loft tanks*	57-LH-HT-NP-NS-NT		
	26-AG-HT-TK-NS-TT		58-LH-HT-NP-NS-TT		
	27-AG-HT-TK-PD-NT		59-LH-HT-NP-PD-NT		
	28-AG-HT-TK-PD-TT		60-LH-HT-NP-PD-TT		
	29-AG-HT-TK-AD-NT		61-LH-HT-NP-AD-NT		
	30-AG-HT-TK-AD-TT		62-LH-HT-NP-AD-TT		
	31-AG-HT-TK-RTAD-NT		63-LH-HT-NP-RTAD-NT		
	32-AG-HT-TK-RTAD-TT		64-LH-HT-NP-RTAD-TT		

To exemplify the approach, a route through the design toolkit is defined in Figure 3.5 (highlighted in dashed lines) and a resultant configuration is exemplified in Figure 3.6. This combination of components enables two novel approaches to be integrated giving a new RWH configuration that uses gravity fed loft tanks to feed household water demands. In addition the system has an active control system that can ensure that the tanks always have some capacity to satisfy a designer's source control objective (e.g. capture the 1 in 100 year 6 hour storm event).

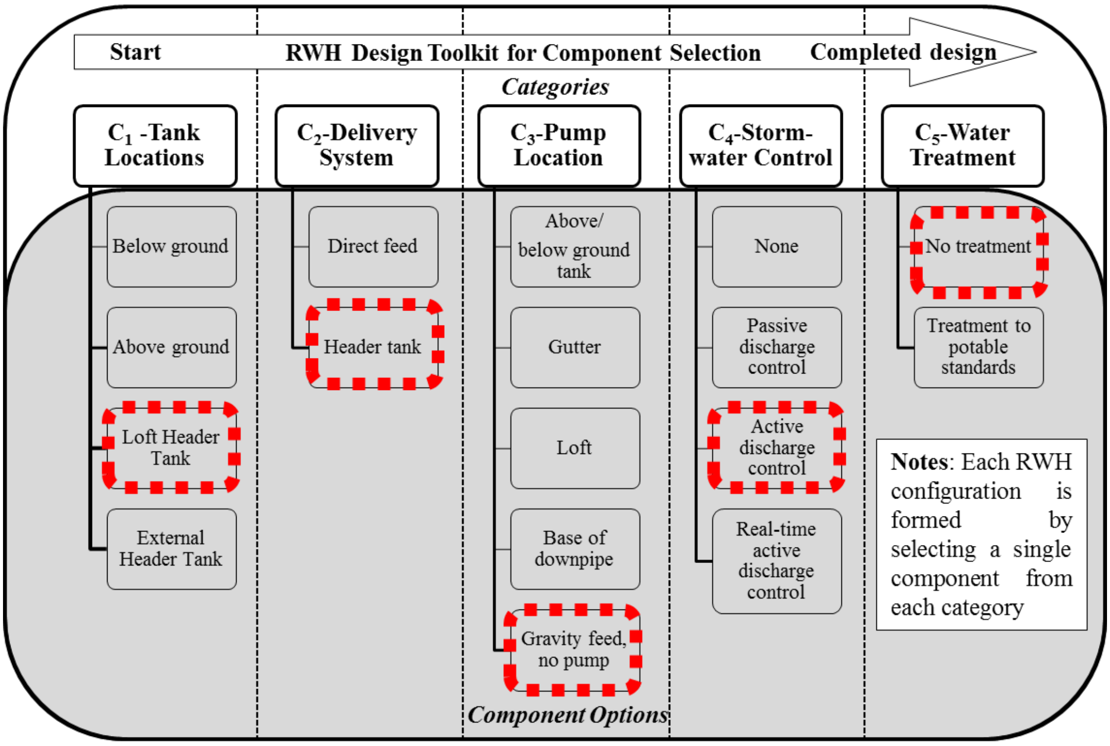


Figure 3.5 – Using the design toolkit to define a new RWH configuration

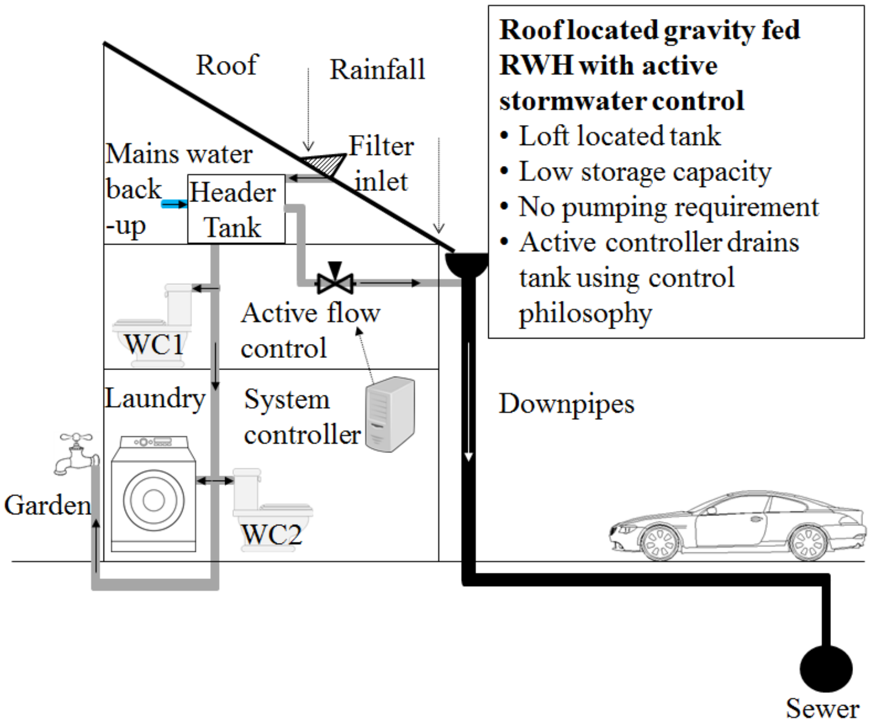


Figure 3.6 – Previously undescribed RWH configuration as defined in Figure 3.5

With a holistic set of RWH configurations defined in Table 3.3, the following section investigates the practical application of the process using high level design scenarios.

3.9 Demonstrating a new RWH Selection Process

The set of 72 RWH configurations described in this chapter can potentially be deployed at new build or retrofit sites. To date, SuDS designers have been limited in their ability to specify a range of RWH systems as UK RWH suppliers only offer a handful of design configurations. Using the approach described in this chapter a designer can identify a range of RWH designs that could be suitable at a potential site. Subsequently, the costs and benefits of each RWH system can be calculated as set out in BS8515:2013 ((BSI), 2013b) or using a tool such as RainCycle (Roebuck, 2008). The designer would then be able to make an evidence-based decision to identify the most cost effective configuration for the site, ideally using a whole life cost approach.

Three scenarios are defined below to outline how a preferred configuration might be defined by differing decision makers. The assumptions made in the scenarios are based on the authors' knowledge.

Scenario A – A housebuilder must satisfy a planning condition which requires a RWH system to be constructed that provides all non-potable water for the site (WCs and laundry and garden uses), *AND* incorporate a SuDS feature to capture and attenuate the critical 1 in 100 year rainfall event. Hence, traditional RWH with passive source control (3 or 11 in Table 3.3) or traditional RWH with RTC (7 or 15 in Table 3.3) may be considered as the preferred option as these configurations are able to *fully satisfy* both of the housebuilder's criteria while many of the alternative configurations do not.

Scenario B – A householder wishes to retrofit a RWH system at the lowest possible capital cost. No other criteria hold importance in the system selection process. The two lowest capital cost systems are therefore potentially appropriate roof located, gravity fed RWH, or externally located, gravity fed gravity RWH (47 or 65 in Table 3.3).

Scenario C – A WSP plans to retrofit houses with RWH as a water demand reduction measure. They also have a secondary objective to reduce peak stormwater flows at a local sewage pumping station. Costs are not an important factor as no alternative solutions have been identified by the WSP. Hence traditional RWH with passive source control (3 or 11 in Table 3.3) or traditional RWH with RTC (7 or 15 in Table 3.3) may be considered as the preferred option as these configurations are able to *fully satisfy* both of the designer's criteria.

The three scenarios described above each illustrate the broad ability of RWH configurations to satisfy a range of design and performance objectives, and exemplify the need for better comprehension of the lesser known configurations within the water sector. With just a single RWH design available to designers, RWH is more likely to be ruled out during a strategic evaluation phase. However, with a broader range of RWH configurations available within a designer's toolkit, there is an increased chance that a cost effective solution can be selected.

3.10 Limitations

The RWH design toolkit described above is a simplified method to enable designers to define a more complete set of RWH configurations. The approach is intended for use at a conceptual or strategic level by users considering how they could integrate RWH into a new or existing property. In turn it presents opportunities for RWH to be installed in a wider range of niches than currently perceived possible by the design community / RWH installation providers.

Several key limitations have been identified in the development of the research presented in this chapter:

1) The combination of novel components to generate new configurations may result in the design of RWH systems that cross-cut existing intellectual property rights such as patents or design rights. i.e. their implementation may not be permissible.
2) The RWH design toolkit represents a strategic level tool. It does not enable a site-level analysis to be conducted. Detailed site-specific data will be necessary to support designers in sizing tanks and selecting suitable components to incorporate within RWH systems for a given location.
3) A wide range of components are available from suppliers. For example, tanks come in a range of materials, shapes and sizes and a large number of pumps are available for use within RWH systems. The RWH design toolkit does not differentiate between the specifications of such items and consequently, each of the 72 conceptual configurations can be further varied during the detailed design stage to finalise an appropriate specification for each component.

3.11 Conclusions

This chapter presented the identification and description of existing and novel RWH configurations that could be adopted at UK households to satisfy a broad range of property and regime level drivers. In addition, through categorising the components identified in the novel configurations, a series of new RWH configurations was described. The evidence collated to undertake this research illustrates that a broad range of RWH configurations is emerging in the UK marketplace. Through describing the opportunities to combine a range of components, it is argued that RWH installations could potentially now take place at a wider set of technical niches / site locations. The specific configuration selected for a given location will depend on the preferences of the decision maker and should be based on local data wherever possible. Furthermore, a second tier of decision making is necessary in order to specify each component (i.e. pump sizing, tank selection, filtration selection etc.) Based on the evidence collated, it is suggested that minor alterations to existing RWH configurations, such as integration with real time stormwater control devices, could see demand for RWH systems grow in the years ahead. This may be especially valid where stormwater control is desirable to meet drainage design criteria at new developments, or to reduce sewer flooding and spills in existing combined sewer catchments. The identification of RWH systems as a multi-functional technology is exemplified in this chapter. This chapter has also highlighted the opportunity to develop further methods that investigate the day to day functionality of the configurations described. The development of a RWH performance evaluation method under a range of criteria is therefore described in Chapter 4.

Chapter 4: A Methodology for Evaluating RWH Configurations as Water Demand Management and Stormwater Control Devices

4.1 Chapter Overview

Chapter 3 defined a framework for evaluating RWH configurations at a specific location as described in the conceptual model in Figure 3.1. The investigation described a range of novel components that could be combined to enable 72 RWH configurations to be defined. Building on Chapter 1’s investigation of RWH decision support tools, this chapter describes the development of a new RWH evaluation methodology, and associated decision support tool. The methods have been developed to enable AWR/SuDS designers to evaluate the full range of 72 RWH systems using site specific data for a given set of design objectives (e.g. minimise peak stormwater discharges for 1 in 100 year event). Furthermore, the methods can also be used to enable detailed design of the system to be completed, for example through the specification of RWH configurations and tank storage volumes for both water demand and stormwater control functions.

The following research objective (as described in Figure 1.2) is addressed in this chapter: “Develop and test a methodology (the RWH Evaluation Method) for the design and evaluation of RWH systems against water efficiency, stormwater and cost objectives.” To support this two further goals were identified:

- Build on current literature to develop an improved methodology which enables the performance of a range of RWH configurations to be simulated in terms of water efficiency, annual stormwater discharge reductions and peak stormwater discharge reductions.
- Develop a decision support tool to enable designers of RWH systems to rapidly evaluate and interrogate a broad set of design options using the new methodology.

The methodology is then implemented to simulate the performance of a wide range of RWH configurations at case study sites throughout the UK as described in Chapter 6.

4.2 Summary of Existing RWH Simulation Methods

Previous research identified in the literature review, Section 2.13 evidences a wide range of methods and decision support tools that have been developed by both research and industrial communities to evaluate RWH systems (Dixon *et al.*, 1999, Roebuck *et al.*, 2011, Campisano and Modica, 2012b, DeBusk, 2012, Ward *et al.*, 2012c). Key RWH evaluation tools that were assessed to support the methods developed in this chapter are summarised in Table 2.7.

Building on the work completed by international researchers, a set of opportunities have been identified in existing research methods. The limitations of historical studies and the opportunities to extend their methods are described in Table 4.1. The development of a methodology which builds upon the strengths of existing research approaches represents the overarching aim of this chapter. To achieve this, solutions relating to each of the opportunities described in Table 4.1 have been incorporated within the new methodology.

Table 4.1 – Opportunities for improved and extended RWH evaluation methods

Opportunities to improve upon limitations of historical approaches	**Strengths to incorporate in a new approach**
1) Rainfall yield analysis is frequently undertaken using annual-average-rainfall datasets.	1) Daily rainfall datasets will be used to drive simulations of rainwater yield. Sub-daily data sets may also warrant further investigation for the purposes of interrogating peak discharge flows however.
2) Time series analyses which successfully use site specific data to establish the yield are often limited to a single year's evaluation data.	2) 20 year rainfall datasets will be used to drive simulations of rainwater yield.
3) Uncertainty is introduced within existing methods when spatially coarse rainfall data sets from regional-scale	3) Locally available rain gauge data will be used to ensure local rainfall variations are more accurately represented in the model.

Opportunities to improve upon limitations of historical approaches	Strengths to incorporate in a new approach
summaries are used to drive simulations.	
4) Whole life benefits evaluate the quantity and value of water savings, whilst ignoring the broader benefit of controlling stormwater discharges.	4) Both water savings and stormwater control functionality will be evaluated and reported.
5) Metrics and values for stormwater control capabilities are infrequently calculated or reported.	5) Stormwater control capabilities will be evaluated at an equal importance to water demand management by assessing annual and peak daily overflows.
6) RWH model tools focus on evaluating a single configuration without ability to evaluate many of the innovative RWH systems described in Chapter 3.	6) Simulation approaches will enable the flexible evaluation of a range of RWH configurations to be completed. This will include a novel step to enable evaluation of stormwater control features designed into the RWH system.
7) Design of dual purpose RWH which focusses on the need to control stormwater as a key objective has been weakly investigated to date.	7) RWH systems will be evaluated in a manner that enables iterative design of dual purpose RWH systems to be investigated.
8) RWH methods described in academic and industry literature in the UK can be complicated to deploy and comprehend by stakeholders.	8) Outputs from the methods should be clearly set out within a decision support tool to enable RWH scenarios to be easily evaluated using an iterative design approach. Outputs should be clearly useable by research and industrial communities to maximise impact.

4.3 Developing a New RWH Evaluation Methodology

Many of the RWH evaluation methods and tools described in the literature use mass-balance approaches with a prevalence of effort to enable accurate water demand modelling. The efforts to achieve this are well founded as many key facets of RWH investigations can be accurately investigated using mass balance models (Roebuck, 2008, Campisano and Modica, 2014, DeBusk, 2012). However, to date, there has been a prevalence for mass balance models to focus solely on water demand management benefits (Fewkes and Butler, 2000). This methodology extends these approaches to better enable stormwater overflows to be investigated by incorporating some of the principles described in work conducted by Kellagher and Maneiro Franco (2007) and Burns *et al.* (2014).

The starting point for method development is the YAS approach described in Fewkes and Butler (2000) and used to good effect in the RainCycle decision support tool developed by Roebuck (2008). In addition to this, the new methods incorporate the use of site specific time-series-rainfall datasets and the ability to include stormwater control devices such as those described in Chapter 3. The new methodology was implemented using an Excel-based VBA simulation tool referred to as “The Rainwater Harvesting Evaluation Tool (RainWET)”.

4.4 Goals for RainWET Development

RainWET was developed with flexibility in mind to satisfy the following goals:

1) To use high resolution (daily time step) rainfall and water meter data from literature and primary data collection studies to drive simulations.

2) To use long term time series analysis approaches to select / design RWH systems (20 years+).

3) To use local site specific data from proximal rain gauges when possible.

4) To simulate the performance of a wide range of RWH configurations, without being limited to the traditional RWH solutions considered in previous investigations.

5) To provide evaluation metrics which focus on stormwater discharge (both peak runoff and reduction in annual volumes) alongside water saving efficiency.

6) To enable the evaluation of dual purpose RWH configurations to be simulated and compared alongside traditional RWH designs.

7) To enable methods to be accessed within a decision support environment which can facilitate industry users to rapidly evaluate or design RWH options without the need for time-costly, bespoke calculation approaches.

4.5 RainWET description

The system parameters within the RainWET are described in Figure 4.1 and Table 4.2. Rainwater (R_t) arriving at the roof's (plan area) (A) is passed through the mass balance steps illustrated in Figure 4.1 and the resulting outputs recorded at each time step.

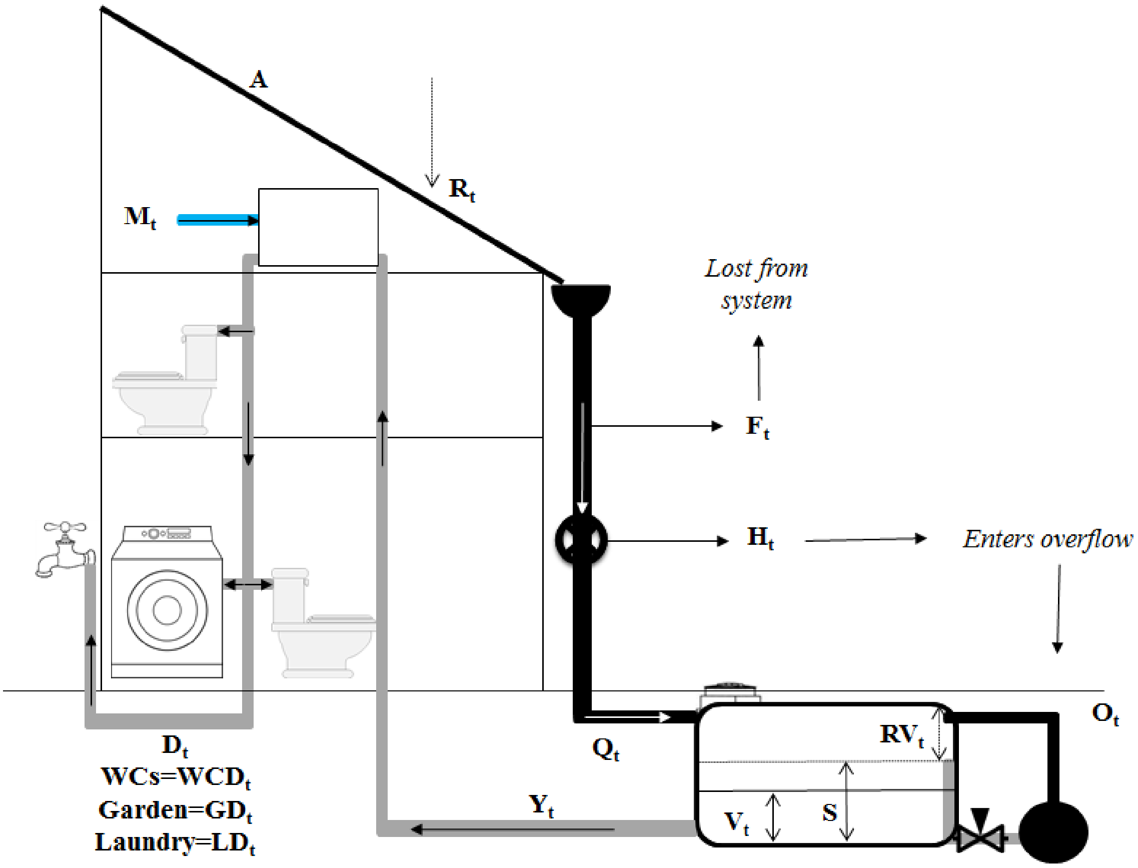


Figure 4.1 – Rainwater Harvesting Evaluation Tool (RainWET) Model Configuration. (Labels as described in Table 4.2)

The underlying algorithm driving the RainWET is based on the YAS approach described in Fewkes and Butler (2000). Full details of the steps within the calculation module and information describing their selection and application are described in Table 4.2.

Table 4.2 – Description of the calculation parameters and steps within the RainWET

Parameter	Description and Equations	Comments
A	**Area (m^2)** The plan area of the roof feeding the RWH system is defined using the input sheet (Figure 4.2). Areas can be manually measured on-site, taken from scale site plans or estimated using web-based mapping tools. $A = User\ Defined$	Although the plan area may remain constant, the variation of roof pitch (and material) can cause variation in rainwater volumes reaching the gutter system. Flat roofs, green roofs, and complex roofs may all influence the flows entering a RWH tank ((BSI), 2013b). The model has a default assumption that 100% of rainfall arriving at the roof enters the gutters and downpipes. However, the H_t value can be manipulated to take into account any need for roof-runoff coefficients to be applied. Alternatively the user can manipulate the R_t values in order to adjust rainwater runoff volumes entering the filter.
R_t	**Rainfall (mm)** The rainfall volume reaching the roof for a given time step is obtained from historical rain gauge data. Rainfall data is increasingly freely available from local enthusiasts who publish real time weather station data (Whipton Weather, 2016) In addition, freely available Environment Agency datasets represent a comprehensive resource for UK-wide time-series analyses. Open source and freedom of information platforms have eased access to this data in recent years (DATA.GOV.UK, 2016). $R_t = User\ Defined$	Default settings use a daily time step however, the RainWET can also be adapted to investigate finer resolution datasets as needed to match the ultra-high resolution studies that have recently been carried out (Campisano and Modica, 2014). Where daily rainfall data is not available, the best available data (e.g. the annual average rainfall figures) can be used to generate 365 rows of data (i.e. a single value can be used for daily rainfall if a very basic estimate is warranted). Although other studies have successfully deployed time-series approaches (Gerolin *et al.*, 2010), here the default setting is to analyse a site using 20 years of rainfall data, whereas previous UK-based methods have either suggested the use of synthetic time series data, or shorter simulation periods; single year

Para-meter	Description and Equations	Comments
		(Roebuck, 2008), 3-5 years ((BSI), 2013b)). In addition, the rainfall input files have been configured in a manner that enables climate change weather generators to provide synthetic data. This can be downloaded for use in a given location, and thus facilitate the analysis of future rainfall scenarios where desired (Lash *et al.*, 2014).
F_t	**First Flush Losses (l)** First flush losses may be included if such technologies (i.e. those which deliberately spill the first flush flows) are used at a given site. Their inclusion can be achieved as a user defined setting by selecting a suitable volume on the input sheet. $F_t = User\ Defined$	All modelling has been conducted with this parameter fixed at a default setting of 5l/rainday. Rainwater associated with the F_t parameter is lost from the system, i.e. it is assumed to be routed to ground (Roebuck, 2008).
H_t	**Hydraulic Filter Loss Coefficient** Before arriving at the tank, the rainwater is assumed to be filtered under gravity. Losses associated with the self-cleansing features of the filter are included here. $H_t = User\ Defined$	Unless stated otherwise, all modelling has been conducted with this parameter fixed at the default setting of 0.9 ((BSI), 2013b) to enable 90% of rainwater arriving at the roof to reach the tank. The 10% runoff which bypasses the tank is not lost from the simulation. It is added to the overflow volume for each time-step.
Q_t	**Total Volume of Rainfall Arriving at Storage Tank (l)** With losses subtracted and filter coefficients applied to the R_t value, the volume arriving at the tank is calculated. (Equation 5.1) $Q_t = (A \times R_t \times H_t) - F_t$	For larger rainfall events, this volume can exceed both the V_t and S values and hence necessitate an overflow from the system.
S	**Maximum Functional Tank Storage Volume (l)** This is the maximum capacity of the functional region of the RWH system's storage tank.	RWH tanks can be configured to receive mains water top-ups into a header tank (as illustrated in Figure 4.1) or directly into the main storage tank. Hence the volume of the tank which is filled

Para-meter	Description and Equations	Comments
	$S = User\ Defined$	by these “top-up” systems must be subtracted from the tank’s specified total volume to ensure the true functional capacity of the tank is modelled. S is equal to the working capacity of the tank and may also be limited by the level of the pump’s inlet and the invert level of the overflow pipework. In addition where passive release, active release or pumped release of rainwater occurs within the simulation tool, the S value is further reduced to include only the region of the tank that is capable of storing water. The portion of the storage volume used for intentional releases is separately defined in the simulation tool as RV_t.
V_t	**Total Volume Stored within the Tank (l)** At the end of each time-step, V_t is calculated to illustrate the volume of water stored within the RWH tank. (Equation 4.2) Subject to: $V_t \geq 0$ $V_t = \min\{^{RV_{t-1}+Q_t - O_t - RV_t - Y_t}_{S-Y_t}$ If $V_t < 0\ then\ V_t = 0$	This volume is calculated using the YAS method. V_{t-1} is added to Q_t for the current time-step. If the value exceeds S, this volume is spilled to generate an overflow (O_t). Next the intentional discharge (RV_t) is released (if this feature is enabled) and finally the demand is extracted from the remaining volume to give a tank level at the end of each time step (Fewkes and Butler, 2000). Volumes are reported at a daily time-step in l/day.
V_{start}	**Total Starting Volume Stored within the Tank (l** At the beginning of each simulation the starting tank level must be user specified. $V_{start} = User\ Defined$	The starting tank level for the RWH simulation is entered into the input sheet to enable the first time-step calculation to be initiated with S values defining the tank as having a water level between 0-100%.
O_t	**Overflow Volume (l)** The rainwater discharge spilled into the downstream network is defined as follows: (Equation 4.3) $O_t = (V_{t-1} + Q_t + (Q_t - (Qt \times H_t)) - S$	Using the YAS approach, all stormwater is assumed to spill before any demand (and intentional releases) are discharged. Flows that are initially separated by the hydraulic losses at the filter are recombined and

Para-meter	Description and Equations	Comments
	(Equation 4.4) Where $V_{t-1} + Q_t > S$	passed to the overflow outlet at this step. Volumes are reported at a daily time-step in l/day.
Y_t	**Rainwater Yield (l)** The rainwater yield is calculated as the rainwater demand which is met by the configuration at each time-step. The calculation is based on the YAS equations: (Equation 4.5) $Y_t = \min\begin{cases} D_t \\ V_{t-1} \end{cases}$	Where yield is monitored at real world sites using water meters, the mains water top-up and rainwater use data can be used to compare simulated outputs with empirical findings.
D_t	**Rainwater Demand (l)** Demand for rainwater can be estimated from literature, taken from historic averages or based on site-specific smart meter data. It represents the sum of all potential rainwater demands at a given time step including WCs, Laundry and Garden Demands. It is also equivalent to the total non-potable water demand which is fully satisfied by rainwater yield plus mains water top-up. (Equation 4.6) Hence $D_t = WCD_t + LD_t + GD_t$ And $D_t = Y_t + M_t$	Where site specific data is unavailable, rainwater demand can be fixed as a single daily value based on approaches described in the British Standard ((BSI), 2013b). Where rainwater demand is monitored at real world sites using water meters, the mains data can be used to compare simulated outputs with empirical findings.
M_t	**Mains Water Top-Up (l)** Where demand at a given time-step exceeds the available rainwater volume, the non-potable appliances within the property draw water from the mains. (Equation 4.7) Hence $M_t = D_t - Y_t$	When the value of S reaches zero, the rainwater demand is not necessarily fully satisfied by rainwater available in the system at each time-step. Where this is the case, the remainder is made up by the mains water top-up system. Where metered data is available for this value, comparison between the metered mains water usage and those projected by the simulations can be used to help guide user assumptions to fit the simulation data to the empirical site data.

Para-meter	Description and Equations	Comments
RV_t	**Maximum (Active or Passive) Release Volume (l)** Where active controls or passive discharge outlets are included within the RWH tank, it is necessary to define the volume of the tank which is permitted to enter these devices at each time step. For example a tank might be configured with 50% of the storage volume draining via passive control orifice after each storm. Where passive orifice controls are modelled, the RV_t value is fixed for the entire simulation (for example if a trickle outlet is installed half way up the tank). However, the RV_t value can also be adjusted for each time step based on the desired storage capacity (for source control) of the tank. This could be achieved using a pre-programmed controller (perhaps achieving different target tank levels governed by the seasonal average rainfall data), or controlled by an external communications device as a true real-time control system. $RV_t = User\ Defined$	The RV_t value is specified based on the user's objectives. An iterative approach can thus be used to enable a RWH system to be designed to satisfy specific stormwater control objectives, such as "the site must always maintain capacity to capture the 1 in 1 year 60 minute rainfall event."
$PRVD_t$	**Passive Release Volume of Discharge (l)** Where a detention zone is incorporated within the RWH tank that captures rainwater and manually drains after a storm, the volume of the passive discharge is calculated for each time step as follows: (Equation 4.8) $PRVD_t = min\begin{cases} O_t \\ RV_t \end{cases}$	The $PRVD_t$ value represents the flow discharged from the tank via the passive control outlet. For small storms, this trickle-discharge will see the upper region of the tank fill during the storm and trickle back into the network at a controlled rate. For large storms which exceed the capacity of RV_t overflows are still generated in the model. A designer can iteratively increase the RV_t value and re-run the simulation until a target design (e.g. zero spills during 1 in 1 year storm) has been achieved. At this point $PRVD_t = RV_t$ as all unintentional spills are controlled.
$ARVD_t$	**Active Release Volume of Discharge (l)** Where an active release valve is incorporated within the RWH tank that can release rainwater into the downstream	Here it is assumed that the overflow at O_{t+1} can be accurately defined using a weather forecast to enable an optimum use of the

Para-meter	Description and Equations	Comments
	network based on a control philosophy, the whole volume (S) of the RWH tank can potentially be deployed as a stormwater control volume. Many potential control strategies exist (e.g. drain to a maximum tank level at the end of each time-step; e.g.2 drain a specific volume each time-step; e.g.3 drain to telemetry-specified maximum tank level at the end of each timstep.) Where a fixed maximum tank level is desired, the RainWET can model this in the same manner as the $PRVD_t$ calculation. In order to enable simulation of this approach the active controls (which might be varied on a daily basis) used for a scenario which seeks to fully prevent overflows at the next time step, the $ARVD_t$ volume is calculated as follows: (Equation 4.9) Where $O_{t+1} > S - V_t$ $ARVD_t = min\begin{cases} V_t \\ O_{t+1} - (S - V_t) \end{cases}$	tank's storage volume to be achieved in terms of capturing rainwater at the next time step.

With calculation steps defined in Table 4.2, another set of equations was developed to define a set of metrics which could be used to draw comparison between different RWH simulations. The metrics used in the outputs from the RWH Evaluation Method are described in Table 4.3,

Table 4.3 - Reported Performance Metrics from RainWET (symbols as defined in Table 4.2)

Metric	Description	Comments
E_T	**Water Saving Efficiency** (Equation 4.10) $E_T = \frac{\sum_{t=1}^{T} Y_t}{\sum_{t=1}^{T} D_t}$	Also referred to as volumetric reliability (Ward *et al.*, 2012c), this equation enables the evaluation tool to calculate the percentage of rainwater demand that is met by the rainwater yield over a given timeframe. The RainWET is configured to report annual figures for this metric. With 20 1-year simulations completed, a summary sheet is generated to describe minimum, maximum, mean, and median values for E_T.
O_T	**Rainwater Overflow Ratio** (Equation 4.11) $O_T = \frac{\sum_{t=1}^{T} O_t}{\sum_{t=1}^{T} Q_t}$	Also referred to as stormwater discharge ratio, this equation enables the evaluation tool to calculate the percentage of rainwater inflow (Q_t) that is used vs. that which is discharged from the system over a given timeframe. The RainWET is configured to report annual figures for this metric. With 20 1-year simulations completed, a summary sheet is generated to describe minimum, maximum, mean, and median values for O_T.
RO	**Reduction of Uncontrolled Overflow** (Equation 4.12) $RO = \frac{O_{ref} - O_{RWH}}{O_{ref}}$	The RainWET simulations can be completed for many different RWH configurations. Hence, a reference case (e.g. a site without RWH) can be tested to generate a runoff volume for a given time period. Next the user can run a range of different configurations through the RainWET to test various tank sizes and stormwater control devices (whilst keeping all other parameters the same). Comparison between the reference scenario and each new configuration can be achieved using the RO metric. Where a stormwater control design objective exists (e.g. Overflows must equal zero for all storms in the simulation period) then the user must take an iterative design approach to

		ensure the RWH tank's capacity and stormwater control configuration satisfy the objective. In reality the user may specify an oversized tank and then continue reducing the size of the tank until the objective is met at the least cost. Additionally, passive, active or real time control configurations can be tested. Where stormwater control solutions are integrated in the RWH model, the overflow reduction reported here permits rainwater to be discharged to the downstream network without declaring it as an overflow because the flows are intentionally released either at a very low flow rate, or actively discharged during a time when the sewer network is not receiving rainfall inputs. Recent studies have included an equation / output such as this although alternative terminology is applied (Palla *et al.*, 2011, Campisano *et al.*, 2014).
RPO	Reduction Peak Overflow (Equation 4.13) $RPO = \frac{PO_{ref} - PO_{RWH}}{PO_{ref}}$	Akin to the RO parameter, this metric describes the peak discharge from the RWH configuration by identifying the largest discharge in the reference scenario and evaluating the performance of the new scenario. With the time step fixed at daily and the simulation driven by 20, 1 year rainfall files, PR compares the largest daily overflow from the system over the 20 year simulation window under the reference scenario and the tested RWH scenario.
ARV	Increased Attenuated Release Volume. (Equation 4.14) $ARV = ARV_{RWH} - ARV_{ref}$	Here we describe a further parameter for the first time which represents the volume intentionally discharged to the overflow system which was controlled (attenuated) by some form of passive, active or real time control device. In the reference case with no RWH modelled ($ARV_{ref} = 0$), as there will

	be no controlled volume as all overflows leave the system in an uncontrolled manner. However, where a discharge is intentionally released at a given time-step, this parameter describes the volume of the discharge in comparison to the base reference case.

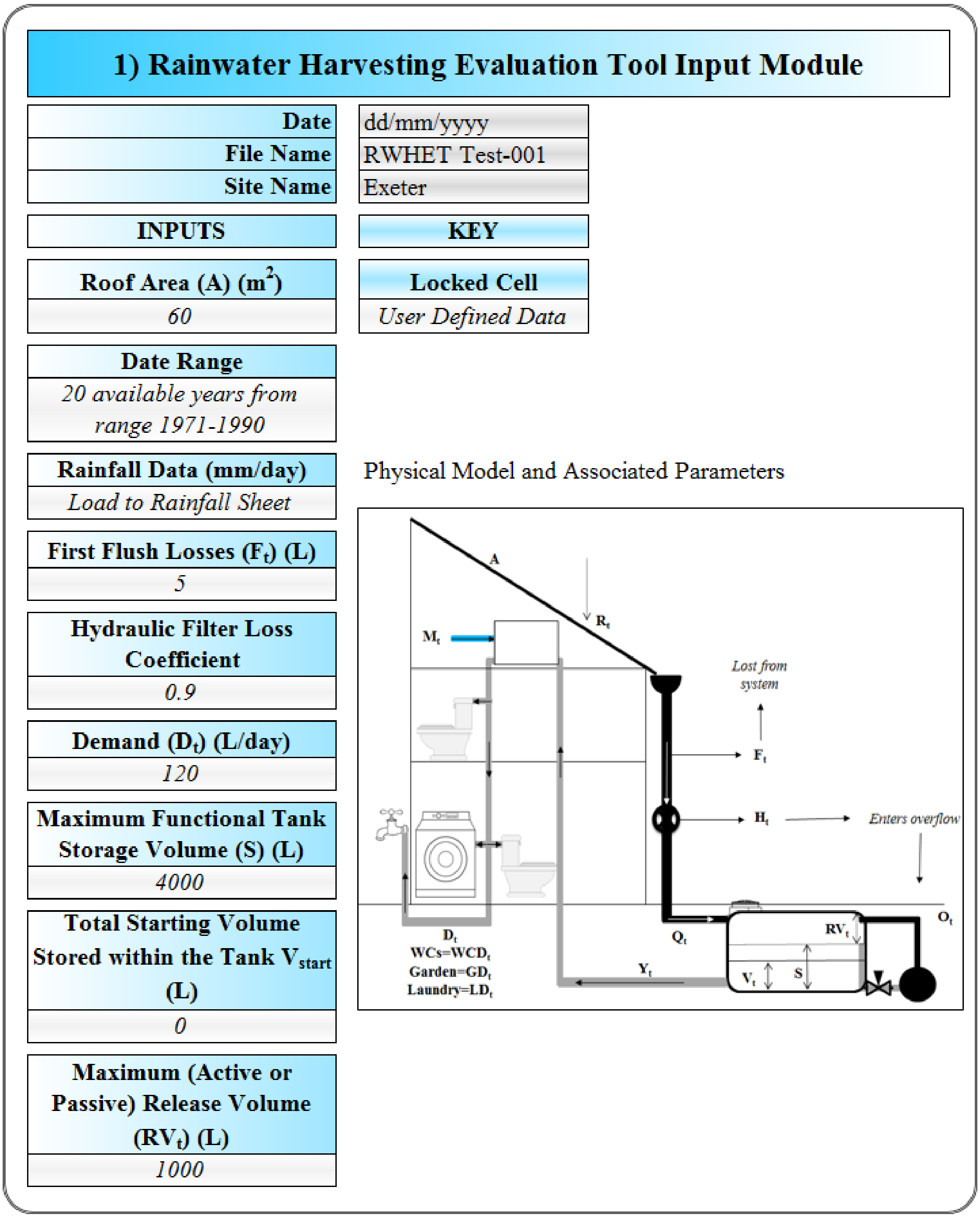
4.6 Using RainWET to evaluate RWH systems

4.6.1 Input Parameters

The equations described in Table 4.2 are embedded within the simulation tool, and calculated automatically once the user-defined input values have been added and the macros executed. The fixed parameters can be varied one by one in order to generate optioneering/sensitivity outputs which can help a user select a solution that meets a specified level of service. The following describes the use of the RainWET to evaluate a single RWH system at a given site.

4.6.2 Fixed input parameters: User Defined Values

The RainWET was developed to enable a user to easily adjust parameters within the model so that iterative evaluations can be quickly undertaken and compared with a baseline reference case. With the algorithms that drive the evaluation tool defined in the above section, the input parameters can be varied in order to test a wide range of RWH configurations. The primary inputs that drive the model are all added to the “Inputs Module” illustrated in Figure 4.2. In addition to defining these parameters, the rainfall data must be appropriately processed.



1) Rainwater Harvesting Evaluation Tool Input Module

Date	dd/mm/yyyy
File Name	RWHET Test-001
Site Name	Exeter

INPUTS

Roof Area (A) (m^2)
60

Date Range
20 available years from range 1971-1990

Rainfall Data (mm/day)
Load to Rainfall Sheet

First Flush Losses (F_t) (L)
5

Hydraulic Filter Loss Coefficient
0.9

Demand (D_t) (L/day)
120

Maximum Functional Tank Storage Volume (S) (L)
4000

Total Starting Volume Stored within the Tank V_{start} (L)
0

Maximum (Active or Passive) Release Volume (RV_t) (L)
1000

KEY

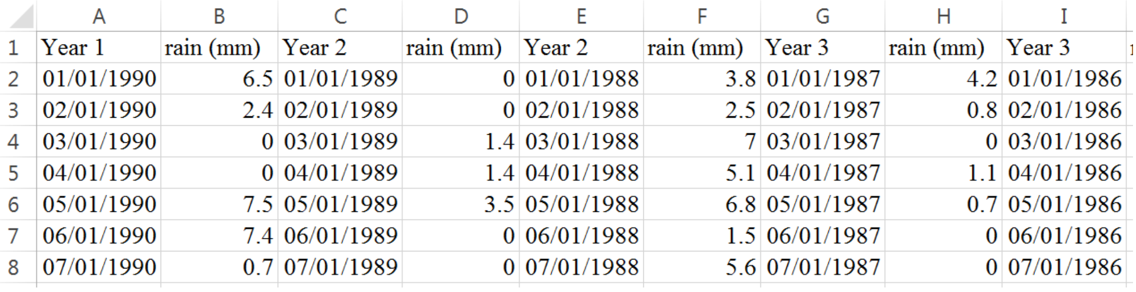
Locked Cell
User Defined Data

Physical Model and Associated Parameters

Figure 4.2 – RainWET Input Module

4.6.3 Rainfall Data Inputs

Rainfall data must be processed into 40 columns with 366 rows (one for each day of a simulation plus the heading). The columns are described as "*A = Year 1 Dates, B = Year 1 Rainfall Data, C = Year 2 Dates, D = Year 2 Rainfall Data etc.*" Erroneous data (such as any inputs which are not numerical) or datasets which include data gaps must be cleaned prior to this stage. Any data which includes a leap year must have values for the 29th February deleted from the simulation input. An example of the cleaned data ready for inclusion in the RainWET is illustrated in Figure 4.3.



	A	B	C	D	E	F	G	H	I
1	Year 1	rain (mm)	Year 2	rain (mm)	Year 2	rain (mm)	Year 3	rain (mm)	Year 3
2	01/01/1990	6.5	01/01/1989	0	01/01/1988	3.8	01/01/1987	4.2	01/01/1986
3	02/01/1990	2.4	02/01/1989	0	02/01/1988	2.5	02/01/1987	0.8	02/01/1986
4	03/01/1990	0	03/01/1989	1.4	03/01/1988	7	03/01/1987	0	03/01/1986
5	04/01/1990	0	04/01/1989	1.4	04/01/1988	5.1	04/01/1987	1.1	04/01/1986
6	05/01/1990	7.5	05/01/1989	3.5	05/01/1988	6.8	05/01/1987	0.7	05/01/1986
7	06/01/1990	7.4	06/01/1989	0	06/01/1988	1.5	06/01/1987	0	06/01/1986
8	07/01/1990	0.7	07/01/1989	0	07/01/1988	5.6	07/01/1987	0	07/01/1986

Figure 4.3 – Processed rainfall data for the RainWET simulations

4.7 Simulation Steps: Deploying the Simulation Toolkit

The simulation tool utilises coded macros to enable the simulations to be run by the user. Hence, when the tool is first opened, the user is presented with a series of unfilled template sheets which are pre-formatted to be easily printed (or saved to .pdf) once the simulations are completed.

Having defined the input parameters and rainfall data, the user can select from the macros illustrated in Figure 4.4 to drive the simulation process.

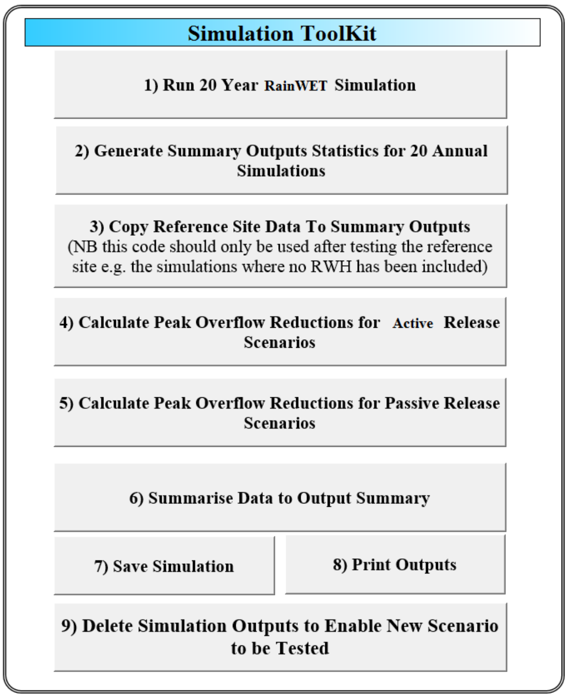
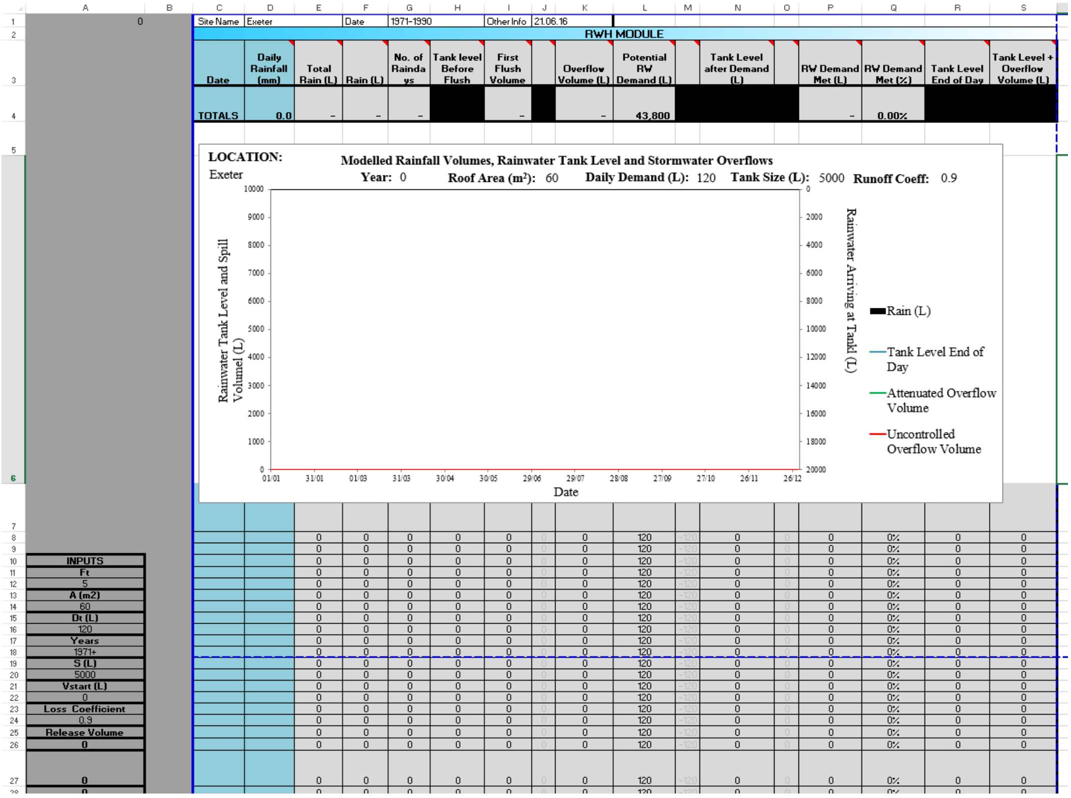


Figure 4.4 – Simulation ToolKit within RainWET software

Clicking the first button *"Run 20 Year RainWET Simulation"* will open the *SIM-MASTER* sheet. The code copies columns A&B from the *RainFiles* sheet. These are pasted into cell C8&D8 of *SIM-MASTER* and the embedded algorithms solve all of the equations at a daily time-step for the first year's data. Summary data is displayed in row 4 of the *SIM-MASTER* sheet and it is re-named using the A1 cell from the *RainFiles* dataset. The procedure is repeated with the other 19 years of rainfall data until all 20 years have been individually simulated and saved as new sheets (named *1-20*). The process is illustrated in Figures 4.5 and 4.6. Figure 4.5 shows the blank *SIM-MASTER* sheet with its preformed template chart and summary rows across the top. Figure 4.6 illustrates the completed simulations with 20 new sheets created each representing one of the simulation years. For the purposes of simulations the starting water level is assumed to be zero on January 1st each year. This gives a conservative estimate of rainwater yield. In contrast, running simulations with the rainwater tank full on January 1st gives a conservative stormwater analysis. In reality, users are able to link years together and undertake a continuous simulation should that be preferred.



0

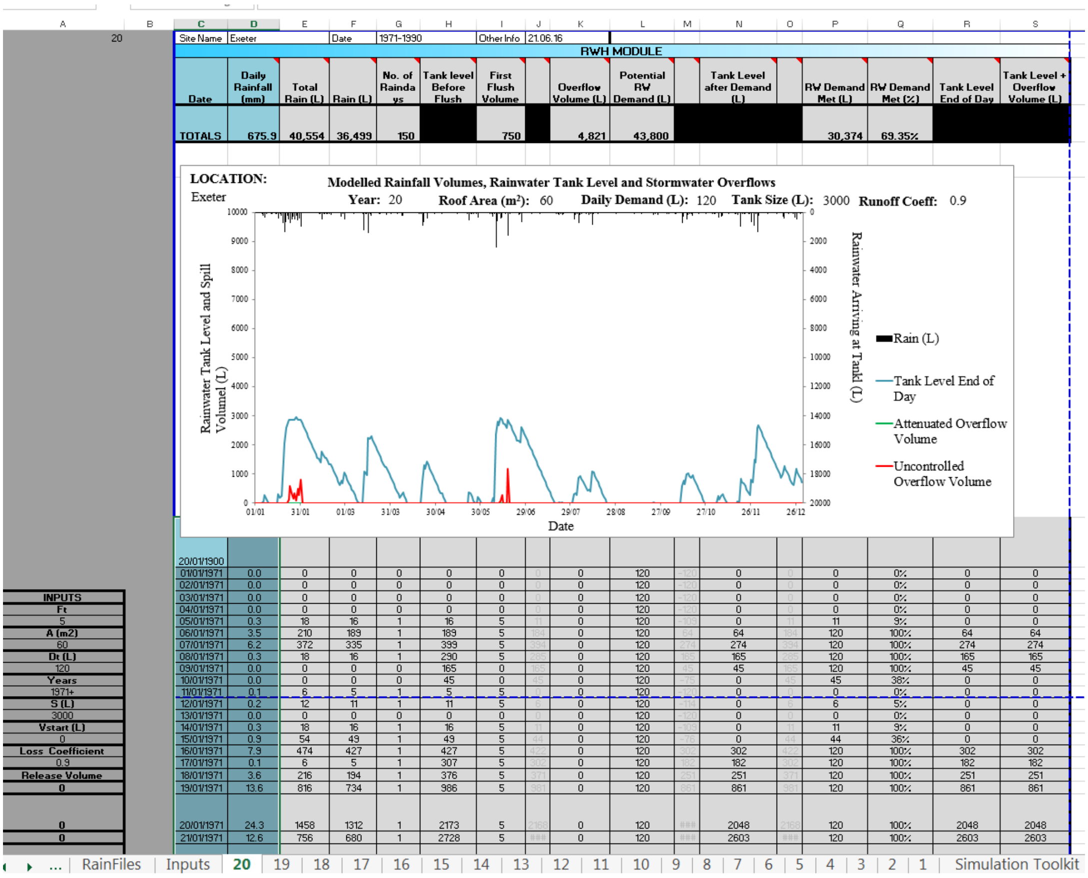
Site Name: Exeter
Date: 1971-1990
Other Info: 21.06.16

INPUTS
Ft: 5
A (m2): 60
Dt (L): 120
Years: 1971+
S (L): 5000
Vstart (L): 0
Loss Coefficient: 0.9
Release Volume: 0

Date	Daily Rainfall (mm)	Total Rain (L)	Rain (L)	No. of Rainays	Tank level Before Flush	First Flush Volume		Overflow Volume (L)	Potential RW Demand (L)		Tank Level after Demand (L)		RW Demand Met (L)	RW Demand Met (%)	Tank Level End of Day	Tank Level + Overflow Volume (L)
TOTALS	0.0	-	-	-		-		-	43,800				-	0.00%		
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
		0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0

0

Figure 4.5 – Simulation Master sheet within RainWET



20

Site Name: Exeter
Date: 1971-1990
Other Info: 21.06.16

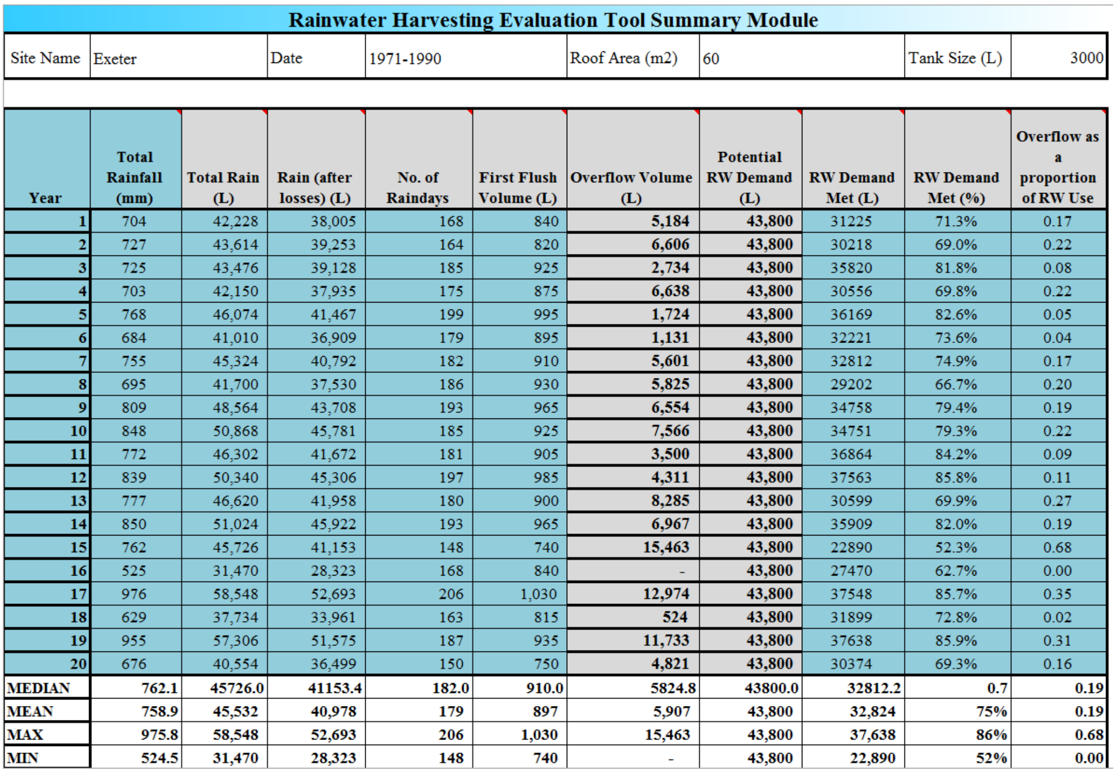
INPUTS
Ft: 5
A (m2): 60
Dt (L): 120
Years: 1971+
S (L): 3000
Vstart (L): 0
Loss Coefficient: 0.9
Release Volume: 0

Date	Daily Rainfall (mm)	Total Rain (L)	Rain (L)	No. of Rainays	Tank level Before Flush	First Flush Volume		Overflow Volume (L)	Potential RW Demand (L)		Tank Level after Demand (L)		RW Demand Met (L)	RW Demand Met (%)	Tank Level End of Day	Tank Level + Overflow Volume (L)
TOTALS	675.9	40,554	36,499	150		750		4,821	43,800				30,374	69.35%		
20/01/1900																
01/01/1971	0.0	0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
02/01/1971	0.0	0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
03/01/1971	0.0	0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
04/01/1971	0.0	0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
05/01/1971	0.3	18	16	1	16	5	11	0	120	-109	0	11	11	9%	0	0
06/01/1971	3.5	210	189	1	189	5	184	0	120	64	64	184	120	100%	64	64
07/01/1971	6.2	372	335	1	399	5	394	0	120	274	274	394	120	100%	274	274
08/01/1971	0.3	18	16	1	290	5	285	0	120	165	165	285	120	100%	165	165
09/01/1971	0.0	0	0	0	165	0	165	0	120	45	45	165	120	100%	45	45
10/01/1971	0.0	0	0	0	45	0	45	0	120	-75	0	45	45	38%	0	0
11/01/1971	0.1	6	5	1	5	5	0	0	120	-120	0	0	0	0%	0	0
12/01/1971	0.2	12	11	1	11	5	6	0	120	-114	0	6	6	5%	0	0
13/01/1971	0.0	0	0	0	0	0	0	0	120	-120	0	0	0	0%	0	0
14/01/1971	0.3	18	16	1	16	5	11	0	120	-109	0	11	11	9%	0	0
15/01/1971	0.9	54	49	1	49	5	44	0	120	-76	0	44	44	36%	0	0
16/01/1971	7.9	474	427	1	427	5	422	0	120	302	302	422	120	100%	302	302
17/01/1971	0.1	6	5	1	307	5	302	0	120	182	182	302	120	100%	182	182
18/01/1971	3.6	216	194	1	376	5	371	0	120	251	251	371	120	100%	251	251
19/01/1971	13.6	816	734	1	986	5	981	0	120	861	861	981	120	100%	861	861
20/01/1971	24.3	1458	1312	1	2173	5	2168	0	120	###	2048	2168	120	100%	2048	2048
21/01/1971	12.6	756	680	1	2728	5	###	0	120	###	2603	###	120	100%	2603	2603

0
0

Figure 4.6 – Screenshot of RainWET following completion of 20 annual simulations (Year 20 summary graph shown)

Next, the user must run the second macro to synthesise the data from each tab into the Summary Master module. Again this is a template sheet into which the macros deposit the values which are copied from each annual simulation sheet. The user is required to run a "No RWH included" scenario at the start of any simulation session. This enables the baseline scenario (i.e. one in which no RWH is installed) to be loaded into the Summary Master sheet to facilitate comparison against future simulations. The third macro is clicked to copy the reference scenario into the relevant cells. The completed Summary Master sheet is illustrated in Figure 4.7 with the stormwater reduction tables shown in Figure 4.8.

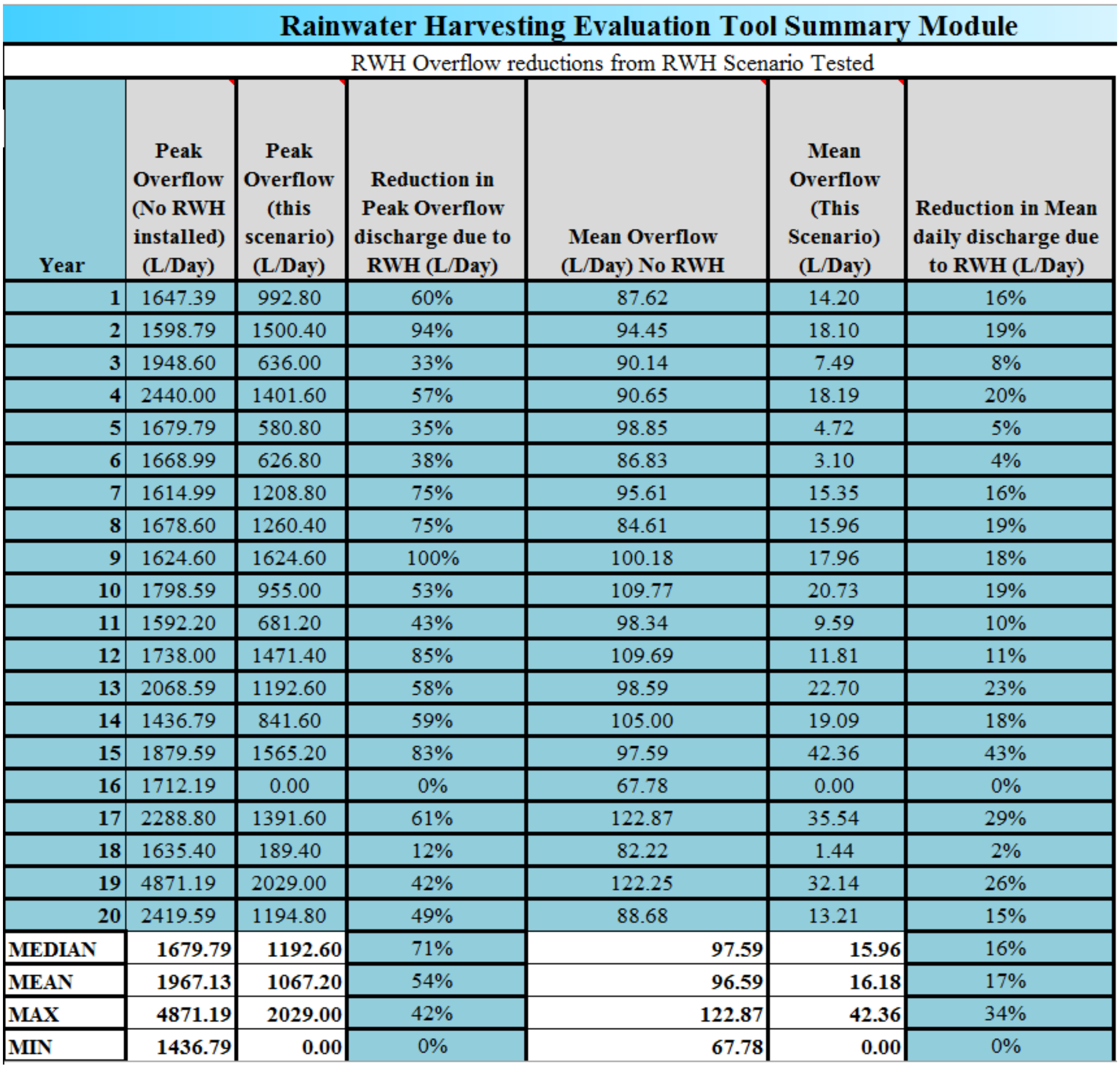


Rainwater Harvesting Evaluation Tool Summary Module

Site Name	Exeter	Date	1971-1990	Roof Area (m2)	60	Tank Size (L)	3000

Year	Total Rainfall (mm)	Total Rain (L)	Rain (after losses) (L)	No. of Raindays	First Flush Volume (L)	Overflow Volume (L)	Potential RW Demand (L)	RW Demand Met (L)	RW Demand Met (%)	Overflow as a proportion of RW Use
1	704	42,228	38,005	168	840	5,184	43,800	31225	71.3%	0.17
2	727	43,614	39,253	164	820	6,606	43,800	30218	69.0%	0.22
3	725	43,476	39,128	185	925	2,734	43,800	35820	81.8%	0.08
4	703	42,150	37,935	175	875	6,638	43,800	30556	69.8%	0.22
5	768	46,074	41,467	199	995	1,724	43,800	36169	82.6%	0.05
6	684	41,010	36,909	179	895	1,131	43,800	32221	73.6%	0.04
7	755	45,324	40,792	182	910	5,601	43,800	32812	74.9%	0.17
8	695	41,700	37,530	186	930	5,825	43,800	29202	66.7%	0.20
9	809	48,564	43,708	193	965	6,554	43,800	34758	79.4%	0.19
10	848	50,868	45,781	185	925	7,566	43,800	34751	79.3%	0.22
11	772	46,302	41,672	181	905	3,500	43,800	36864	84.2%	0.09
12	839	50,340	45,306	197	985	4,311	43,800	37563	85.8%	0.11
13	777	46,620	41,958	180	900	8,285	43,800	30599	69.9%	0.27
14	850	51,024	45,922	193	965	6,967	43,800	35909	82.0%	0.19
15	762	45,726	41,153	148	740	15,463	43,800	22890	52.3%	0.68
16	525	31,470	28,323	168	840	-	43,800	27470	62.7%	0.00
17	976	58,548	52,693	206	1,030	12,974	43,800	37548	85.7%	0.35
18	629	37,734	33,961	163	815	524	43,800	31899	72.8%	0.02
19	955	57,306	51,575	187	935	11,733	43,800	37638	85.9%	0.31
20	676	40,554	36,499	150	750	4,821	43,800	30374	69.3%	0.16
MEDIAN	762.1	45726.0	41153.4	182.0	910.0	5824.8	43800.0	32812.2	0.7	0.19
MEAN	758.9	45,532	40,978	179	897	5,907	43,800	32,824	75%	0.19
MAX	975.8	58,548	52,693	206	1,030	15,463	43,800	37,638	86%	0.68
MIN	524.5	31,470	28,323	148	740	-	43,800	22,890	52%	0.00

Figure 4.7 – Summary Master sheet. RWH Metrics from RainWET for a hypothetical site with a RWH system



Rainwater Harvesting Evaluation Tool Summary Module

RWH Overflow reductions from RWH Scenario Tested

Year	Peak Overflow (No RWH installed) (L/Day)	Peak Overflow (this scenario) (L/Day)	Reduction in Peak Overflow discharge due to RWH (L/Day)	Mean Overflow (L/Day) No RWH	Mean Overflow (This Scenario) (L/Day)	Reduction in Mean daily discharge due to RWH (L/Day)
1	1647.39	992.80	60%	87.62	14.20	16%
2	1598.79	1500.40	94%	94.45	18.10	19%
3	1948.60	636.00	33%	90.14	7.49	8%
4	2440.00	1401.60	57%	90.65	18.19	20%
5	1679.79	580.80	35%	98.85	4.72	5%
6	1668.99	626.80	38%	86.83	3.10	4%
7	1614.99	1208.80	75%	95.61	15.35	16%
8	1678.60	1260.40	75%	84.61	15.96	19%
9	1624.60	1624.60	100%	100.18	17.96	18%
10	1798.59	955.00	53%	109.77	20.73	19%
11	1592.20	681.20	43%	98.34	9.59	10%
12	1738.00	1471.40	85%	109.69	11.81	11%
13	2068.59	1192.60	58%	98.59	22.70	23%
14	1436.79	841.60	59%	105.00	19.09	18%
15	1879.59	1565.20	83%	97.59	42.36	43%
16	1712.19	0.00	0%	67.78	0.00	0%
17	2288.80	1391.60	61%	122.87	35.54	29%
18	1635.40	189.40	12%	82.22	1.44	2%
19	4871.19	2029.00	42%	122.25	32.14	26%
20	2419.59	1194.80	49%	88.68	13.21	15%
MEDIAN	1679.79	1192.60	71%	97.59	15.96	16%
MEAN	1967.13	1067.20	54%	96.59	16.18	17%
MAX	4871.19	2029.00	42%	122.87	42.36	34%
MIN	1436.79	0.00	0%	67.78	0.00	0%

Figure 4.8 – Stormwater Discharge Metrics from RainWET comparing a site with and without a RWH system

With an initial RWH scenario evaluated the user can quickly simulate a wide range of RWH configurations using the tool. The simulation sheets only need to be produced once, after which the user can return to the input file, adjust any parameters as desired and all of the summaries and charts automatically update in sheets *1-20*. Once the user is content with the revised input parameters, the 2nd macro is clicked again to update the *Summary Master*. In practice, the user can test a range of tank sizes, roof areas, filter designs, or RWH configurations by; 1) amending the input data, 2) clicking the summary sheet button, and 3) saving the file under a suitable name for future reference. Once a range of parameters have been tested, additional outputs such as the frequently described RWH storage volume vs. water saving efficiency trade off chart can be generated. Figure 4.9 illustrates an example of such an output whilst including the peak overflow discharge volume as an additional decision support metric.

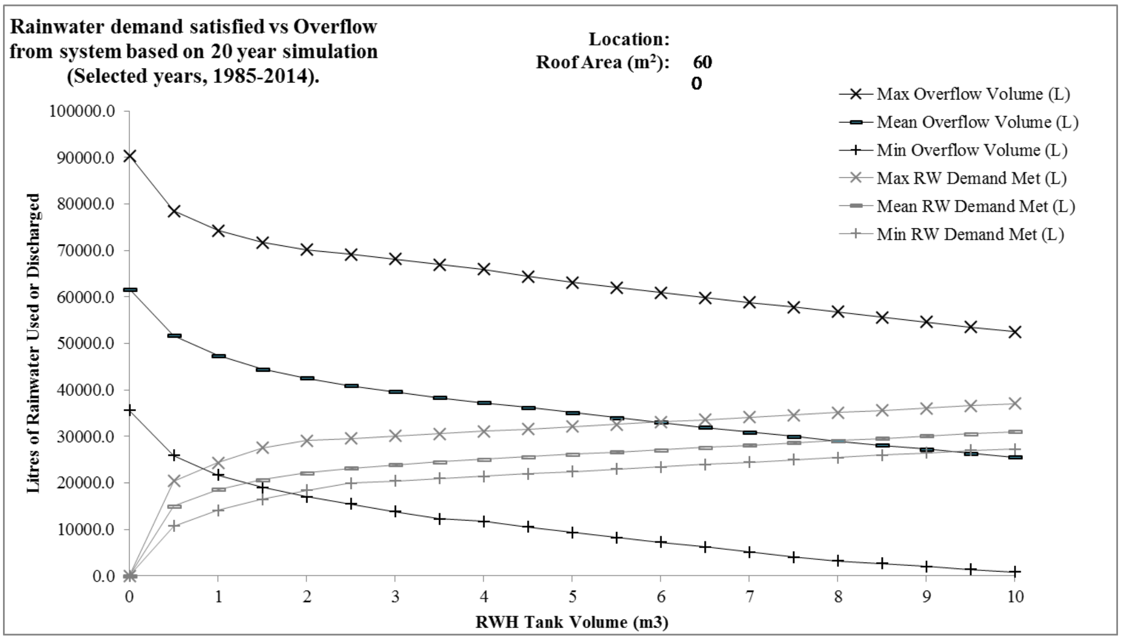
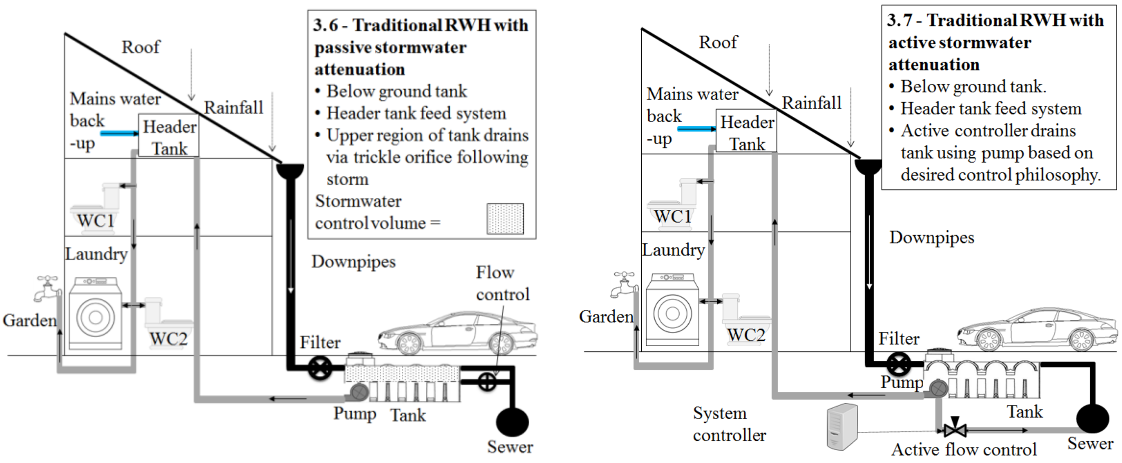


Figure 4.9 – Example Decision Support Output from RainWET: Range of Simulated Overflow and Water Demands Satisfied Over 20 Years.

The addition of the max, mean and min overflow volumes within the RainWET software outputs represents a novel step towards enabling RWH specifiers to select systems based on stormwater control characteristics alongside water saving benefits.

4.8 Using RainWET to Evaluate the Effectiveness of RWH systems with In-built Stormwater Control Features

One key goal for the development of the RainWET was to enable scenarios to be assessed in which stormwater control configurations (e.g. dual purpose RWH) such as those described in Figure 4.10 are being evaluated at a given site.



a) RWH with passive source control outlet; b) RWH with active source control
Figure 4.10 – Novel, dual purpose RWH configurations

4.8.1 Passive source control devices

In order to simulate the opportunity posed by installing RWH in the above configurations, a source control volume (Melville-Shreeve *et al.*, 2016a)) can be added above the lower region of the tank which contains the non-potable volume ("the detention zone and retention zone" (Herrmann and Schmida, 1999)) . For a passive control device such as a flow control orifice (SuDS Solutions, 2016), Maximum Release Volume (RV_t) volume is fixed at every time step. In the event that incoming rainwater exceeds the level of the orifice, excess water is discharged at a controlled rate depending on the head-discharge curve for the selected flow control. Discharges are passed to the overflow system.

When the passive stormwater control device is included within the RainWET software the maximum release volume ($PRVD_t$) is calculated at each time step. With the simulation running at a daily time-step, the passive control valve is assumed to fully discharge the rainwater before the end of each day. It is recognised that further evaluation of the actual discharge regime may be beneficial as an extension to this assessment. The controlled overflow volume discharged at each time step (from the passive outlet) is calculated as described in Equation 4.9 (in Table 4.2) as the lesser of either the overflow volume for the time step or the maximum storage volume in the detention zone of the tank.

4.8.2 Active source control devices

Where an active discharge is made (for example to achieve the objective of minimising an overflow at the next time-step), Equation 4.10 (in Table 4.2) is used to identify the intentional volume of release. The RainWET tool, duplicates each annual simulation and calculates the $PRVD_t$ and $ARVD_t$ for each time-step. Again the user is able to iteratively test the simulations using the graphs as a visual cue for assessing the total volumes of stormwater discharges for each RWH design tested. In the scenario where a designer is seeking to fully prevent stormwater overflows at the next time step, the process can be continued (by increasing the RVD_t value) until the chart illustrates that no overflows (red line on Figure 4.11) are discharged for every storm event within the 20 year simulation set. With a selected design finalised, the remaining toolkit macros can be deployed to summarise active and passive flow control performance, save the file and print the outputs. An example of a RWH system that has an active controller and an $ARVD_t$ of up to 3,000l is illustrated in Figure 4.11 alongside a similar RWH system with the same (retention) storage volume, but without the active control storage/system (i.e. $ARVD_t$ = 0l) in Figure 4.12. This illustrates how the stormwater discharges can be fully controlled by a suitably designed active RWH system whereas the traditional RWH system shown in Figure 4.12 allows stormwater discharges to occur which coincide with extreme storms.

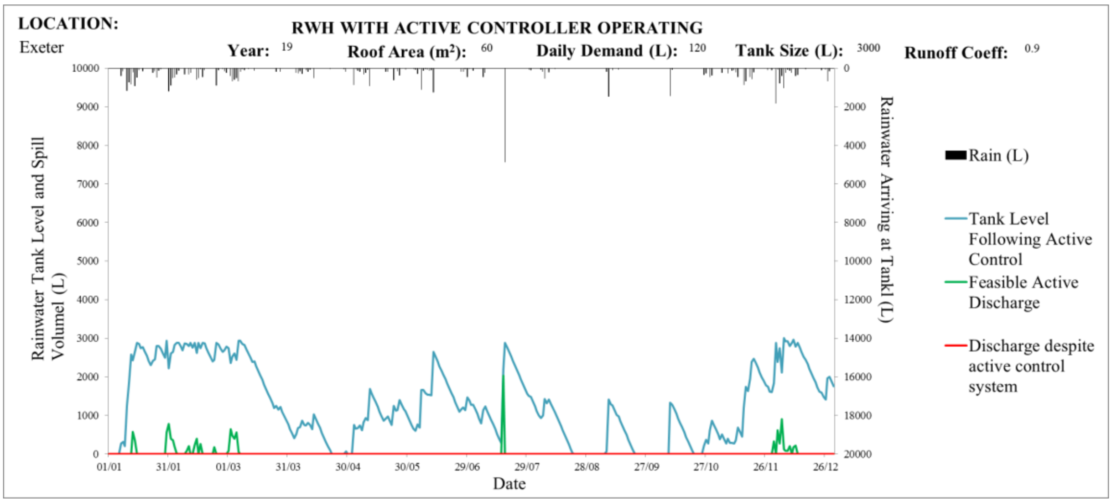


Figure 4.11 – RainWET Output for 6000l tank with 3,000l (50%) available for active stormwater control.

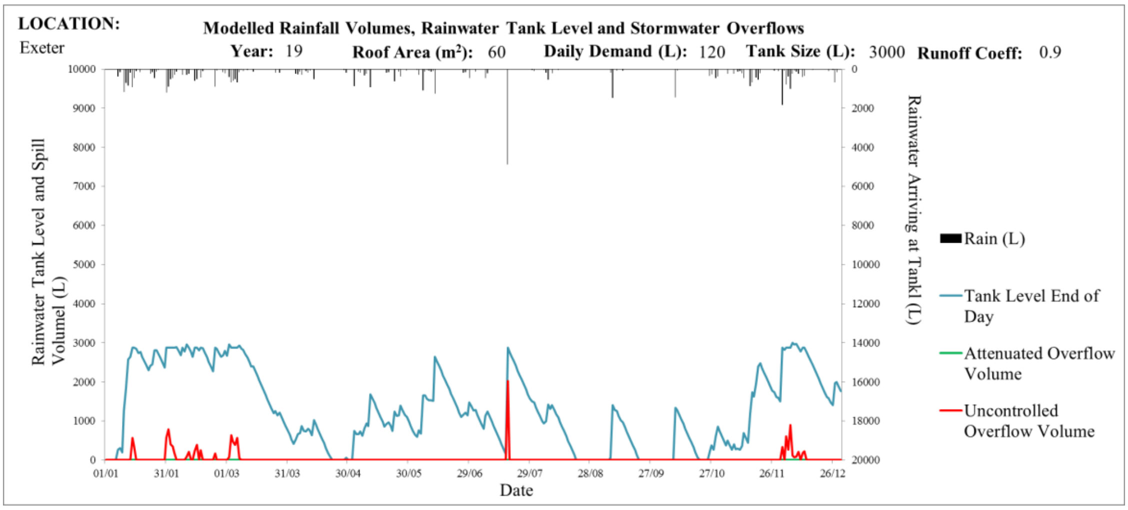


Figure 4.12 – RainWET Output for 3,000l tank without active stormwater control.

A further opportunity for itterative evaluation within the tool is to vary the $ARVD_t$ throughout a simulation (i.e. to enable the source control capacity to vary depending on seasonal data or real time predictions). This philosophy can enable a user to test the performance of a RWH system which has a variable $ARVD_t$. In reality such a system might be configured to have $ARVD_t = 0l$ for the summer months, (to provide an increased storage volume for non-potable demand during drier months, or to satisfy an increased demand for garden usage etc.) with an increased $ARVD_t$ volume implemented using a controller during wetter winter months.

4.9 Flexible simulation approaches: Varying fixed parameters

The RainWET software was designed with flexibility in mind. For example it is recognised that designers and drainage evaluators do not necessarily have access to high resolution local rainfall / water demand data for every site. Consequently the tool can be run with a fixed daily demand pattern or average rainfall data. In contrast, a user may have a precise dataset for water demand based on a nuanced variation pattern. The user can overwrite this data within the *SIM-MASTER* sheet at the beginning of a simulation session to make best use of the high quality water demand data in all simulations.

Once an initial simulation has been completed, the tool enables the user to quickly repeat each simulation using a range of values. Hence sensitivity analyses can be conducted by varying any of the user defined parameters to establish the relative importance of each input parameter. Such an approach can also be used to enable the user to investigate climate change scenarios, For example, the rainfall volumes can be increased by up to 40% (Environment Agency, 2017) to enable stormwater control features to be designed for a future scenario in which increased rainfall might be encountered due to a changing climate.

4.10 Monitoring Rainwater Harvesting Performance

The work presented in this chapter sets out a flexible desktop appraisal method for RWH systems. As with any model, the quality of input data is linked to the value of the outputs. Hence, a number of data collection studies were implemented in order to generate data sets pertaining to the performance of a range of RWH configurations. Results from these studies are described in Chapter 5. The data collection studies each illustrate the performance of a specific RWH configuration in a specific location. They represent the first step towards observing the true performance of RWH systems in the UK. However, due to the wide variability in building types, rainfall patterns and water demands, it is not appropriate to assume that the monitoring studies are representative of RWH systems deployed elsewhere in the UK. Hence it was necessary to further investigate the nationwide-applicability of the data described in Chapter 4. Furthermore, data from one site, can also be used to inform the design at alternative locations and support the development of an improved design. Application of the RainWET in a UK-wide study is presented in Chapter 6.

4.11 Conclusions

This chapter describes the expansion of existing RWH evaluation methodologies which have historically been used to enable water demand benefits of RWH systems to be appraised by the global research community. Building on existing equations, new methods were defined to enable an extended methodology to be reported. The existing calculation methods were extended through the inclusion of new parameters which enable stormwater control benefits to be defined for a range of RWH configurations:

1. $RV_{t.}$ Maximum (Active or Passive) Release Volume
2. $PRVD_t$. Passive Release Volume of Discharge
3. $ARVD_t$. Active Release Volume of Discharge

The addition of these calculation steps has enabled design and evaluation of stormwater control benefits of dual purpose RWH systems to be quantified in an extended methodology. In addition to developing a method for evaluating a wide range of RWH configurations using a 20 year time-series approach, a decision support tool RainWET has been developed. This provides a user friendly interface that allows multiple scenarios to be tested, saved and analysed. In addition, an automatic summary table and output graph module were developed to aid interpretation of the RainWET simulations. The tool has potential to enable RWH designers to rapidly evaluate opportunities for installing RWH systems in retrofit and new-build scenarios using a time series evaluation method. With a fast evaluation process available, the methods set out in this chapter show promise in supporting users of the RainWET to demonstrate the true value of traditional and dual purpose RWH systems as both water demand management and stormwater control devices.

Chapter 5: Data collection studies investigating RWH performance

5.1 Chapter Overview

This Chapter reports a series of studies that were completed to generate a broader understanding of the performance and attributes associated with a range of RWH configurations. The studies include laboratory work and evidence from a series of field studies:

5.1. A laboratory study into a novel, retrofittable rainwater harvesting system

5.2. Evaluating FlushRain retrofittable rainwater harvesting: a pilot study

5.3. Rainwater harvesting for water demand management and stormwater control: traditional rainwater harvesting system performance

5.4. Design and analysis of a dual purpose rainwater harvesting system: a pilot study

The studies within this chapter have been published within conference proceedings or academic journals in an alternative form. Where applicable, this chapter also draws upon additional data from each study to support a wider understanding of each study in the context of the thesis.

5.1 A Laboratory Study of FlushRain Retrofittable Rainwater Harvesting

5.1.1 Introduction

The first step in assessing the feasibility and efficacy of a novel RWH configuration is to establish and examine its baseline operational characteristics. To undertake this for the FlushRain system, two tests rigs were constructed within the laboratories at the Centre for Water Systems during June 2014 (Melville-Shreeve *et al.*, 2015).

5.1.2 Materials

The FlushRain RWH (FRWH) system is described by UK patent GB2449534 and is illustrated in

Figure 5.1.1. The system uses downpipe chambers, flexible hoses and a suction pump located within the loft space of a house to draw water from the downpipes into a loft tank during a rainfall-runoff event. Harvested rainwater can be supplied under gravity to non-potable end uses throughout the property. The system has been developed to address three design objectives that are perceived to be weakly addressed by existing RWH products (FlushRain Ltd, personal communication, 29 May 2015); “1) The capital cost should not exceed £1,000; 2) Electricity costs should be less than alternative water resources including traditional RWH systems and municipal water supplies. 3) RWH needs to be retrofittable.

Appraisal against the first two design objectives was undertaken through the construction of a FRWH system in the University of Exeter’s Laboratories. Details of the system installed are described below.

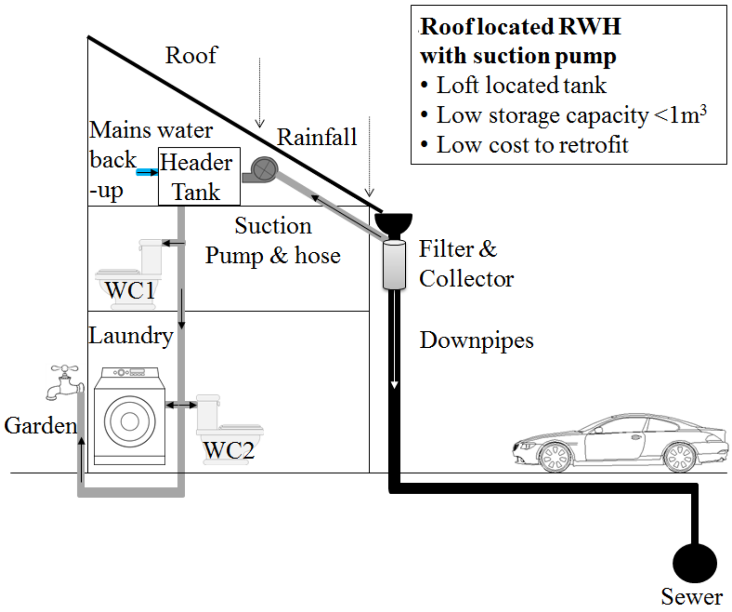
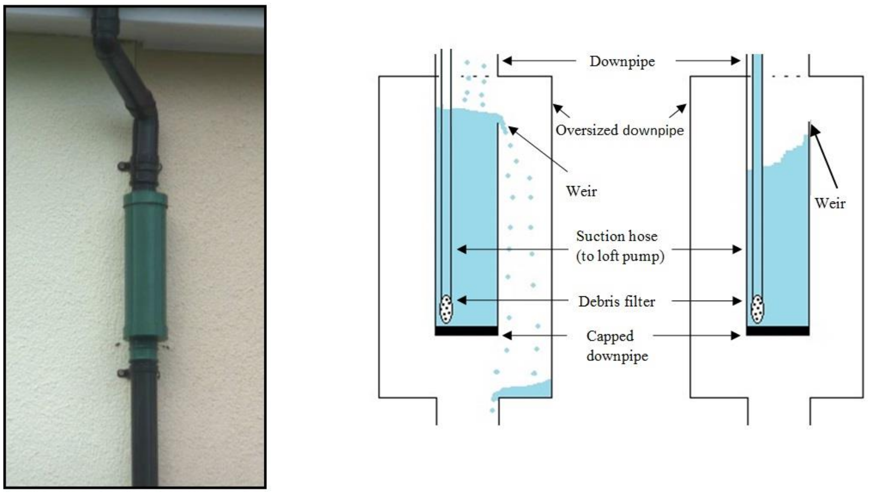


Figure 5.1.1 – Schematic of FlushRain RWH configuration

Downpipe Collector: The downpipe collection chambers capture approximately 2l of rainwater in the existing downpipe. The downpipe is capped causing it to surcharge up to the level of an overspill weir. Water spilling from this weir is re-captured in the outer chamber and returned to the lower section of the downpipe as illustrated in

Figure 5.1.2.



A) Chamber connected to downpipe B) Illustration of chamber discharging to downpipe C) Illustration of chamber being pumped empty

Figure 5.1.2 – Illustration of the downpipe collection chambers and filters

Debris Filter and Non-return Valve: A debris filter is located at the inlet to each suction hose at the base of the collection chambers. It is designed to prevent leaf litter from reaching the pump and storage tank using a two stage screen with 4mm holes and a fine mesh.

Water Level Sensors: A capacitance float switch is installed at the top of the downpipe chamber. The switch activates when it is submerged in water and closes a circuit on the control board. One switch is included at the top water level in each downpipe collector. Another sensor in the top of the storage tank is programmed to prevent the pump from activating when the tank is full.

Collection Hoses: The system uses flexible 15mm diameter hoses to collect water from each chamber. These are fed up through the downpipe and passed into the property through the roof fascia boards. The hoses are laid through the loft space and attached to the pump.

Rainwater Pump: A diaphragm pump (The Whale Gulper 220 DC) with a specified maximum suction head of 3m is installed in the loft. The pump is able to self-prime and is unlikely to experience major issues associated with short periods of dry running. The pump is controlled by a circuit board connected to the water level sensors.

Tanks: A free-flowing outlet from the pump enters the top of the storage tanks via a suspended foam filter gauze which can be washed for reuse. Standard WRAS approved cold water loft tanks are used to store the water in the loft. For the purposes of this study, a tank with 230l of storage was utilised, although in real world installations multiple tanks can be connected subject to the structural loading capacity and space available in the loft. Suitable insulation blankets and pipe lagging are included on the tanks and pipework. Finally, a mains water top-up is installed to allow a shallow level of water to be maintained in the tanks when no rain is available. This is designed to ensure the non-potable supply pipework is always fed with water, even when rainwater has been exhausted.

System Function: During a rainfall-runoff event, runoff fills both collectors and their water level sensors are activated. A ten second delay allows debris collected in the chamber (i.e. leaf litter) to wash through the weir into the overflow pipe. Residual sediment must be cleaned out during maintenance of the system. Following the delay, the pump is activated and the suction hoses feed runoff via the filter into the storage tank. During low intensity rainfall-runoff events, the pump empties the runoff from the collectors and the float switches recognise they are no-longer full. The pump is programmed to continue running for 15 seconds in order to remove excess runoff from the downpipe collectors at the end of a rainfall-runoff event. Once further runoff has accumulated in the collectors, the system restarts. After heavy rain, the tank may become full and the pump stops when the top water level sensor is activated. An overflow from the loft tank provides a failsafe discharge point in case this sensor fails. Harvested rainwater stored in the loft is then plumbed directly to WCs and washing machines.

5.1.3 Method

Test rigs fitted with water meters and data loggers were used to record flow rates and electrical use under a range of scenarios. The two test rigs are illustrated in Figure 5.1.3 and Figure 5.1.4. The two rigs were configured to enable performance data to be collected as follows:

Test Rig 1: Monitoring Head-flow Relationships

A laboratory test rig was constructed to mimic the pipe arrangements of the FRWH system as illustrated in Figure 5.1.3. The arrangement allowed for the pump to be mounted at a range of static heads (0.26m to 2.56m) above a source water tank. At each mounting level, the system was turned on and allowed to prime with water. The flow from the pump was then routed into a tank located upon a set of scales. The mass collected in the tank over a period of time was used to establish the pump's flow rate. The equipment was used to establish a maximum acceptable static head (i.e. vertical distance) between the collection chambers and the pump, above which the pump is unable to draw water into the tank (i.e. elevation and friction head exceeds suction head). The horizontal pipe lengths were kept fixed throughout the tests using 4.85m of 15mm hose. As the static head was increased, an additional length of 22mm pipe was added to the system to allow the pump to be connected at the increased height above the water tank. Thus the measurement of static heads represents a real world installation in which pipe lengths would increase as the vertical distance between collection chamber and the pump increases.

For Test Rig 1, tests were repeated three times at each static head and mean results recorded. Testing was undertaken by altering two variables:

1) The number of pipes connected to the pump (either 1 or 2 were connected);

2) The static head was increased in five steps from 0.26m to 2.56m in order for a head-flow curve to be derived.

Test Rig 2 – Calculating Electrical Consumption

Test Rig 2 comprised an installation in a section of full scale roof as illustrated in Figure 5.1.4. The FRWH system was installed with 2 x 4.85m lengths of 15mm diameter pushfit pipework laid within the roof space. Pumped water was routed into a measuring vessel in order for flow rates to be monitored during testing. A control valve was used to deliver water to the gutter at a rate which exceeded the pump’s maximum flow rate. The second collection hose was placed in a constant-head tank adjacent to the downpipe. This allowed both collectors to have access to unlimited water (mimicking an extreme rainfall event) throughout the tests.

Test Rig 2 was used to monitor the electrical usage of the system under constant incoming flow conditions from two collection hoses. Electricity usage was recorded using an EL-USB-ACT data logger in combination with a current clamp. The AC current at the pump’s control board was monitored using the current clamp. The data logger required an assumed voltage to be set and following testing an average value of 230V was used. The logger recorded the wattage of the system at a 0.25s resolution. For the purposes of identifying the energy usage, the pump was switched on and the flow routed into a collection vessel with a known volume. A stopwatch was used to record the time taken to fill the vessel. For each scenario this was repeated three times and the mean time to fill the vessel was used to establish a pump flow rate. The pump was run for an hour and the power consumption recorded. This data was used to calculate the average electrical consumption required to collect $1m^3$ under optimal (pump permanently on) running conditions. These tests were then repeated with a single collection hose attached to the pump.

During low intensity rainfall events, the FRWH system's pump is sufficiently powerful to empty the downpipe collection chambers. Consequently, in day to day operation, the pump switches on and off frequently during a rainfall event. Hence it was necessary for the power consumption associated with this sub-optimal pump operation to be investigated. The process of pump switching (on-off) was monitored to establish if turning the pumps on and off caused higher electricity usage per unit of water delivered to the tank. In order to assess this factor, the pumping system was switched on and off rapidly to identify any spikes in the electricity required to start the pump when the system activates. Results were recorded for analysis in the following section.

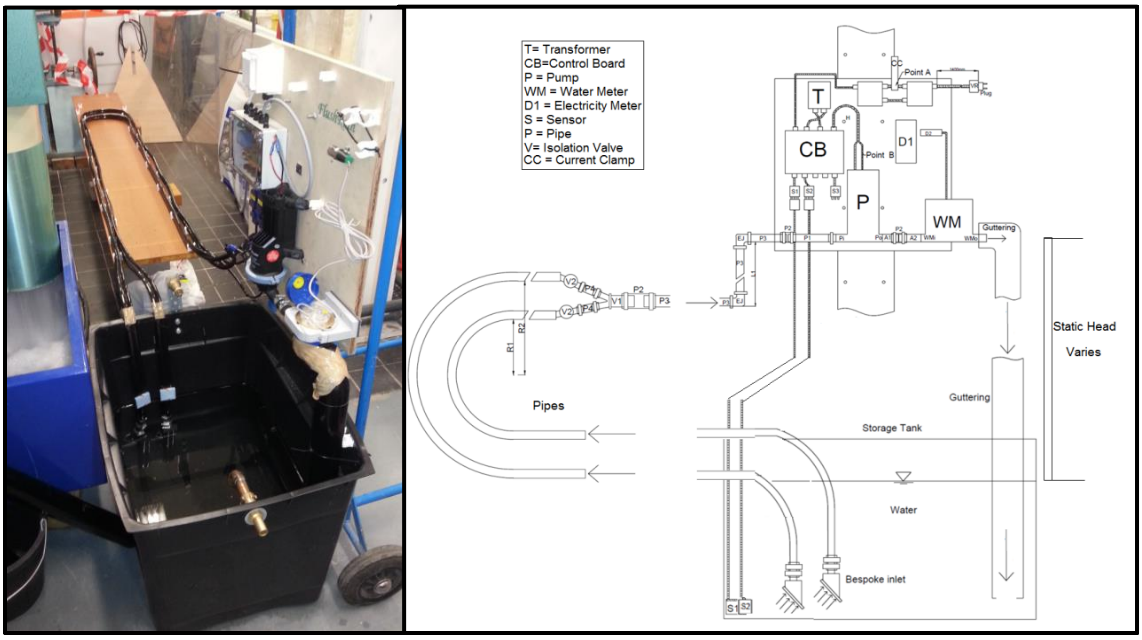


Figure 5.1.3 – Photo and layout drawing of Test Rig 1

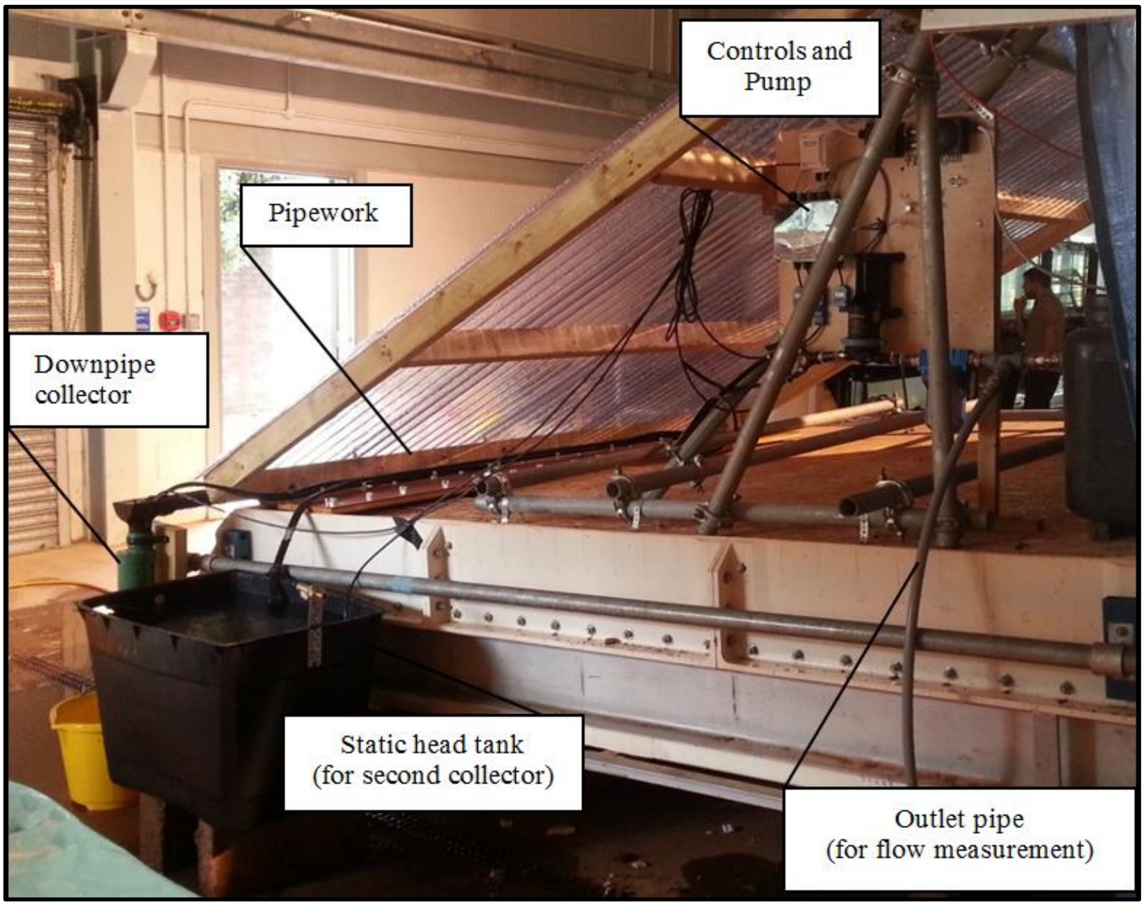


Figure 5.1.4 – Illustrated Image of Test Rig 2

5.1.4 Results and Discussion

Establishing Head-Flow Relationships

Results from the tests conducted on Test Rig 1 were used to establish the head-flow relationships that might be expected in a real world installation. The results are illustrated in Figure 5.1.5.

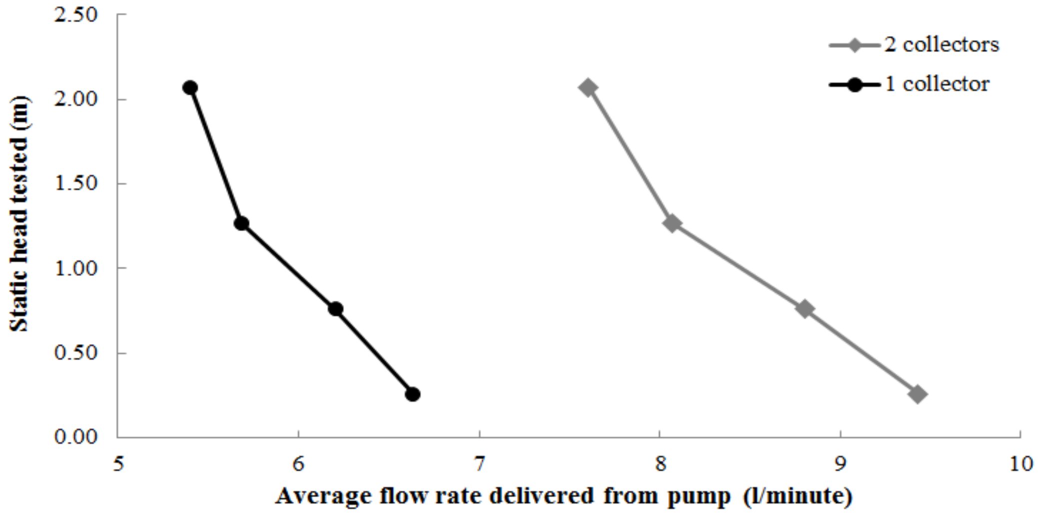


Figure 5.1.5 – Head-flow relationships for FRWH system from Test Rig 1

Minimum and maximum values for each static head tested did not vary by more than +/- 0.1l/s from the mean value. Although a small sample set was collected, the standard deviation did not exceed 0.12. The data illustrates that the FRWH system can operate with either one or two collection chambers connected. As might be expected, the rate of flow decreases as the static head increases, and the system is able to deliver a greater volume of flow when pipe friction is reduced (i.e. both 15mm pipes are connected). This illustrates that the pump is able to function more efficiently when two downpipe collectors are attached (i.e. front and back of house) rather than having a single pipe connected to a single pump. Flow rates of >9l/m were observed for the lowest static head when two pipes were connected. In contrast, the lowest flow rate recorded was 5.4l/m for a single collector at 2.08m static head (i.e. a vertical distance of 2.08m between the inlet to the pump and the water being lifted). For both one and two collectors, the system failed (i.e. the pump only drew air into the tanks and was unable to self-prime) when a static head of 2.56m was tested. This also suggests that installations with collectors that are installed more than 2.08m below the pump inlet would not be advisable in a real world setting.

Establishing Power Consumption

The system was operated with two pipes connected to the pump for a one hour test and the resulting electricity consumption data analysed as illustrated in Figure 5.1.6. The data shows the pump's power demand constantly fluctuates between approximately 50-100W.

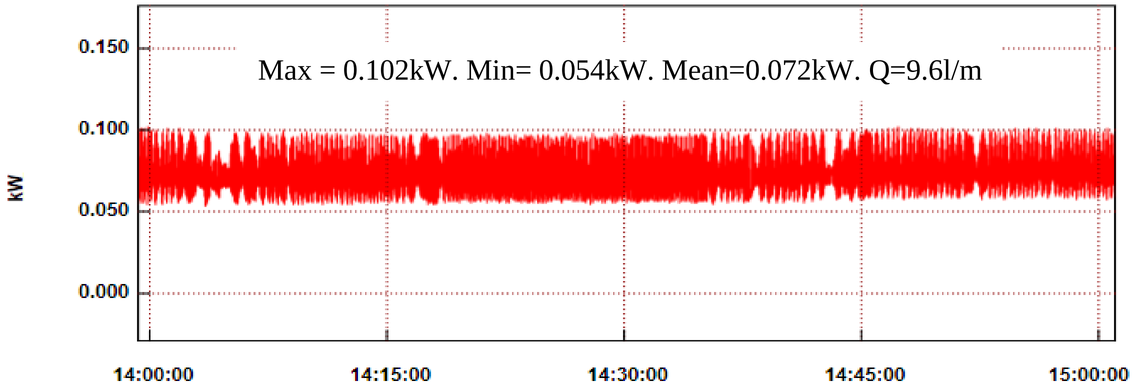


Figure 5.1.6 – Power consumption at 0.25s resolution for 2 collectors pumping for 1 hour

The average kW usage recorded was 0.072kW (±5.3%). Scaled to an hour of usage this equates to 0.072kWh (±5.3%). Records of the pumped flow during the one hour window illustrate an average flow rate of 9.6l/m. Repeating the test with a single collector connected for one hour yielded power usage as illustrated in Figure 5.1.7. As with the two collector scenario, the pump operates at a power usage of approximately 50-100W.

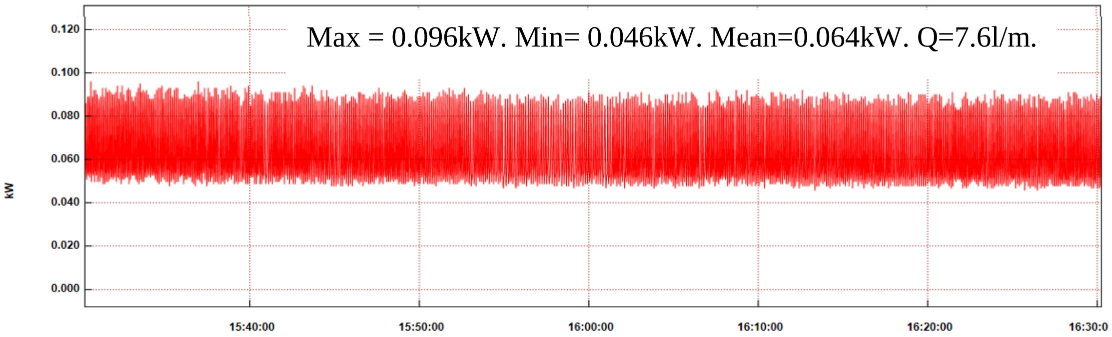


Figure 5.1.7 – Power consumption at a 0.25s resolution for 1 collector pumping for 1 hour

The results obtained are consistent with the findings of a number of other tests conducted using Test rig 2 which verified that the pump runs at a consistent electrical consumption rate, within a band of approximately 50-100W, regardless of the static head, friction head or flow rate. The pump's consistency allows relatively accurate estimations to be made of the electricity required to collect rainfall-runoff using the FRWH system. Taking an average electrical consumption of the pump running over one hour as 0.072kWh (±5.3%) and a recorded flow rate of 9.6l/m (±3.8%) it is possible to assert, that under optimum laboratory conditions, the energy usage for provision of 1m^3 of water equates to 0.124kWh (±9.5%), costing 1.68p at 13.52 p/kWh (EST, 2014) . This figure increases to 0.139kWh for a flow of 7.6l/m (±3.53%) giving 1.88p/m^3 in the event that a single collector is operating. This compares to South West Water's municipal water charge of £2.05/m^3, generating a potential saving of £2.03/m^3 collected (South West Water, 2014a). However, it is unreasonable to assume that the pumping regime would be operating for long periods of time. In practice, rainfall-runoff events would cause the pump to switch on and off as the collection chambers filled and were pumped empty.

The system was run for a number of test windows with the pumps turned on and off by artificially removing the water level sensors from the water. Each time the pump activated, the switch was manually removed. When the pump stopped the switch was reintroduced to the water. A 20 minute window of this data is illustrated in the power curve in Figure 5.1.8. With flows starting and stopping as the pump is switched on and off, the average flow rate was less than the 'pump on' scenario and averaged 6.7l/m (±3.6%). It is evident that even when the pumps are switching on and off frequently, the mean power required does not exhibit spikes in power consumption. Figure 5.1.8 also illustrates that a standby power (associated with the control board) of 11W was recorded when the pump was not operating. The pump-switching tests illustrate that 6.7l/min can be delivered at a cost of 0.049kW. This equates to a cost of 1.65p/m^3, less than the cost when the pump is permanently operating. In contrast to the expected outcome, this implies that pump switching on and off does not increase the overall cost of water collection.

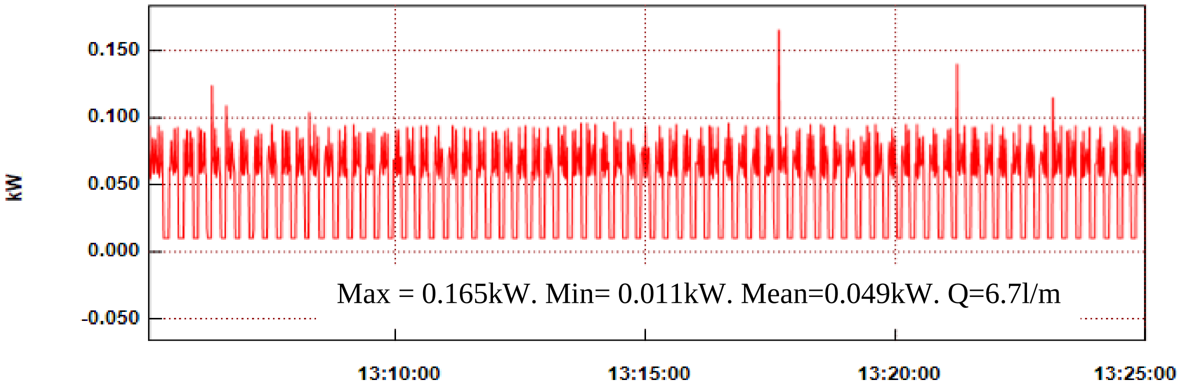


Figure 5.1.8 – System power usage at a 0.25s resolution for 2 collectors pumping for 20 minutes with maximum pump switching

The electricity consumption for the pump used in the novel RWH system assessed in this study (0.12kWh/m^3) compared favourably to literature describing existing RWH systems (0.54kWh/m^3) monitored by Ward *et al.* (2012b) which also notes that UK municipal water supplies use around 0.60kWh/m^3. This can be attributed to; 1) the low power consumption for the pump (~50-100W), the low operating head, and the lack of increased power consumption during pump start-up. A further comparison was drawn against the existing market leader for household RWH which claims a value of 0.68kWh/m^3 for its RainDirector system (Rainwater Harvesting ltd, 2013a). Internationally, Vieira *et al.* (2014) reviewed empirical data from 10 RWH studies and identified a median power usage of 1.40kWh/m^3. For contrast this study also offers a figure for global desalination of water at 3.60kWh/m^3.

The annual electricity costs for pumping were projected to be very low at less than £1 per year (assuming a nominal 30m^3 usage consuming 3.72kWh at 13.52p/kWh). In comparison, water rates for the highest-charging water company (SWW, 2014) would cost a customer £61.50 based on a rate of £2.05/m^3. However, the electronics supporting the system were found to have a mean standby power consumption of 11W. A total standby energy cost of 96.36 kWh/year was projected at a cost of £13.41. Assuming a 30m^3 per annum usage, a total electricity usage of 3.34kWh/m^3 was projected from the results, five times higher than the operational power consumption of average municipal supplies. A reduction in the standby power consumption of the FRWH system will be necessary if the system is to match the mean values reported for existing water supply infrastructure. If the standby power consumption can be eliminated then the system is likely to achieve lower electricity use per m^3 delivered than existing RWH systems.

5.1.5 Conclusions

The following conclusions can be drawn from the laboratory study;

1) The FlushRain RWH system can function with one or two pipe collectors connected although a greater volume of rainfall-runoff can be collected when two pipes are connected.

2) Flow rates reduced as the static head was increased. The system failed to operate at a static head of 2.56m and consequently, taking a practical perspective, it is not recommended for installation where the static head exceeds 2.00m.

3) Results showed the electrical consumption of the pump to be 0.12kWh/m^3 or 3.72kWh/year assuming 30m^3 of harvested water is used. This was found to be significantly lower than mean power consumption data in literature relating to existing RWH technologies, municipal water systems and desalination supplies. However, the

control electronics were found to use 11W and, as they are permanently on, this contributes an additional 96.36kWh/year. The average power consumption for the system in a real world setting was therefore projected to be greater than municipal supplies at 3.34kWh/m^3. Consequently, reconfiguration of the standby control system will be needed if the system seeks to limit its power consumption levels to those documented for existing water supply systems.

To fill a gap in knowledge relating to novel RWH system configurations, this case study examined the baseline operational characteristics of a novel RWH system in a laboratory setting. The next stage in assessing the feasibility and efficacy of such a technology is to examine its performance in the real world, which is undertaken in Chapter 5.2.

5.2 Evaluating FlushRain Retrofittable Rainwater Harvesting: A Pilot Study

5.2.1 Introduction

This project builds upon Chapter 5.1 to examine the performance of the FlushRain RWH system at a series of pilot installations. The FlushRain RWH system was retrofitted to three properties in Exeter and monitored for a year from October 2014 (Melville-Shreeve, 2016c). The datasets are presented and further analysis of the best performing property used to investigate the potential for the system as a water demand and stormwater management device.

5.2.2 Materials

The FlushRain RWH (FRWH) system described in Chapter 5.1 was retrofitted to three properties in Exeter during the autumn of 2014. The systems comprised a loft-located suction pump, which draws water from downpipe chambers into a header tank with a 280l functional volume. A control-board enabled the pump to activate and empty the downpipe collectors into the tank when rainfall was detected. Rainwater stored in the loft tank was fed under gravity to the upstairs WC. The FRWH system and associated monitoring devices are described and illustrated Figure 5.2.1.

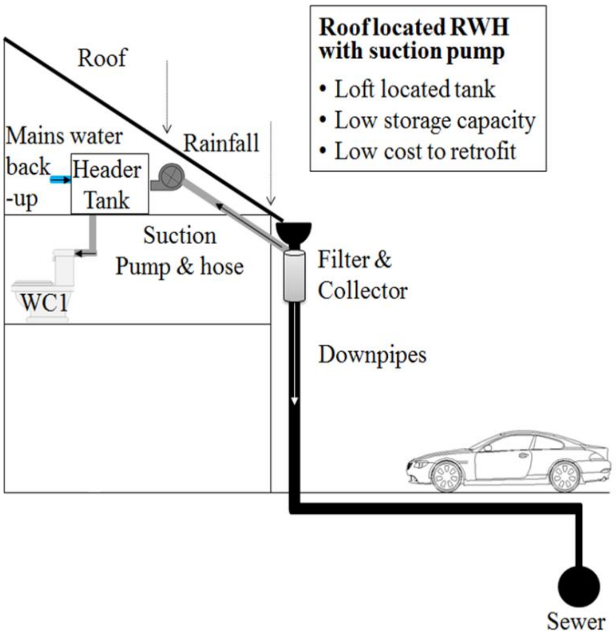


Figure 5.2.1– FlushRain configuration and monitoring equipment installed at trial sites

5.2.3 Methodology

As illustrated in the development of Chapter 4, RWH systems can be modelled based on mass balance equations. However, the ability of the FRWH system to provide an AWR was projected to be limited as the small tank needs frequent small rainfall events to generate a steady supply of rainwater to the property's WC. The rainwater yield was measured in terms of total rainwater used (m^3/annum) and also compared as a percentage of total household water demand. Three volumetric water meters (with data loggers capturing usage in 1l increments at 15 minute intervals) were installed at the properties as illustrated in Figure 5.2.1. These measured; Total household mains water demand (WM1); Total mains water top-up entering the rainwater tank (WM2); and Total water used for (upstairs) WC flushing (WM3). A fourth "virtual water meter" (WM4) was calculated by subtracting WM2 from WM3 for each 15 minute time step. Manual water meter readings were also taken during monthly site visits over a 380 day period. Data processing allowed data to be analysed at daily, monthly and annual time-steps.

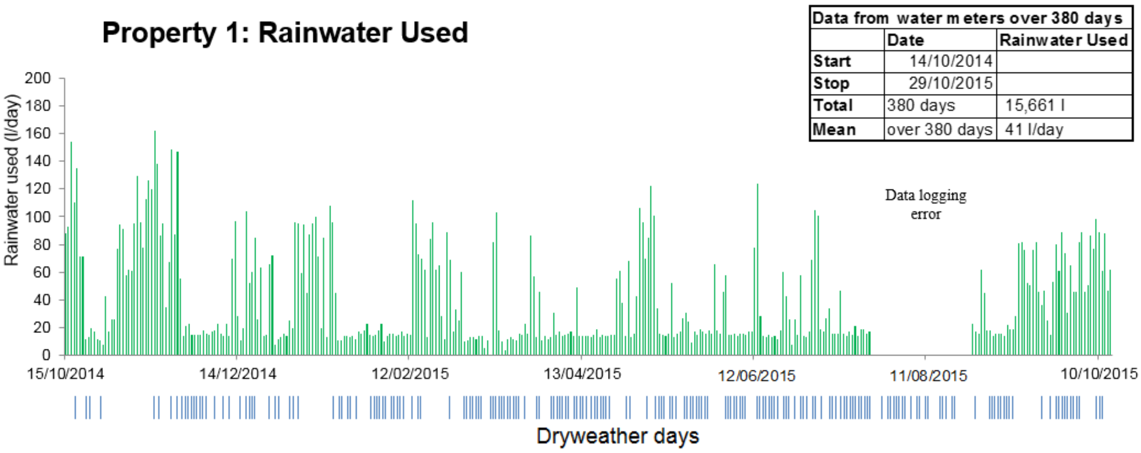
Electrical power consumption (kWh) was measured monthly at the control-board for each system. This data was analysed alongside the water meter outputs to identify the electrical consumption in kWh/m^3.

The properties had an un-insulated loft space which increased the possibility that pipework and rainwater within the tank could freeze in winter months. Furthermore, the lack of insulation could have led to increased bacteriological activity within the rainwater tank (associated with warm temperatures during summer months). A temperature logger was installed below the minimum water level in the rainwater tank to capture this data at a 15 minute time step.

5.2.4 Results and Discussion

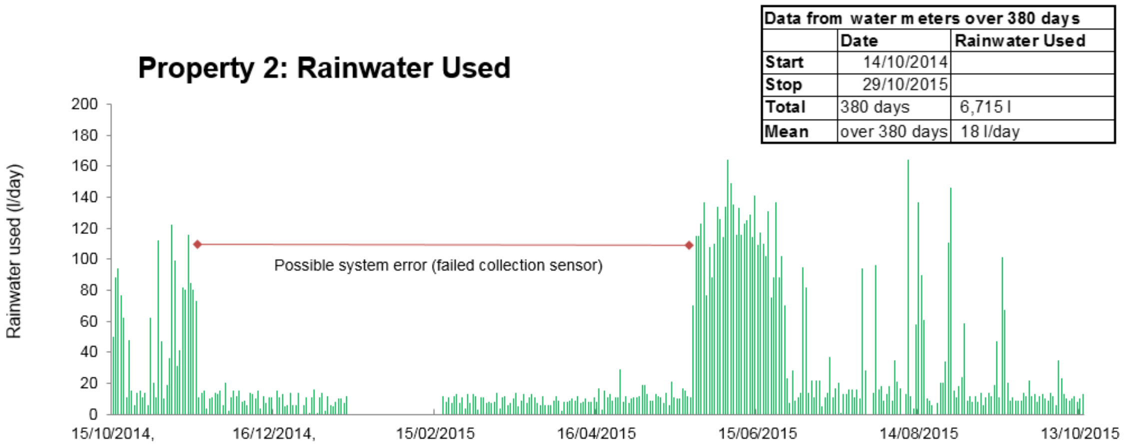
Rainwater used at three pilot systems

The three pilot sites had differing characteristics as they each had a range of occupancy rates, roof areas and thus water demands and yields respectively. In addition system failures and data logging errors limited the value of the data collected at Property 2 and 3. The rainwater demand satisfied at the three properties over the yearlong study is illustrated in Figures 5.2.2 – 5.2.4. Each chart shows data derived from the data loggers, whereas the tables in each figure show the rainwater used based on visual readings from the water meters (to overcome any missed data associated with data logging / system failures).



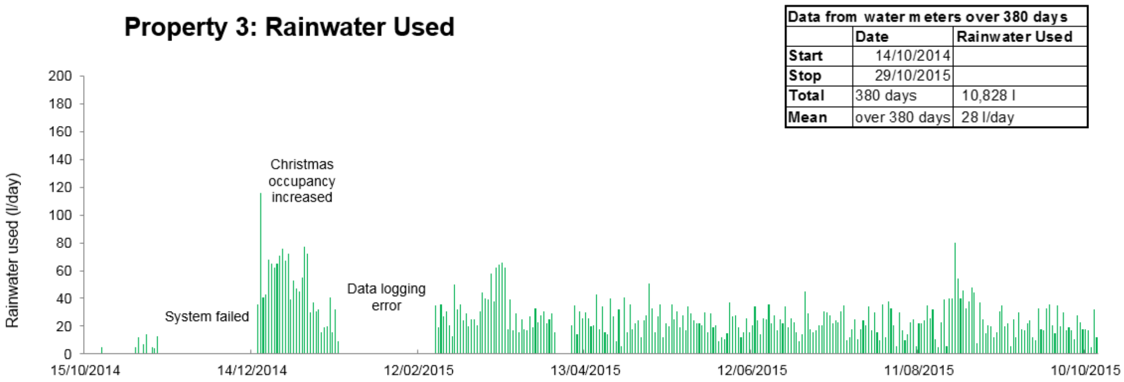
Data from water meters over 380 days		
	Date	Rainwater Used
Start	14/10/2014	
Stop	29/10/2015	
Total	380 days	15,661 l
Mean	over 380 days	41 l/day

Figure 5.2.2 – Rainwater used over 12 months at Property 1, Occupancy = 4 people, Roof area = 55m^2



Data from water meters over 380 days		
	Date	Rainwater Used
Start	14/10/2014	
Stop	29/10/2015	
Total	380 days	6,715 l
Mean	over 380 days	18 l/day

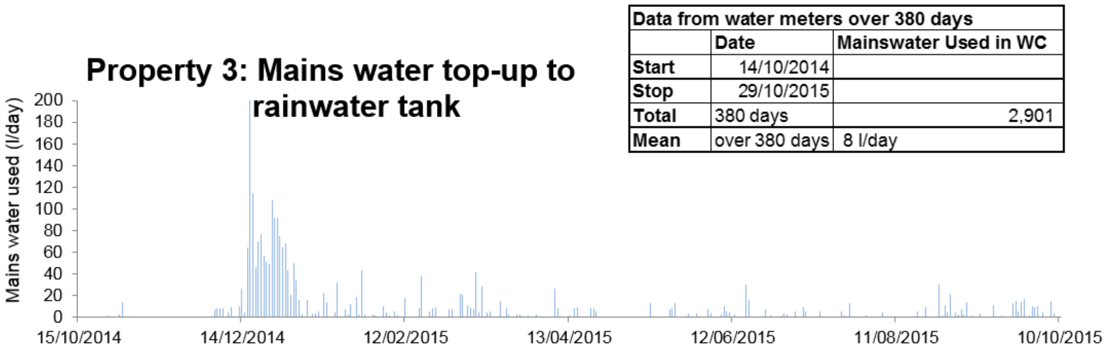
Figure 5.2.3 – Rainwater used over 12 months at Property 2, Occupancy = 3 people, Roof area = 75m^2



Data from water meters over 380 days		
	Date	Rainwater Used
Start	14/10/2014	
Stop	29/10/2015	
Total	380 days	10,828 l
Mean	over 380 days	28 l/day

Figure 5.2.4 – *Rainwater used over 12 months at Property 3, Occupancy = 1 person, Roof area = 50m^2*

The data collected a the property with a single occupant (Property 3) showed a consistent rainwater demand was satisfied throughout the year, with an average of 28 litres of rainwater used each day. There is a marked increase in water demand when the occupancy increased over the Christmas period. When this period is taken out from the analysis, (i.e. when a single tenant was using the rainwater), the data illustrated in Figure 5.2.5 shows that the mains water feed into the rainwater tank was largely inactive for the remainder of the year. With the Christmas period (13/12/14 – 04/01/15) discounted, the mains water top-up to the rainwater tank was found to total just 1,703l, an average of 8l/day.



Data from water meters over 380 days		
	Date	Mainswater Used in WC
Start	14/10/2014	
Stop	29/10/2015	
Total	380 days	2,901
Mean	over 380 days	8 l/day

Figure 5.2.5 – Mains water used in WC over 12 months at Property 3.

The system installed at Property 1 had the largest occupancy and least data logging failures during the monitoring period. A detailed review of the evidence from this site was conducted to further evidence the potential of the FRWH system.

Detailed Review of Property 1

The annual water demand was calculated from the data recorded at the water meters. 35 days of corrupted data was captured over the 365 day study which was removed from the analysis during pre-processing. The processed data indicated that total household (mains) water demand averaged 337l/day (111m^3/year) with a maximum of 676l/day. The mean WC consumption (upstairs WC only) was 88l/day of which 40l/day was provided by rainwater. This suggests the FRWH system achieved a total water demand reduction 14,600l/year or 11.6% of total household water demand. A review of manually recorded water meter readings illustrated that the data loggers slightly under-recorded rainwater usage by 3% when compared with the manual readings over a 380 day period. The manual water meter reading data indicated that 15,042l of rainwater was saved in a single year. At a cost of £5.52/m^3 (SWW, 2014), an £83 reduction in the annual water bill was calculated. Although capital costs for the pilot installation were notably higher, the target cost of future installations has been estimated at approximately £1000. At this price point, a simple payback period of 12 years would be achieved, assuming water prices remain static and maintenance costs are not included. However this calculation does not take into account electrical power demand. In addition SWW's revised RWH policy requests that rainwater introduced to the sewer from RWH systems is metered and charged at the waste water rate. This would reduce the annual saving to approximately £31/annum (at £2.05/m^3).

The work described in Chapter 5.1 demonstrated that the system's pump can deliver 1m^3 using 0.12kWh of electricity in a lab setting (Melville-Shreeve *et al.*, 2015). Data collected at Property 1 showed an average usage of 3.08kWh/m^3 was required to supply the rainwater over a 380 day period. Rainwater usage and power consumption were poorly correlated (i.e. months with low rainwater use still experienced high power consumption). Data from the trial site concurs with work done at a laboratory scale which suggested that high electricity consumption for the control-board is the largest contributor to system's electricity consumption (£6.95/year). Hence it is likely that the true cost of such a RWH configuration could be notably reduced through integration of low power control technologies.

The risk of freezing was evaluated by monitoring the tank's water temperature throughout the study. Mean monthly tank water temperatures were observed in the range of 11.5-20.6^{o}C. Temperatures recorded within the tank are shown in Figure 5.2.6 for the 12 month study. A maximum summer temperature of 25.3^{o}C was recorded with a minimum of 7.7°C during winter. This evidence suggests that the risk of the tank freezing at this site are low as temperatures never approached 0°C.

The data shows vertical spikes where the temperature reduces rapidly as a result of rainfall entering the tank. This data suggests that (in the absence of a rainfall event) the water within the tanks slowly increases in temperature, i.e. it is heated by the sun and potentially captures heat from the property below during cold periods. The loft tank was located within a "cold roof" (i.e. one which is not insulated) however, it was wrapped using a standard insulation blanket. It is anticipated that this insulation reduced the risk of the water freezing in the winter whilst slowing the increase in temperatures during the hottest days. This in turn is likely to inhibit legionella growth within the tank which reaches its highest virulence at around 37°C (HSE, 2000).

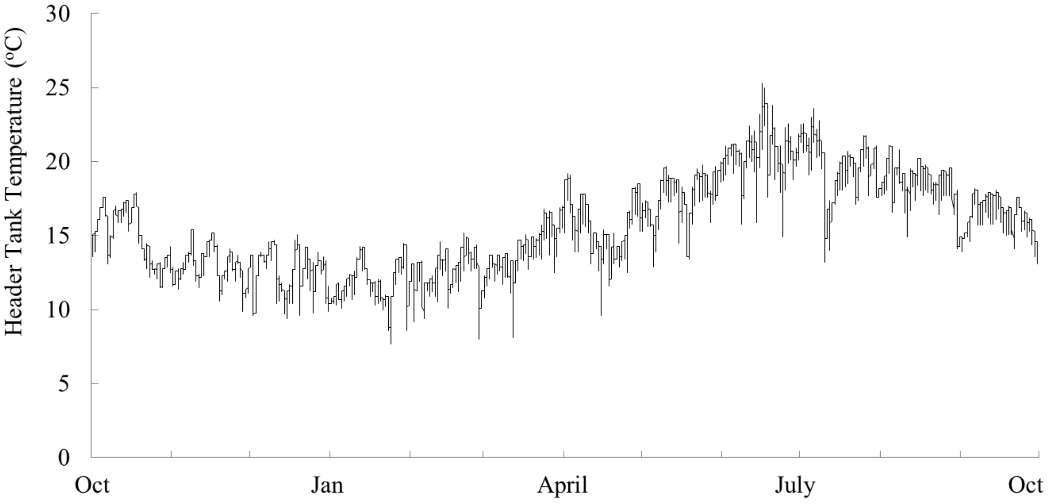


Figure 5.2.6 – FlushRain rainwater tank temperatures at Property 1 (October 2014-2015)

As evidenced in Chapter 2, the potential for RWH to offer stormwater management benefits is increasingly analysed within RWH studies. The benefits to stakeholders (e.g. stormwater management authorities) of using RWH to manage stormwater poses a significant opportunity for further empirical studies. Rain gauge data for a nearby site (Whipton) was analysed to identify available rainwater to the FRWH system at Property 1 (roof area = 55m^2). The rain gauge showed 169 rain-days comprising a total annual volume of rainwater available to the property 39,546l (assuming average loss coefficient of 10% and a 5l/day loss for first-flush losses). The largest volume of rainwater available to the FRWH system in a single day was 1,871l (24/7/2015). The water meter data showed the rain tank was empty at the beginning of this storm and full after the event. Hence the FRWH system's capacity of 280l reduced the peak discharge from this storm by 15%. Over the year monitored, the property used 15,042l of rainwater. This reduced the total annual stormwater discharges by 38% in comparison to an equivalent property without FRWH installed.

5.2.5 Conclusion

The FRWH system was installed and monitored for a 12 month period at three properties in Exeter. Where the system was installed with a low water demand (i.e. single occupancy, an average of just 8l/day of mains water was required to feed the WC. The mean rainwater demand for the same period was 28l/day. This suggests that properties with FlushRain installed that have a single occupancy can potentially access more than 70% of their annual WC demands. The following conclusions can be drawn from the best performing system in the study; 1) The FRWH system was successfully installed and operated without the need for maintenance, feeding rainwater to the upstairs WC at a site in Exeter with four occupants and a roof of 55m^2; 2) Potable water demand for the WC was reduced by 15,042l over the one year monitoring period; 3) Cash savings of £83 were realised assuming a water cost of £5.52/m^3; 4) Future installations could achieve a 12 year payback period assuming the data collected for the study is representative of long term functionality and water costs; 5) Electrical consumption was identified as reaching 3.08kWh/m^3 due to high power consumption of the control systems; 6) Mean monthly tank water temperatures were observed in the range of 11.5-20.6^{o}C; 7) The largest annual storm was reduced in volume by 15% with total annual stormwater discharges reduced by 38% over the one year study.

This case study supports observations recorded in a laboratory setting and examined the baseline operational characteristics of a novel RWH system at three pilot sites. The data illustrated the potential for RWH systems to be retrofitted using small loft-based tanks. In addition the system was observed to reduce stormwater discharges by 15% during the largest annual storm. This evidence demonstrates the potential for well-designed RWH systems to be installed as part of a source control strategy. The functionality of the RWH system monitored in this case study demonstrated limited stormwater control characteristics as the loft based tanks were limited to just 280l. Chapter 5.3 investigates the ability of traditional RWH systems with large storage tanks to provide source control benefits based on demand for rainwater providing capacity for stormwater to be captured during storm events.

5.3 Rainwater Harvesting for Water Demand Management and Stormwater Control: Traditional Rainwater Harvesting System Performance

5.3.1 Introduction

A research gap was identified to evaluate the performance of RWH systems at a plot scale. This case study examines the performance of a traditional RWH system installed with a 5,000l below ground tank in Truro, Cornwall. The work investigates the system's ability to reduce water demand and limit downstream rainwater discharges based on a 113 day monitoring period to August 2015. This study interrogates the design process for a RWH installation which was completed as part of a WSP initiative to reduce rainwater entering a combined sewer network (primary objective) whilst providing the householder with an alternative water resource (secondary objective).

5.3.2 Materials

In accordance with the UK's British Standard for RWH ((BSI), 2013b), the property's RWH system was designed to provide non-potable water for WC flushing, laundry use and garden watering. The property was selected as it was located within South West Water's WaterShed Truro project (South West Water, 2014b), and the system could be installed whilst causing minimum household disruption as part of an ongoing extension at the house. It represents one of several SuDS interventions installed as part of a wider surface water management scheme.

Tank sizing calculation: BS 8515:2009+A1:2013

The proposed total RWH tank volume was calculated using the 'intermediate approach'. This method defines the tank volume required for a RWH system as the lesser of two volumes (Y_R or D_N) calculated using Equations 5.3.1 and 5.3.2;

Equation 5.3.1 $Y_R = A \times e \times AAR \times h \times 0.05$

where Y_R is 5% of the annual rainwater yield (l); A is the collecting area (m^2); e is the yield coefficient (%); AAR is the annual depth of rainfall (mm); h is the hydraulic filter efficiency.

Equation 5.3.1 $D_N = Pd \times n \times 365 \times 0.05$

where D_N is the annual non-potable water demand (l); P_d is the daily requirement per person (l); and n is the number of persons.

Table 5.3.1 describes the parameters and calculation results for the key RWH design parameters for the site.

Table 5.3.1 – RWH design parameters and tank sizing values

Parameter	Value	Units	Comments
A	85	m^2	Estimated from planning drawings
e	0.9	-	Estimate ((BSI), 2013)
AAR	1,200	mm/year	SAAR ((BSI), 2013b)
h	1.0	-	Losses accounted for in e parameter
Y_R	4,590	l	Calculated
P_d	50	l	Estimated potential rainwater demand
n	4	Occupants	Known household occupancy
D_N	3,650	l	Calculated
Y_R/D_N	1.26	-	Yield exceeds demand

Where $D_N<Y_R$, BS8515 states that the tank size for provision of non-potable water should be equal to approximately D_N (3,650l) ((BSI), 2013b). In addition, the designing for stormwater control annex in BS8515 suggests an oversized tank can be specified where RWH is to be used for stormwater control. However the method is not applicable where Y_R/D_N is >0.7. Hence the guidance suggests that adding additional volume of storage for stormwater control is not deemed to be appropriate in this location. If Y_R/D_N <0.7, 5,000l of additional stormwater storage would have been necessary to satisfy the simplified approach (i.e. 8,650l total). This requires a source control volume equivalent to the area feeding the tank capturing a 60mm storm.

The supplier for the RWH system provides tanks with 1,500l, 3,000l and 5,000l capacities. Hence a 5,000l tank was selected for this location to maximize water availability for the household as the 3,000l tank would have been 650l smaller than the design volume defined using the BS8515 method.

Details and specifications of the RWH installation were described in the installation documentation made available from the product manufacturer, Rainwater Harvesting Limited (Rainwater Harvesting, 2015). The RWH configuration evaluated here is illustrated in Figures 5.3.1 and 5.3.2. The system selected includes a 5,000l shallow-dig tank fed from an 85m^2 roof. An inline filter enables rainwater to wash debris into the overflow pipework, whilst diverting rainwater into the tank. Overflows are routed to a 1000l geocellular soakaway at the rear of the property. A system controller and associated sensors operate the 800W submersible pump which feeds the header tank. The controller uses sensors to minimise pump cycling by ensuring the pump delivers >50l every time it activates. The manufacturer's literature advises the header tank configuration should be installed when space permits. The system was designed to overcome the need for direct feed pumps to activate every time a small demand event occurs (e.g. a WC flush). The header tank configuration reduces pump-starts and thus reduces pump cycles and pressure fluctuations in the pipework and is intended to maximise the life of the RWH pump and control valves.

The RWH system's header tank is plumbed by gravity into the house's WCs, laundry and garden tap. The system controller's auto-flush function detects when the property is vacant (for example, during holidays) and uses the refresh feature to drain rainwater from the header tank back to the 5,000l tank. The mains water top up fills the header tank with chlorinated potable water until the tank is drained again when the occupant returns. The mains water feed also activates during periods of dry weather to feed mains water to the non-potable applications in the event that the 5,000l tank has been exhausted.

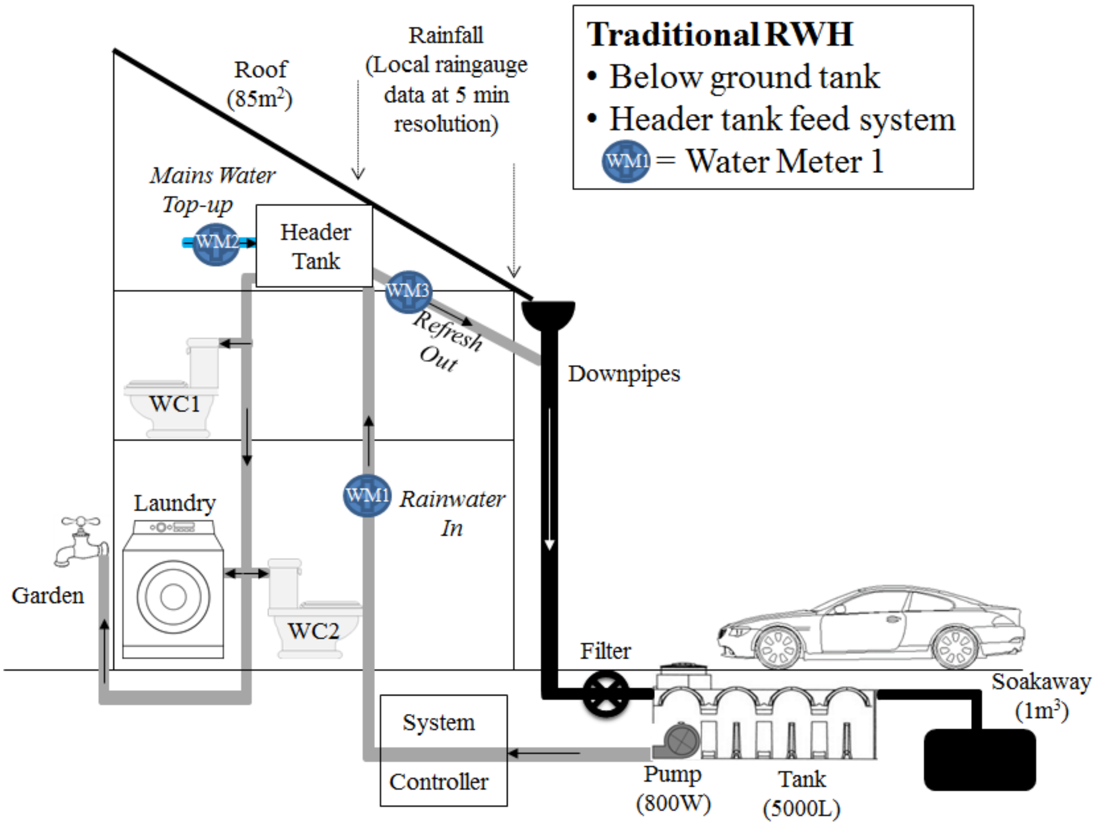


Figure 5.3.1 – RWH configuration at pilot site

The RWH system was installed during spring 2015, and commissioned on 29/04/2015. The three volumetric water meters illustrated in Figure 5.3.1 were monitored for 113 days between 19/06/2015 and 08/10/2015. Data was collected for 15 minute intervals with a minimum resolution of 1l. Data from a local rain gauge was obtained for the same period from a site less than 1km from the property. Figure 5.3.2 illustrates RWH components and monitoring equipment installed at the property. The water meter and rain gauge data was interrogated to evaluate the performance of the system.

5.3.3 Methodology

The intermediate approach set out in the British Standard for RWH ((BSI), 2013b) was used to provide an estimate for the RWH system’s performance before construction. With the system installed, smart water meters and data loggers were used to record water usage and local rainfall for the duration of the study. Calculations were used to estimate water savings, financial benefits, and reductions in stormwater discharging from the system at a daily time step. Finally comparisons were drawn between projected water savings and observed data. In addition a detailed design assessment method using a twenty year rainfall dataset was used to evaluate the long term water demand and stormwater control benefits associated with the RWH installation. Full details of the installation, design methods and calculation steps are set out in the following sections.

Calculating Water Demand

This was assessed in terms of total rainwater used for a given period. The water meters measured: Rainwater usage (WM1); Total mains water top-up entering the header tank (WM2); and Refresh water returned from the header tank (WM3). A fourth “virtual water meter” (WM4) was calculated to establish total non-potable water demand (i.e. water used at WC’s, laundry and garden) by summing WM1 and WM2 and subtracting WM3 for each time step. Data processing allowed data to be viewed at daily, monthly and annual (projected) time steps. However, with only 113 days of demand data available, annual values were estimated by scaling the recorded values using a factor of 3.23.

Calculating Power Consumption

This was evaluated by taking monthly readings of rainwater demand from WM1 and estimating total power demand (kWh) based on empirical data available from laboratory studies completed by the manufacturer.

Calculating Rainwater Discharges

The RWH installation is fed from a roof area of 85m^2 which historically drained into the combined sewer. Furthermore, the overflow is now routed into a soakaway chamber. The total rainfall arriving at the site over a single year was used to estimate the total flow reduction in the combined sewer. Rainwater usage data for the system was also used as a measure of the system’s ability to reduce downstream discharges.

Figure 5.3.2 – RWH components (clockwise): 1) Photo of Header Tank & Refresh Water Meter (WM3); 2) System Controller; 3) System pump; 4) 5,000l Tank

5.3.4 Results and Discussion

Analysis of the rain gauge and water meter data was completed for each day in the 113 day data set enabling the RWH tank's level to be estimated throughout the study. By adjusting the initial tank level (i.e. stored rainwater at the start of the study period), the simulations were matched to fit the measured water demand data. The initial tank level was not recorded when the tank was commissioned. The closest measured tank level was 1,875l on 20/5/2015. Through iteration (available range 0-5,000l), a starting tank level of 1000l was selected for the time series analysis as this enabled the projected rainwater demand estimates within the simulation tool to correctly match the metered water demands for the period (89% satisfied). The outputs based on recorded rainfall (at the rain gauge) and recorded water demands were used to estimate the tank level and associated overflows for each day of the study as illustrated in Figure 5.3.3 and Table 5.3.2.

Date	Daily Rainfall (mm)	Total Rain (L)	Rain (L)	No. of Raindays	First Flush Volume	Overflow Volume (L)	Potential RW Demand (L)	RW Demand Met (L)	RW Demand Met (%)
TOTALS	287.0	24,395	21,956	62	310	4,272	16,835	15,019	89%

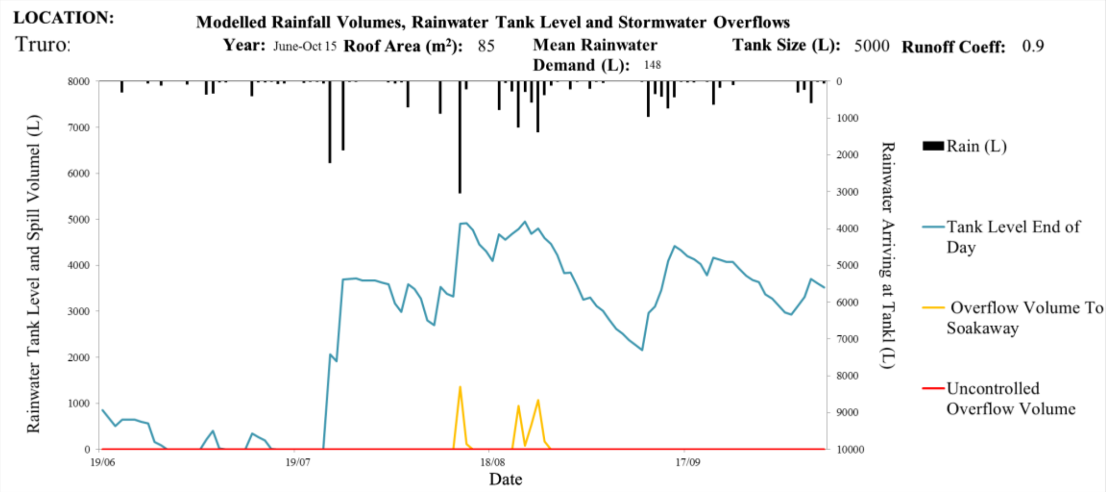


Figure 5.3.3 – Rainfall data and projected rainwater tank level, spills and demand data for study period

Table 5.3.2 –Rainfall, Overflows*, Rainwater Demand, Rainwater Demand Satisfied* and Tank Level* for each day of study (*denotes calculated, not measured empirically).

Time Step	Daily Rainfall (mm)	Roof Area (m^2)	Total Rain (l)	Rain After 10% Losses (l)	Count Raindays	First Flush Volume (l)	Overflow Volume (l)	Metered Rainwater Demand (l)	RW Demand Satisfied (l)	Tank Level End of Day (l)
TOTALS	**287.0**	**-**	**24,395**	**21,956**	**62**	**310**	**4,272**	**16,835**	**15,019**	**-**
19/06/2015	0.0	85	0	0	0	0	0	149	149	851
20/06/2015	0.0	85	0	0	0	0	0	168	168	683
21/06/2015	0.0	85	0	0	0	0	0	172	172	511
22/06/2015	4.0	85	340	306	1	5	0	163	163	649
23/06/2015	0.0	85	0	0	0	0	0	0	0	649
24/06/2015	0.0	85	0	0	0	0	0	0	0	649
25/06/2015	0.0	85	0	0	0	0	0	46	46	603
26/06/2015	0.8	85	68	61	1	5	0	100	100	559
27/06/2015	0.0	85	0	0	0	0	0	405	405	154
28/06/2015	1.6	85	136	122	1	5	0	181	181	91
29/06/2015	0.0	85	0	0	0	0	0	179	91	0
30/06/2015	0.0	85	0	0	0	0	0	44	0	0
01/07/2015	0.0	85	0	0	0	0	0	95	0	0
02/07/2015	1.2	85	102	92	1	5	0	150	87	0
03/07/2015	0.0	85	0	0	0	0	0	47	0	0
04/07/2015	0.0	85	0	0	0	0	0	0	0	0
05/07/2015	4.8	85	408	367	1	5	0	150	150	212
06/07/2015	4.4	85	374	337	1	5	0	146	146	398
07/07/2015	0.4	85	34	31	1	5	0	403	403	20
08/07/2015	0.4	85	34	31	1	5	0	47	46	0
09/07/2015	0.0	85	0	0	0	0	0	206	0	0
10/07/2015	0.0	85	0	0	0	0	0	48	0	0
11/07/2015	0.0	85	0	0	0	0	0	47	0	0
12/07/2015	5.2	85	442	398	1	5	0	54	54	339
13/07/2015	0.4	85	34	31	1	5	0	101	101	263
14/07/2015	0.4	85	34	31	1	5	0	96	96	193
15/07/2015	0.2	85	17	15	1	5	0	194	194	9
16/07/2015	1.0	85	85	77	1	5	0	253	0	0
17/07/2015	0.8	85	68	61	1	5	0	197	56	0
18/07/2015	0.0	85	0	0	0	0	0	50	0	0
19/07/2015	0.0	85	0	0	0	0	0	195	0	0
20/07/2015	0.6	85	51	46	1	5	0	204	0	0
21/07/2015	0.2	85	17	15	1	5	0	151	10	0
22/07/2015	0.2	85	17	15	1	5	0	104	10	0
23/07/2015	0.8	85	68	61	1	5	0	155	56	0
24/07/2015	29.0	85	2465	2219	1	5	0	150	150	2064
25/07/2015	0.0	85	0	0	0	0	0	150	150	1914

Time Step	Daily Rainfall (mm)	Roof Area (m²)	Total Rain (l)	Rain After 10% Losses (l)	Count Raindays	First Flush Volume (l)	Overflow Volume (l)	Metered Rainwater Demand (l)	RW Demand Satisfied (l)	Tank Level End of Day (l)
26/07/2015	24.6	85	2091	1882	1	5	0	98	98	3692
27/07/2015	0.2	85	17	15	1	5	0	0	0	3703
28/07/2015	0.2	85	17	15	1	5	0	0	0	3713
29/07/2015	0.0	85	0	0	0	0	0	46	46	3667
30/07/2015	0.0	85	0	0	0	0	0	0	0	3667
31/07/2015	0.0	85	0	0	0	0	0	0	0	3667
01/08/2015	0.0	85	0	0	0	0	0	47	47	3620
02/08/2015	0.4	85	34	31	1	5	0	54	54	3592
03/08/2015	0.8	85	68	61	1	5	0	477	477	3171
04/08/2015	0.4	85	34	31	1	5	0	206	206	2990
05/08/2015	9.2	85	782	704	1	5	0	102	102	3587
06/08/2015	0.0	85	0	0	0	0	0	105	105	3482
07/08/2015	0.0	85	0	0	0	0	0	202	202	3280
08/08/2015	0.0	85	0	0	0	0	0	475	475	2805
09/08/2015	0.0	85	0	0	0	0	0	104	104	2701
10/08/2015	11.6	85	986	887	1	5	0	57	57	3527
11/08/2015	0.0	85	0	0	0	0	0	151	151	3376
12/08/2015	0.0	85	0	0	0	0	0	52	52	3324
13/08/2015	39.8	85	3383	3045	1	5	1363	96	96	4904
14/08/2015	2.8	85	238	214	1	5	113	201	201	4912
15/08/2015	0.0	85	0	0	0	0	0	151	151	4761
16/08/2015	0.0	85	0	0	0	0	0	309	309	4452
17/08/2015	0.0	85	0	0	0	0	0	151	151	4301
18/08/2015	0.0	85	0	0	0	0	0	208	208	4093
19/08/2015	10.2	85	867	780	1	5	0	195	195	4674
20/08/2015	0.6	85	51	46	1	5	0	151	151	4563
21/08/2015	3.6	85	306	275	1	5	0	143	143	4691
22/08/2015	16.4	85	1394	1255	1	5	940	209	209	4791
23/08/2015	3.8	85	323	291	1	5	77	50	50	4950
24/08/2015	7.6	85	646	581	1	5	526	310	310	4690
25/08/2015	18.2	85	1547	1392	1	5	1077	203	203	4797
26/08/2015	5.0	85	425	383	1	5	175	578	578	4597
27/08/2015	1.6	85	136	122	1	5	0	253	253	4461
28/08/2015	0.2	85	17	15	1	5	0	247	247	4224
29/08/2015	0.0	85	0	0	0	0	0	393	393	3831
30/08/2015	2.8	85	238	214	1	5	0	202	202	3838
31/08/2015	0.2	85	17	15	1	5	0	288	288	3561
01/09/2015	0.0	85	0	0	0	0	0	305	305	3256
02/09/2015	2.6	85	221	199	1	5	0	147	147	3303
03/09/2015	0.2	85	17	15	1	5	0	193	193	3120
04/09/2015	0.6	85	51	46	1	5	0	144	144	3017

Time Step	Daily Rainfall (mm)	Roof Area (m²)	Total Rain (l)	Rain After 10% Losses (l)	Count Raindays	First Flush Volume (l)	Overflow Volume (l)	Metered Rainwater Demand (l)	RW Demand Satisfied (l)	Tank Level End of Day (l)
05/09/2015	0.0	85	0	0	0	0	0	207	207	2810
06/09/2015	0.0	85	0	0	0	0	0	190	190	2620
07/09/2015	0.0	85	0	0	0	0	0	100	100	2520
08/09/2015	0.0	85	0	0	0	0	0	144	144	2376
09/09/2015	0.0	85	0	0	0	0	0	101	101	2275
10/09/2015	0.2	85	17	15	1	5	0	127	127	2158
11/09/2015	12.6	85	1071	964	1	5	0	148	148	2969
12/09/2015	4.6	85	391	352	1	5	0	212	212	3104
13/09/2015	5.4	85	459	413	1	5	0	50	50	3462
14/09/2015	9.6	85	816	734	1	5	0	98	98	4093
15/09/2015	5.6	85	476	428	1	5	0	95	95	4422
16/09/2015	0.2	85	17	15	1	5	0	101	101	4331
17/09/2015	0.4	85	34	31	1	5	0	151	151	4206
18/09/2015	0.4	85	34	31	1	5	0	102	102	4129
19/09/2015	0.0	85	0	0	0	0	0	103	103	4026
20/09/2015	0.2	85	17	15	1	5	0	247	247	3790
21/09/2015	8.4	85	714	643	1	5	0	266	266	4161
22/09/2015	2.2	85	187	168	1	5	0	199	199	4126
23/09/2015	0.0	85	0	0	0	0	0	51	51	4075
24/09/2015	1.4	85	119	107	1	5	0	106	106	4071
25/09/2015	0.0	85	0	0	0	0	0	151	151	3920
26/09/2015	0.0	85	0	0	0	0	0	149	149	3771
27/09/2015	0.0	85	0	0	0	0	0	94	94	3677
28/09/2015	0.0	85	0	0	0	0	0	47	47	3630
29/09/2015	0.0	85	0	0	0	0	0	255	255	3375
30/09/2015	0.0	85	0	0	0	0	0	102	102	3273
01/10/2015	0.0	85	0	0	0	0	0	144	144	3129
02/10/2015	0.0	85	0	0	0	0	0	150	150	2979
03/10/2015	0.0	85	0	0	0	0	0	51	51	2928
04/10/2015	4.0	85	340	306	1	5	0	97	97	3132
05/10/2015	3.0	85	255	230	1	5	0	49	49	3307
06/10/2015	7.8	85	663	597	1	5	0	196	196	3703
07/10/2015	0.2	85	17	15	1	5	0	98	98	3615
08/10/2015	0.8	85	68	61	1	5	0	151	151	3520

Data from the water meters was used to establish the water saving efficiency of the RWH system using Equation 5.5.3:

(Equation 5.3.3) $$E_T = \frac{\sum_{t=1}^{T} Y_t}{\sum_{t=1}^{T} D_t}$$

Where E_T is the water saving efficiency, Y_t is the yield and D_t is the demand.

Analysis of the water meter data illustrated that the RWH system met 89% of the household’s non-potable water demand throughout the 113 day period (15,019l). The range of rainwater demand satisfied in the study was 0-568l/day. Assuming this level of water demand can be satisfied throughout the year, the annual RWH yield is extrapolated as 48,513l.

With water and sewerage charges of £5.52/m^3 (South West Water, 2014a) the system generated a saving of £82 during the study. An estimated financial saving of approximately £267/annum was calculated before operation and maintenance costs are deducted. These assumptions are likely to represent a conservative estimate of rainwater availability as the system was monitored during a drier than average spell, with the study investigating performance during the summer / autumn period. As observed in Chapter 5.2, SWW’s revised charging scheme would potentially reduce the value of rainwater to £2.05/m^3 as the wastewater charge can still be applied (South West Water, 2014a).

The RWH system evaluated in this study has a reported power consumption of 0.68kWh/m^3. This value is based on a study undertaken by the manufacturer in a laboratory setting where it achieved a power consumption cost of 0.68kWh/m^3 over 1,250 header tank filling cycles (Rainwater Harvesting ltd, 2013a). With an annual rainwater usage of 48.5m^3, the total annual electrical demand is estimated as 32.98kWh. Taking a cost of at 13.52 p/kWh (EST, 2014), the annual electrical cost is estimated as £4.46.

Rainfall for the period studied was assumed to divert directly into the RWH tank after losses were deducted. Losses associated with surface wetting and at the filter were estimated at 10% of total flows plus 5l/day. On this basis, total available rainfall arriving at the tank was estimated as 21,956l during the 113 day period. Data from the water meters illustrate that 15,019l of rainwater was used, in addition Figure 5.3.3 indicates that the RWH tank level increased by 2,520l during the study period. The remaining volume (4,417l) was predicted to have spilled from the system into the soakaway. Hence it is estimated that 68% of rainfall was used, 11% was stored at the end of the period and the remaining 21% was spilled to the soakaway. This finding is in line with the principles set out in the stormwater control annex described in the of BS8515 ((BSI), 2013b) which suggests that RWH systems do not provide guaranteed stormwater volume reductions (for extreme storm events) in locations where $Y_R > D_N$. In this instance, the yield (21,956l) exceeded demand (16,835l) giving a Y_R/D_N equal to 1.30. This value compares with a predicted Y_R/D_N from the BS8515 intermediate method of 1.26 (although it is noted that the designed tank (3,650l) is 27% smaller than the system that was installed and monitored (5,000l)).

Historically, rainwater runoff discharged from the property's roof was routed into the combined sewer. With the new RWH system connected to a soakaway, the total amount of rainwater (21,956l) arriving at the RWH tank represents the reduction in discharge to the sewer over the 113 day study. This value was multiplied by the annual scaling factor (3.23) to give an estimated annual reduction in stormwater discharge of 70,917l.

The projected tank level data was analysed to establish the largest predicted overflow during the study. Evidence from the time series analysis suggests that the largest storm event recorded by the rain gauge (40mm/day on 13/08/2015) was fully captured by the RWH system (3,040l). However, an overflow was projected of 1,363l, which exceeds the total capacity of the soakaway (1,000l). In practice, no overspill was reported by the homeowner, as it is likely the soakaway would have released flow into the ground throughout the day of the storm, giving it an effective daily storage capacity in excess of its total volume.

Designing RWH Systems to Achieve Stormwater Control

With the site located in a region of the UK with relatively high rainfall (SAAR=1200mm), it was anticipated that rainwater yield would exceed the demand. Hence, on an annual basis, rainwater discharges are likely to occur as the demand on the tank is, on average, less than the total volume of rainfall. Although the study was conducted in the drier summer season, the data indicated that overflows occurred from the rainwater tank. Had the system not been fully disconnected to a soakaway, an estimated 21% of the rainwater arriving at the tank would still have been discharged to the combined sewer. In particular, it is relevant that this rainwater was generally projected to discharge during days with back to back rainfall events, i.e. when antecedent conditions are likely to make the catchment more prone to surface water flooding. With an increasing focus on RWH to be able to reduce, or at least attenuate, peak stormwater discharges, the empirical data supports a continued focus on RWH configurations that are specifically designed to achieve such an objective. Hence, the analysis reinforces the need for RWH system’s to be configured in order to intentionally (either actively or passively) control overflows to limit surface water flooding during extreme rainfall events. Modelling methods and design tools are needed which can support stakeholders to accurately design and install RWH systems in configurations which can reliably provide source control in extreme rainfall events. Further research and development activities relating to this are evaluated in the following case study set out in Chapter 5.4.

5.3.5 Conclusions

A traditional RWH system was monitored for a period of 113 days during which time it saved the property owners £82 by providing an alternative water resource. The study illustrates the ability for traditional RWH to be retrofitted in a residential setting as part of a surface water management toolkit. Conclusions are as follows; 1) Potable water demand was reduced by an estimated 48,511 l/annum; 2) Annual cash savings of £267 were estimated assuming no maintenance costs and a water cost of £5.52/m^3; 3) Electrical consumption was identified from the literature and was estimated to cost £4.46/year based on the projected annual demand. 4) As the site was previously connected to the combined sewer, the data suggests that the RWH system was able to reduce stormwater discharge to the combined sewer by 100% with 79% of the rainwater utilised and 21% spilled to a new soakaway. 5) As predicted using the BS8515 design methods, the rainwater yield exceeded the demand during the monitoring study. Consequently, the system was projected to spill flows into the soakaway, even though the study was conducted during the summer months. This reinforces the need for the design of RWH system's which can intentionally (either actively or passively) control overflows to reduce surface water flooding during extreme rainfall events. 6) The empirical data collected in this study can potentially be used to support further work at a national scale to establish the costs and benefits of a range of RWH configurations and hence improve the methods used for RWH design at UK houses. 7) Further research is needed into novel RWH configurations which are designed to achieve source control in extreme rainfall events. This includes the development of design methods, evaluation tools and off the shelf RWH systems which can satisfy UK surface water management objectives. 8) The estimated capital costs of such systems can range £5-10k giving a range

This case study examined performance characteristics of a traditional RWH system in a real world setting. The data illustrated the potential for RWH systems to reduce potable demands whilst limiting downstream discharges by relying on the user demand to free tank capacity for the next storm. However, for new developments, the UK drainage design standards (Environment Agency, 2017) require the 1 in 100 year rainfall event to be captured and either re-used, infiltrated or attenuated. The traditional RWH system monitored in this case study discharged to a soakaway. Had the overflow outlet been discharged to the combined sewer, 21% of the rainfall observed during the monitoring period would have discharged at an unattenuated rate to the combined sewer. This illustrates the need for dual purpose RWH configurations to be designed as a source control method that can manage the 1 in 100 year rainfall event. Such a system is investigated in a modelling study described in Chapter 5.4. The work sets out an approach using proprietary drainage design software and tests the methods to design a novel, dual purpose RWH system at a series of houses at a case study site.

5.4 Design and analysis of a dual purpose RWH system: A pilot study

5.4.1 Introduction

RWH installations in the UK have historically been designed to focus on the sole objective of reducing water demand for the user. Chapter 5.3 investigated the application of RWH systems as stormwater management assets through the reliance on demand to free capacity for future storms. There is a growing evidence base that supports the use of RWH systems to limit the volume and peak discharge rates to downstream drainage networks (DeBusk *et al.*, 2013, Burns *et al.*, 2014, Campisano *et al.*, 2014, Melville-Shreeve *et al.*, 2016a). The scale of the manufacture and installation market for SuDS within the UK has grown to an estimated £500m/year (Kellagher, 2016). Aligning the design of RWH systems to meet the objectives and guidance of the SuDS industry poses a potential opportunity for growth in RWH deployment. The research presented herein evaluates the performance of a RWH system which was designed with the dual purpose goals of; 1) providing non-potable water for WC flushing / laundry use; whilst 2) capturing and attenuating storm events which might otherwise overflow to the downstream sewer in an uncontrolled manner. The study investigates the performance of a dual purpose RWH system (described in Figure 5.4.1.) based on data collected from a monitoring system installed at a residential property in south west England (Truro).

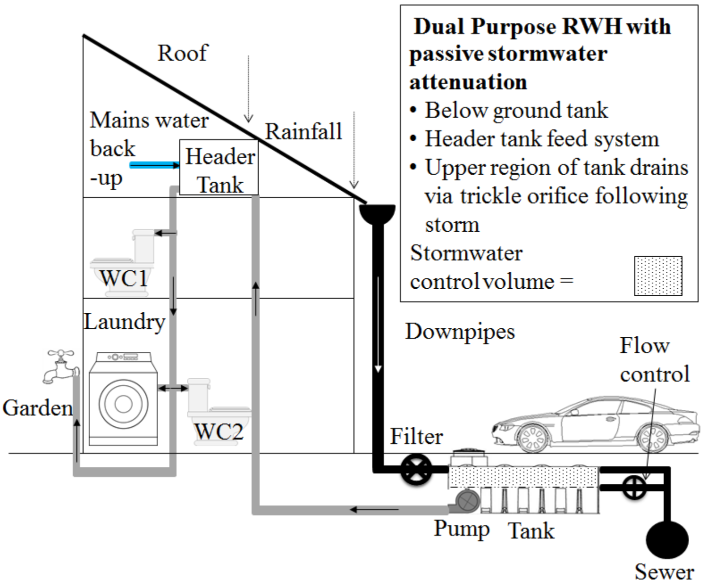


Figure. 5.4.1 – Schematic illustrating a dual purpose rainwater harvesting configuration (Melville-Shreeve et al., 2016b)

5.4.2 Materials and Methods

In accordance with the British Standard for RWH ((BSI), 2013b), the property's RWH system was designed to provide non-potable water for WC flushing, laundry use and garden watering. The property was selected as it was located within South West Water's WaterShed Truro project (South West Water, 2014b), and the system could be installed whilst causing minimum household disruption as part of an ongoing kitchen refit at the property. The installation represents one of several rainwater management systems installed as part of a wider surface water management scheme. In contrast to traditional RWH design, the system was designed to provide attenuation via a trickle discharge valve located at the 50% full level of the 5,000l tank.

Design of the RWH System

The proposed RWH tank volume for non-potable use (V_{NP}) was calculated using the 'intermediate approach' ((BSI), 2013b). This method defines the tank volume required (V_{NP}) for a RWH system as the lesser of two volumes (Y_R or D_N) calculated using Equations 5.4.1 and 5.4.2;

Equation 5.4.1 $Y_R = A \times e \times AAR \times h \times 0.05$

where Y_R is 5% of the annual rainwater yield (l); A is the collecting area (m^2); e is the yield coefficient (%); AAR is the annual depth of rainfall (mm); h is the hydraulic filter efficiency.

Equation 5.4.2 $D_N = Pd \times n \times 365 \times 0.05$

where D_N is the annual non-potable water demand (l); P_d is the daily requirement per person (l); and n is the number of persons.

Table 5.4.1 describes the parameters and calculation results for the key RWH design parameters for the site.

Table 5.4.1 – RWH design parameters and tank sizing values

Parameter	Value	Units	Comments
A	50	m^2	Surveyed on site
e	0.9	-	Tiled roof ((BSI), 2013)
AAR	1,200	mm/year	SAAR ((BSI), 2013b)
h	1.0	-	Losses accounted for in e parameter
Y_R	2700	l	Calculated
P_d	50	l	Estimated potential rainwater demand
n	4	Occupants	Known household occupancy
D_N	3,650	l	Calculated
Y_R/D_N	0.73	-	Demand exceeds yield

Q_{outlet}	0.025	l/s	Peak permissible discharge rate to achieve nominal “greenfield runoff rate” of 5l/s/ha

BS8515 states that the tank volume for provision of non-potable water should be equal to the lesser of Y_R (3,650l) or D_N (2,700l) ((BSI), 2013b). In addition, the stormwater control annex in BS8515 suggests an oversized tank can only be specified where Y_R/D_N <0.70. Hence a dual purpose configuration was designed for the site that included a small outlet orifice to enable a passive release of water at a controlled rate that does not exceed 5l/s/ha. The supplier for the RWH system provides tanks with 1,500l, 3,000l, 5,000l and 7,500l capacities. However, the available space for a RWH tank prevented the 7,500l tank being installed and hence a 5,000l tank was selected. This was configured with a trickle outlet set at the 50% tank level (2,500l) to capture and release extreme storm events. The upper 2500l of the tank comprises the source control volume (V_{SC}). This was configured to release rainwater to the sewer network at an attenuated rate via a 7.5mm orifice which was selected following a laboratory assessment of the proposed configuration as set out in the following section.

Water demands on the RWH tank were observed as represented by the daily reduction in tank level (when the water level is lower than 2,500l). In addition a set of water meters were used to monitor water demand for 111 days from 06/08/15 which recorded a mean rainwater demand of 121l/day (44m^3/annum).

Laboratory Analysis Conducted Prior to Site Installation

Previous research set out a method to use proprietary drainage software (MicroDrainage (XPsolutions, 2013)) to simulate the performance of a RWH system based on hydraulic characteristics at the overflow orifice (Melville-Shreeve *et al.*, 2016a). To validate the use of MicroDrainage as a tool for designing the V_{SC}, a series of laboratory tests were conducted to establish the discharge rates through a range of small orifices. A test rig was constructed as illustrated in Figure 5.4.2 to enable the head vs. discharge relationships to be empirically tested for 5mm, 7.5mm and 10mm orifices.

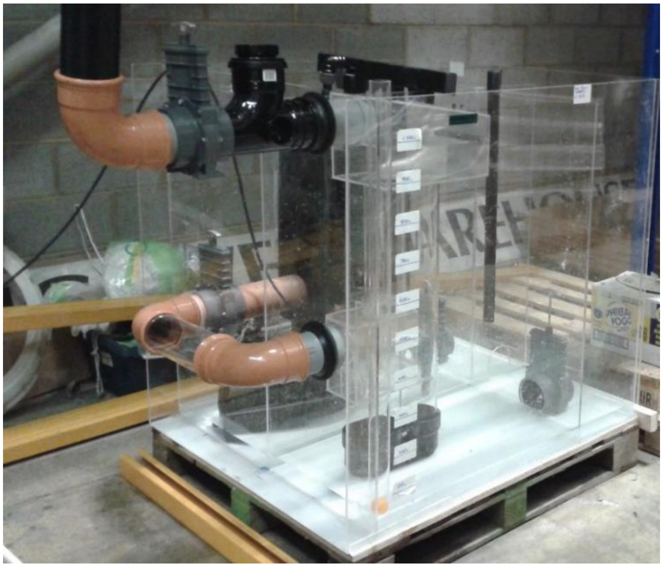


Figure 5.4.2 – Test rig used to measure the discharge rates for a range of outlet orifices

To establish the discharge rate, the penstock downstream of the orifice valve was opened and a full tank of water released through the orifice. This was repeated three times and mean results recorded. The water level (and hence head) of the tank was monitored during each drain-down test using a pressure logger and the rate of discharge was calculated for a range of heads. As noted in Table 5.4.1, the goal for the design was to optimise use of the V_{SC} during the 1 in 100 year storm event (i.e. to minimise the discharge rate from the upper region of the RWH tank). The V_{SC} was constrained to 2,500l due to site constraints.

Pilot Site Monitoring

The RWH system was installed and monitored between September 2016 and January 2017. The monitoring data was used to estimate peak discharge rates from the RWH tank. The water level within the tank was measured using a level probe. Local rain gauge data was also collected at a 15 minute time step. A series of mass balance calculations based on the yield after spillage rule (Fewkes and Butler, 2000, Melville-Shreeve *et al.*, 2016b) were completed to estimate the flows into, and discharges from, the tank to identify the scale of overflows from the RWH tank. When the water level of the tank exceeded the 7.5mm orifice, calculations using the standard orifice equation (Equation 5.4.3) were completed to estimate peak discharge rates from the system.

Equation 5.4.3 $Q = C_d \, A_o \sqrt{2gH}$

Where Q = Flow rate (m^3/s); C_d = Coefficient of discharge; g = 9.81 m/s^2 H = Head (m)

5.4.3 Results and Discussion

The discharge rates for a range of orifices were measured under laboratory conditions using the test rig illustrated in Figure 5.4.2. The mean flow rates for the orifices tested at a range of heads are described in Figure 5.4.3. It is evident from the results that the discharge rates via the smallest (5mm) orifice do need exceed 0.05 l/s at 400mm head. For the same head, the 7.5mm and 10mm orifices discharge at up to 0.10 and 0.21 respectively. The data from the empirical tests was used to iteratively solve the orifice equation for a range of discharge coefficients (C_d) values. The goal was to minimise the sum of mean squared error between empirical lab data and the projected values. A C_d value of 0.9 was identified as an appropriate discharge coefficient when modelling these small orifices using the orifice equation.

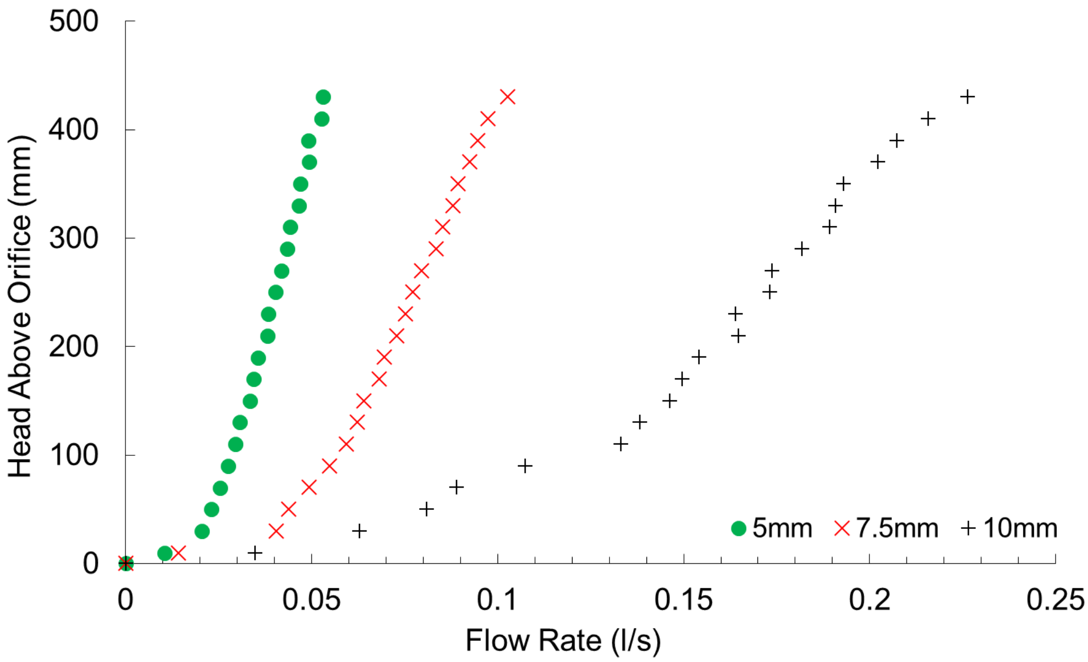


Figure 5.4.3 – Measured discharge rates for small orifices under laboratory conditions

Projected System Performance During 1 in 100 Year Rainfall Event

With the C_d value established, the RWH system's performance as a source control measure during extreme storm events was simulated in the MicroDrainage (XPsolutions, 2013) software as illustrated in the output included as Figure 5.4.4. It was conservatively assumed that the lower region (2,500l) of the tank was full at the start of the storm. Through an iterative analysis, it was established that the low discharge rate associated with the 5mm orifice caused the V_{SC} region of the tank to become full (and hence spill at an uncontrolled runoff rate) during the critical 1 in 100 year storm (3,600l). However, with the 7.5mm orifice selected the V_{SC} reached just 2,400l (i.e. the tank does not experience an uncontrolled overflow for the critical 1 in 100 year storm) so this orifice was selected as illustrated in Figure 5.4.4. The analysis illustrates that upper region (2,500 l) of the

RWH tank can fully capture and control the critical 1 in 100 year rainfall event with a discharge from the orifice not exceeding 0.15 l/s at 500mm head.

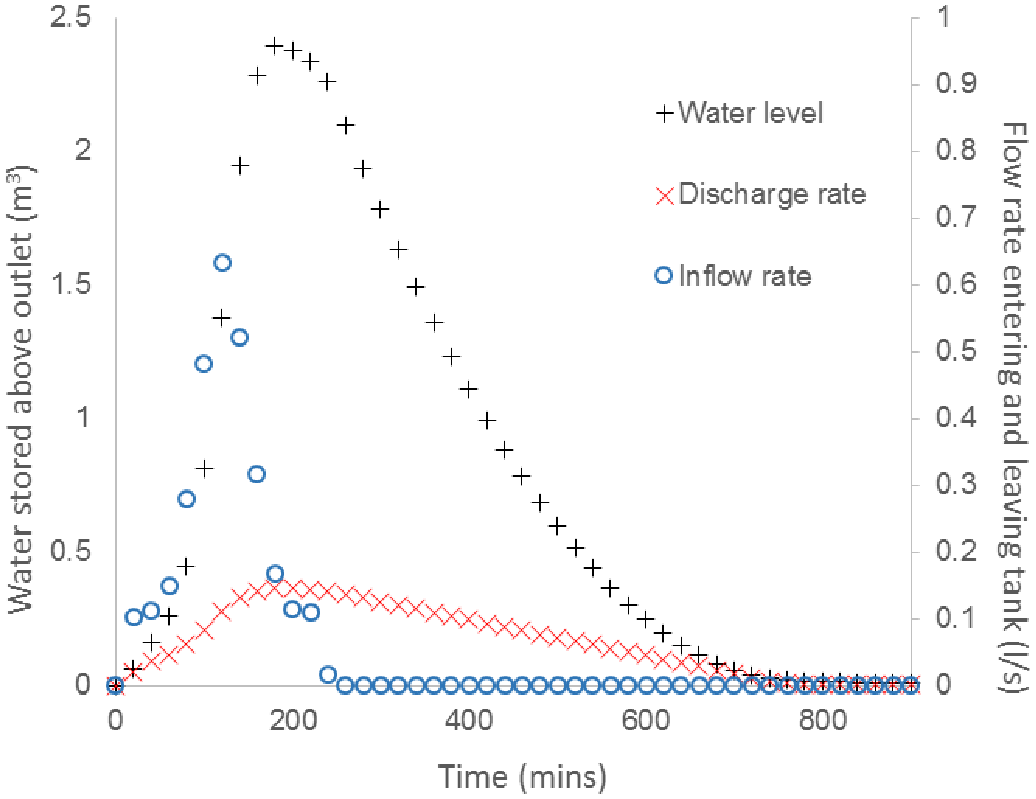


Figure 5.4.4 – Simulated RWH tank performance during critical (four-hour) 1 in 100 year rainfall event

For comparison a further analysis was conducted to simulate the system's performance during more intense storms (the 1 in 100 year 15 minute rainfall event). This data suggests a reduction in peak discharge by up to 96% can be achieved. The RWH system was installed and the tank's water level monitored for three months. The rain gauge captured an intense rainfall event which is estimated to have contributed 466l of rainwater to the RWH tank over 30 minutes. Conservatively assuming a uniform inflow rate over 30 minutes, the peak inflow to the RWH tank was calculated as 0.26l/s.

Empirical data (in the form of the measured head above the outlet orifice) was used to calculate the peak discharge rate for the 7.5mm orifice outlet based on the curve shown in Figure 5.4.3. It is estimated that peak discharges did not exceed 0.02l/s at any stage during the monitoring period. Hence it is projected that the dual purpose RWH system reduced the peak discharge rate by 93% during the largest 30 minute rainfall event observed during the study period.

Traditionally, drainage systems use orifice controls with a diameter greater than 50mm to minimise the risk of blockage. A key innovation shown in this study is the ability of the filtration system to prevent fine debris from entering the RWH tank. This gives a low risk of blockage at the orifice despite its small diameter. In turn, a very slow trickle discharge from the tank is achieved. Evidence from this study supports the potential application of small orifices in the future design of SuDS, subject to high quality filtration of rainwater entering the tank and the usual maintenance requirements. Evidence from the data loggers was analysed at a high resolution to observe the tank's performance when the water level exceeded the V_{SC} orifice. The data logging controls were set to log at 1 minute intervals when the water level exceeded the orifice as illustrated over a period of two days following a large storm on 19/11/2016 in Figure 5.4.5. This data confirms that the tank drains very slowly following the storm as observed in Figure 5.4.5.

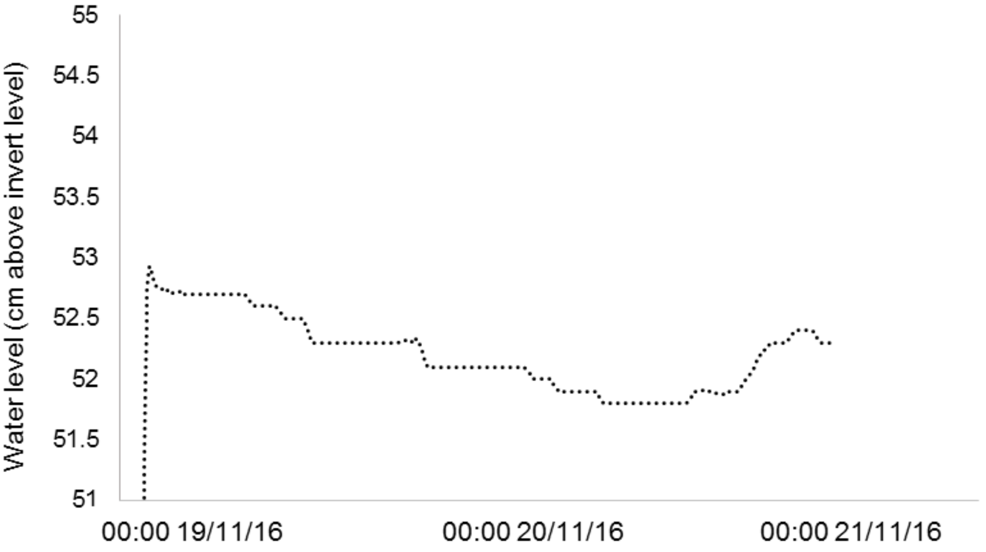


Figure 5.4.5 – Measured tank level following large storm event (1min resolution)

To further illustrate system performance, a series of mass balance calculations (driven by local rain gauge data) were used to project the discharges from the RWH system for the study period as illustrated in Figure 5.4.6. This chart illustrates the measured water level of the tank for the study duration at a daily time step, and confirms the small orifice releasing rainwater from the V_{SC} region was not blocked at any stage during the study.

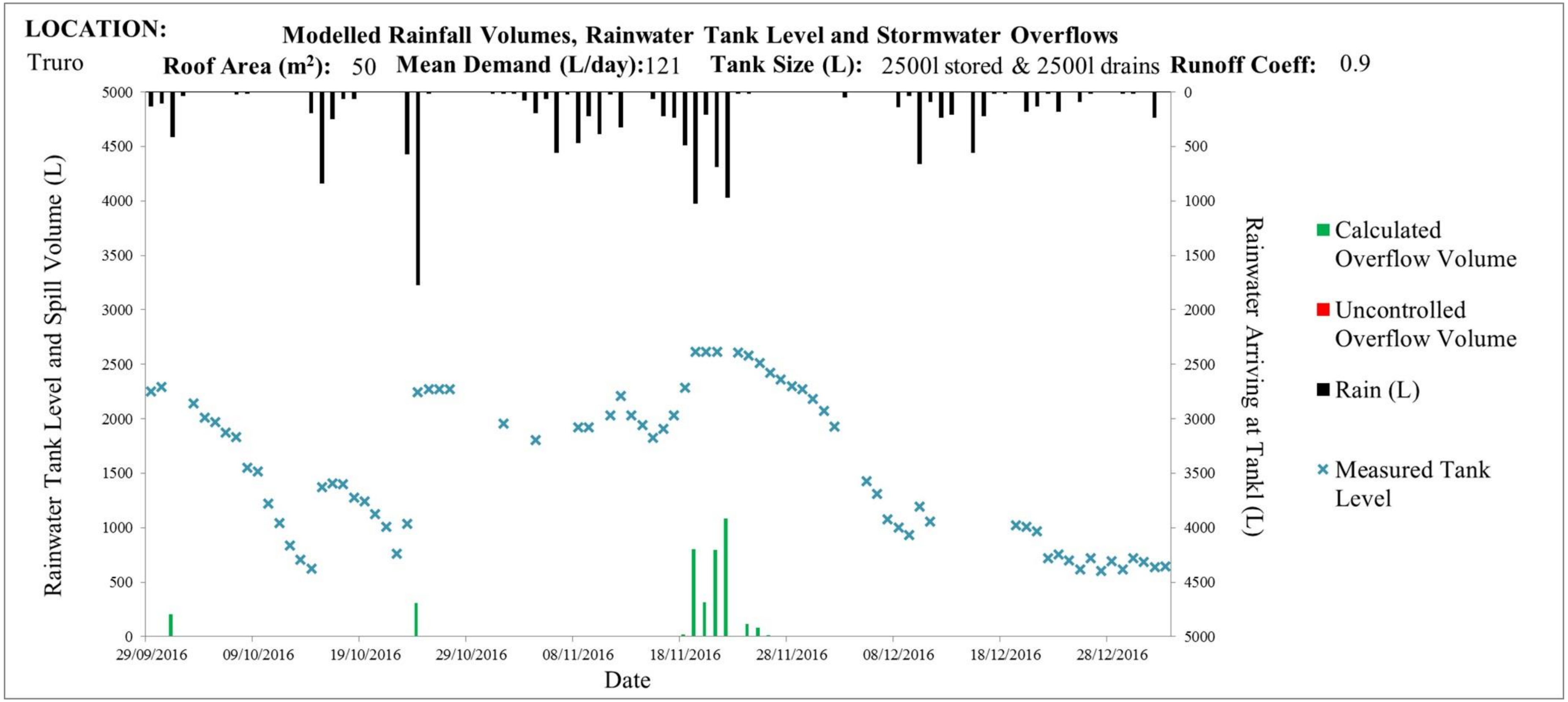


Figure 5.4.6 – Estimated rainfall runoff entering the RWH tank (black); estimated controlled overflows (green); and measured water level (blue crosses)

5.4.4 Conclusions

The study focussed on the stormwater control characteristics of a dual purpose RWH configuration. Evidence from data from the site's water meters illustrated an annual rainwater demand of 44m^3. The design of the RWH system incorporated a 2,500l source control volume which allows a trickle discharge following storms. The following conclusions can be drawn from the study:

1) Discharges from dual purpose RWH tanks with small overflow orifices (5-10mm) can be represented and modelled in proprietary drainage software. 2) Hydraulic simulations of the dual purpose RWH system demonstrated that a 2,500 l source control volume was able to capture and control the property's roof runoff during the critical 1 in 100 year rainfall event. 3) Evidence from hydraulic simulations suggested that the dual purpose RWH system can reduce the peak discharge rate during the 1 in 100 year, 15 minute duration rainfall event by 96%. 4) Peak runoff generated by the roofs of twenty-five houses drained via such dual purpose RWH systems is equivalent to the peak runoff for a single house connected to the sewer network using a traditional drainage connection (i.e. pipe to sewer). 5) Performance data analysed from the property's RWH system over a three month study supports these findings as this data showed peak discharge rates were reduced by approximately 93% during the largest 30 minute storm event. 6) Trickle discharges via the small orifices were observed throughout the three month monitoring period suggesting that there was no blockage of the orifice in the monitoring study completed to date.

5.5 Chapter Summary

A series of case studies were presented based on laboratory and pilot site investigations conducted between 2014 and 2017. These were executed to contribute evidence to the knowledge base relating to the design and application of a range of RWH configurations.

Laboratory and pilot installations of the FlushRain RWH system demonstrated the capacity of the system to reduce annual water demands by up to $15m^3$ at a pilot installation in Exeter. This was achieved despite the relatively small functional storage volume of the system's loft-based tank. However, the low energy consumption projected for this system was found to be higher than alternative water supplies as the control system had a steady standby power consumption of 11W. The evidence collected in this pilot study illustrates the ability for FlushRain to be successfully retrofitted with a small storage tank at a relatively low cost, whilst still reducing potable water demand (and consequently reducing downstream rainwater runoff) by significant volumes ($15m^3$/annum). The data supports the claims of the system provider that small-scale RWH tanks can form part of a rainwater re-use toolkit despite their non-compliance with the RWH tank sizing procedures set out in BS8515 ((BSI), 2013b).

Monitoring data analysed for a traditional RWH system with a 5,000l below ground tank demonstrated a far greater rainwater yield for non-potable applications ($48.5m^3$/annum). In addition the larger volume of the traditional RWH tank (18 times larger than the FlushRain system) demonstrated a greater capacity to capture and control stormwater discharges with 79% of annual rainwater projected to be captured and only 21% spilled from the tank. This contrasts the analysis of the smaller FlushRain RWH tank which released 62% of rainfall to the combined sewer network. It is acknowledged that the findings are not directly comparable as the studies were conducted at different properties, although both sites housed four occupants. The data supports the concept that large RWH tanks have a greater ability to reduce annual rainwater discharges than systems with small storage volumes. As identified in Chapter 2, such a finding has been concluded in many RWH modelling studies undertaken since 1999 (Fewkes and Butler, 2000). The evidence from this pilot study data contributes a small set of empirical data to support the findings of previous desktop studies.

The chapter concludes with a study which investigates the design and installation of a dual purpose RWH configuration that was first described in the 1990's (Herrmann and Schmida, 1999). The work investigated the use of a RWH system which can capture and attenuate the 1 in 100 year storm event using a passive orifice control located 2500l below the tank's top water level. The system's water level was measured and calculations used to establish the peak discharge rates for observed storm events and extreme rainfall events. Evidence from this study suggests that RWH systems which incorporate a zone of source control storage above a passive flow control can potentially be designed as an effective part of a SuDS management train.

Further analysis is warranted to evaluate how the RWH configurations investigated in this chapter might perform when tested alongside one another at a range of locations throughout the UK. Chapter 6 addresses this need to satisfy the final objective of the thesis; to evaluate the performance of a range of RWH systems in terms of yield, peak stormwater overflow reductions and annual stormwater discharge volumes throughout the UK.

Chapter 6: Analysis of traditional and novel RWH systems throughout the UK

6.1 Chapter Overview

This chapter investigates the performance in terms of yield, peak stormwater overflow reductions and annual stormwater discharge volumes for a set of ten RWH scenarios across the UK. The work focusses on the use of RWH at a household scale. Chapter 3 described the features of novel RWH configurations that show potential for application in UK houses. Chapter 4 drew upon the experience from those case studies and set out a RWH evaluation methodology which enables the benefits of RWH systems to be simulated using a time series analysis methodology within a decision support interface, the RainWET. Chapter 5 investigated the real world performance of RWH systems at a series of case studies. This chapter implements the RWH evaluation methodology by deploying the RainWET to evaluate the performance of a set of RWH configurations at ten locations throughout the UK. Rainfall records provided by the Environment Agency were used to perform simulations of the long-term performance of a range of RWH systems. The chapter closes by describing the results of the simulations alongside discussion and summary of the analysis.

6.2 Research Aims

The work described in this chapter aims to satisfy the following objective:

“Demonstrate the RWH Evaluation Method by calculating RWH performance metrics using datasets from locations throughout the UK.”

The work seeks to analyse the long-term performance of ten RWH configurations in terms of water demand management and stormwater control benefits at ten UK locations.

To develop a methodology and interrogate the results generated from the RainWET, it was necessary to define a sub-set of research goals.

6.2.1 Research Goals

1) How do RWH systems perform when deployed at a range of locations throughout the UK?

2) Which RWH configuration and location achieved the greatest rainwater yield?

3) Which RWH configuration and location achieved the greatest reduction in peak stormwater discharges?

4) Which RWH configuration and location achieved the greatest reduction in annual stormwater discharges?

5) Can small-scale RWH systems achieve yields that are comparable to traditional design configurations?

6.3 Methodology

In order to investigate the research questions, a set of RWH systems were identified from those described in Chapter 3. These were selected to cover both traditional systems, dual purpose designs, real time control systems and a high rainwater demand scenario (applicable for sites where a potable treatment of rainwater enables all water on site to be drawn from the RWH system). To align with the core concept of this thesis, the research questions focus on the ability of these systems to mitigate droughts and manage stormwater flooding.

Rainfall patterns vary widely throughout the UK as illustrated in Chapter 2, Figure 2.4. Hence a UK-wide study was necessary to investigate the potential variations in the use of a range of RWH configurations. In order to undertake a comprehensive investigation, time series rainfall files were used to drive the simulation methods set out in Chapter 4. The first step in the analysis necessitated access to daily rainfall data sets for each location.

6.3.1 Input Data: Rainfall Files

Long-term, daily rainfall data for ten locations in the UK was obtained from the Environment Agency as described in Table 6.1 and Figure 6.1. Each data set contains at least twenty years of recent data.

Table 6.1 – Location of rain gauge datasets

Location ID	Location	National Grid Reference
A	Birmingham	SP00728015
B	Bristol	ST4887072010
C	Dover	TR2915848239
D	Exeter	ST0212900543
E	Manchester	SJ7580296100
F	Newcastle	NZ2534467262
G	Norwich	TG2728303087
H	Southampton	SU3883412439
I	London	TQ3776477165
J	Truro	SW8334343245

Long term datasets were obtained for some locations e.g. 1924-2016 in Manchester. However, at most locations the data was constrained to shorter windows (e.g. Birmingham and London <30 years). For each of the datasets, the daily rainfall depths (mm) were manually processed to ensure they only contained numerical values.

Figure 6.1 – Map of rain gauge locations (labels correspond to Table 6.1)
Source: Generated using https://batchgeo.com/map and Google Maps

Furthermore, a set of additional pre-processing was required as set out below to enable input data files to be imported into the RainWET software:

1) The date range was cropped to a twenty year window from 01/01/1996 to 31/12/2015.

2) Leap year values (for 29th February) were deleted to provide exactly 365 days in each data set.

3) Months that contained zero values in every cell AND contained a numerical value in the final cell of the month were assumed to represent data logging failures. The value in the final cell was assumed to be a monthly rainfall value. Fewkes and Butler (2000) demonstrated the inability of monthly data to offer realistic predictions for system performance. Therefore these values were divided by the number of days in the preceding month and the resulting value inserted into every cell. This manipulation

spread the rainfall in a uniform fashion across the month. Failure to adjust these values would have produced some cells with unrealistic rainfall of up to 173mm/day.

4) Where months contained a string of blank cells, the data from the same month in the preceding year was copied into these cells.

5) Where preceding monthly data was unavailable the data from the following year was used.

6) All remaining non-numerical values were set to zero.

7) The resulting twenty year daily rainfall datasets were each saved as tables with twenty columns (one per year) with 365 rows (one per day of the year) for the date range 01/01/1996 to 31/12/2015. The rainfall files referred to in the results provided in this study are based on these processed historic rainfall datasets.

Manual data processing was necessary for approximately 3,000 (4%) of the 73,000 rainfall input cells. The data processing actions taken to prepare the data are described in detail in Table 6.2 Once completed, each calendar year (starting on the 1st January) was used to drive the RainWET software for all of the simulations undertaken for that location.

Table 6.2 – Data quality and processing tasks completed to convert raw rainfall data for use in the RainWET

Location	Data Quality	Data Quality Rank	Number of data points altered	Processing Notes
B - Bristol	High	1	0	No blank cells or errors identified
D - Exeter	High	1	0	No blank cells or errors identified
A - Birmingham	High	1	2	2 blank cells set to “0”
G - Norwich	High	4	31	Oct 2012 replaced with data from Oct 2011.
J - Truro	Mid-High	5	61	May 1996 replaced with data from May 1997 Sept 2005 was blank with a 53.9mm value on the last day of the month. This value was averaged across the month.
F - Newcastle	Mid-High	6	120	July 1996 replaced with July 1997 Nov 1998 replaced with Nov 1997 Dec 2010 replaced with Dec 2009 Aug 1997 50.0m averaged across the month

Location	Data Quality	Data Quality Rank	Number of data points altered	Processing Notes
H - Southampton	Mid	7	335	April 1996 replaced by April 1997 April-May 2009 replaced with April-May 2007 (as 2008 had to be derived from averages) Jul 1997 replaced with Jul 1996 Aug 1996 replaced with Aug 1997 Aug 2002 replaced with Aug 2001 Sept 2998 replaced with Sept 1997 Sept 2003 replaced with Sept 2002 Dec 1998 replaced with Dec 1997 Aug 2014 replaced with Aug 2013 Nov 2011 replaced with Nov 2009 (as Nov 2008 had to be derived from averages) Nov 1998 66.0mm averaged across the month March 2008 80.9mm averaged across the month March 2009 44.5mm averaged across the month April 2008 62.0mm averaged across the month May 2008 116.0mm averaged across the month June 2008 50.0mm averaged across the month June 2009 28.5mm averaged across the month July 2009 64.4mm averaged across the month Nov 2008 85.0mm averaged across the month
C - Dover	Low	8	693	March 1998 replaced with March 1997 April 1999 replaced with April 1998 April 2009 replaced with April 2008 Feb 2007 replaced with Feb 2006 Feb 2008 replaced with Feb 2006 August 1998 replaced with Aug 1997 July-Aug 2000 replaced with July-Aug 1999 Aug 2001 replaced with Aug 1999 Oct 2007 replaced with Oct 2006 Sept 2011 replaced with Sept 2010 1-3 Sept 2011 missing replaced with 1-3 Sept 2010 July 2014 replaced with July 2013 Feb-March 2014 replaced with Feb-March 2013 Nov 2015 replaced with Nov 2014 Jan 2003 80.0mm averaged across the month Jan 2006 30.0mm averaged across the month Aug 2003 31.8mm averaged across the month Sept 2006 19.2mm averaged across the month Dec 2005 79.7mm averaged across the month April 2015 14.0mm averaged across the month May 2009 36.0mm averaged across the month Aug 2009 8.0mm averaged across the month
I - London	Low	9	700	1998 data missing 1997 data duplicated to fill 1998 March 2003 replaced with March 2002 Aug 2010 85.0mm averaged across the month Sept 2010 40.0mm averaged across the month Oct 2010 70.0mm averaged across the month Nov 2010 35.0mm averaged across the month Sept 2002 55.0mm averaged across the month Nov 2002 110.0mm averaged across the month Dec 2000 60.0mm averaged across the month Jan 2009 65.0mm averaged across the month Oct 2008 40.0mm averaged across the month
E - Manchester	Low	10	1,214	26-28 Feb 2001 replaced with 26-28 Feb 2000

Location	Data Quality	Data Quality Rank	Number of data points altered	Processing Notes
				31 March 2002 replaced with 31 March 2001 Feb-March 2011 replaced with Feb-March 2010 March 2014 replaced with March 2013 Oct 2004 replaced with Oct 2003 Feb-March 2013 replaced with Feb-March 2012 May 2005 62.4mm averaged across the month Jan 2006 26.0mm averaged across the month Feb 2006 49.8mm averaged across the month March 2006 99.2mm averaged across the month May 2006 90.4mm averaged across the month June 2007 149.0mm averaged across the month July 2008 125.0mm averaged across the month Aug 2008 107.0mm averaged across the month Sept 2008 112.6mm averaged across the month Jan 2009 49.8mm averaged across the month March 2009 41.6mm averaged across the month Sept 2009 38.1mm averaged across the month July 2010 80.8mm averaged across the month Sep 2010 89.2mm averaged across the month June 2011 65.6mm averaged across the month Nov 2011 47.6mm averaged across the month Dec 2011 173mm averaged across the month Jan 2012 94.8mm averaged across the month May 2012 59.2mm averaged across the month Jan 2013 55.2mm averaged across the month April 2013 19.5mm averaged across the month Feb 2014 67.8mm averaged across the month Aug 2013 46.3mm averaged across the month Oct 2013 135.0mm averaged across the month Sept 2014 9.7mm averaged across the month

6.3.2 Input Data: RWH Configuration Simulation Parameters

A set of fixed parameters was generated to enable comparison of RWH configurations to be undertaken at a typical domestic property. Parameters for a typical UK house are described in Table 6.3. A fixed runoff coefficient was set at 0.9 to include for filter and hydraulic losses. In addition, a 5l/day first flush loss was included for each rain-day. The property was assumed to have: a pitched roof with a plan area of 60m^2, four occupants utilising 150l/person/day (with a usage ratio based on existing literature (Butler and Memon, 2006)). Simulations were undertaken for individual years and the RWH tank was assumed to be empty at the start of each annual simulation. In reality the tank could be anywhere between 0-100% full at the start of the year. This introduces a limitation to the simulation method which can generate errors in annual outputs up to the total volume of the tank's functional storage.

Variable simulation parameters were used to differentiate between the range of RWH configurations. The house was permitted to have either a traditional 3,000l below ground tank or a small loft-based tank with a functional storage of 450l. Dual purpose stormwater control features were represented as a passive outlet valve at 50% tank level (enabling 1,500l of the 3,000l tank to be used to store rainwater and the remaining 1,500l to be released each day). Real time control stormwater features were assumed to predict storms using a 24 hour forecast and empty the necessary volume from the RWH tank on the day prior to a storm. In addition, the rainwater demand could be varied for each RWH design. Rainwater demand for the property was therefore set at 200l/day for the WC-only scenarios and 300l/day for the WC+Laundry scenarios. Where the rainwater was treated to potable standards demand was increased to 600l/day (i.e. demand was equal to total household water demand).

Table 6.3 – Defining simulation parameters

Model Parameter	Reference	Value
Roof Area (m^2)	User Selected	60
Roof Runoff Coefficient	User Selected	0.9
First-Flush Losses (l/day)	User Selected	5
Usage Ratio (WC:Laundry:Potable:Other)	(Butler and Memon, 2006)	30:20:5:45
Fixed Daily Demand (l/day)	User Selected	200l/day (WC), 300l/day (WC+Laundry), 600l/day (All water demands)
Tank storage size (l)	User Selected	• 500l if located in loft (of which 450l is functional storage) • 3,000l if located below ground level (of which 3,000l is functional storage)
Time-series rainfall data (mm/day)	As described in Table 6.2	20 year time series of daily rainfall records for ten locations throughout the UK
Stormwater control volume (l/day)	User Selected	• Up to 1,500l of the 3,000l storage tank was available to drain down each day for the dual purpose RWH configuration • Up to 3,000l was able to discharge automatically the day before a storm for the real time control scenario

6.3.3 Simulation Scenarios

A set of ten RWH configurations (scenarios) was tested including one scenario for a property with no RWH system. The remaining RWH configurations were defined using the RWH design toolkit described in Chapter 3, Figure 3.4 to cover the key innovations defined in the research to date. Table 6.4 describes the ten RWH scenarios that were selected. A full description of these configurations is included in Figure 6.2.

Table 6.4 – Details for all RWH simulation scenarios

RWH System Description			Rain gauge locations and name for scenarios tested									
Tank Size (Functional Volume (l)	**Stormwater capacity (l/day)**	**Demand (l/day)**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
0 - No RWH e.g. Typical House												
0	0	0	A-0-3000-200	B-0-3000-200	C-0-3000-200	D-0-3000-200	E-0-3000-200	F-0-3000-200	G-0-3000-200	H-0-3000-200	I-0-3000-200	J-0-3000-200
1 - Traditional RWH e.g. RainDirector												
3000	0	200	A-1-3000-200	B-1-3000-200	C-1-3000-200	D-1-3000-200	E-1-3000-200	F-1-3000-200	G-1-3000-200	H-1-3000-200	I-1-3000-200	J-1-3000-200
		300	A-1-3000-300	B-1-3000-300	C-1-3000-300	D-1-3000-300	E-1-3000-300	F-1-3000-300	G-1-3000-300	H-1-3000-300	I-1-3000-300	J-1-3000-300
2 - Dual Purpose RWH with Passive Control Outlet e.g. RainActiv												
1500	1500	200	A-2-3000-200	B-2-3000-200	C-2-3000-200	D-2-3000-200	E-2-3000-200	F-2-3000-200	G-2-3000-200	H-2-3000-200	I-2-3000-200	J-2-3000-200
		300	A-2-3000-300	B-2-3000-300	C-2-3000-300	D-2-3000-300	E-2-3000-300	F-2-3000-300	G-2-3000-300	H-2-3000-300	I-2-3000-300	J-2-3000-300
3 - Real Time Control RWH e.g. IOTA												
3000	3000	200	A-3-3000-200	B-3-3000-200	C-3-3000-200	D-3-3000-200	E-3-3000-200	F-3-3000-200	G-3-3000-200	H-3-3000-200	I-3-3000-200	J-3-3000-200
		300	A-3-3000-300	B-3-3000-300	C-3-3000-300	D-3-3000-300	E-3-3000-300	F-3-3000-300	G-3-3000-300	H-3-3000-300	I-3-3000-300	J-3-3000-300
4 - Roof Located RWH with Suction Pump e.g. FlushRain												
450	0	200	A-4-450-200	B-4-450-200	C-4-450-200	D-4-450-200	E-4-450-200	F-4-450-200	G-4-450-200	H-4-450-200	I-4-450-200	J-4-450-200
		300	A-4-450-300	B-4-450-300	C-4-450-300	D-4-450-300	E-4-450-300	F-4-450-300	G-4-450-300	H-4-450-300	I-4-450-300	J-4-450-300
5 - RWH for Potable Use e.g. RainSafe												
3000	0	600	A-5-3000-600	B-5-3000-600	C-5-3000-600	D-5-3000-600	E-5-3000-600	F-5-3000-600	G-5-3000-600	H-5-3000-600	I-5-3000-600	J-5-3000-600

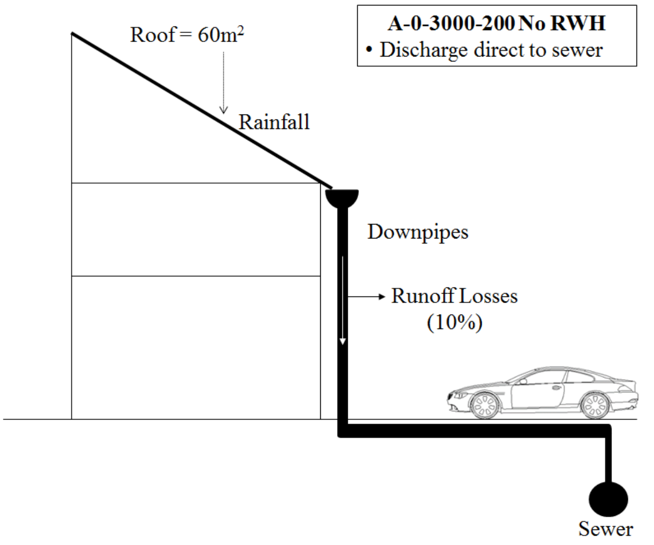
KEY: **A**-1-3000-200 **A** = Location "Birmingham"
A-**1**-3000-200 **1** = RWH Configuration "1 - Traditional RWH"
A-1-**3000**-200 **3000** = Tank volume "3,000l"
A-1-3000-**200** **200** = Demand "200l/day"

<table>
<tr><th>Description</th><th>Configuration and Scenario ID Number</th></tr>
<tr><td>

No RWH
The house was modelled with no RWH system, no stormwater control features or water treatment devices.

The rainfall is assumed to discharge as an overflow to the receiving sewer with a fixed runoff coefficient of 0.9. (i.e.10% losses are assumed).

</td><td>



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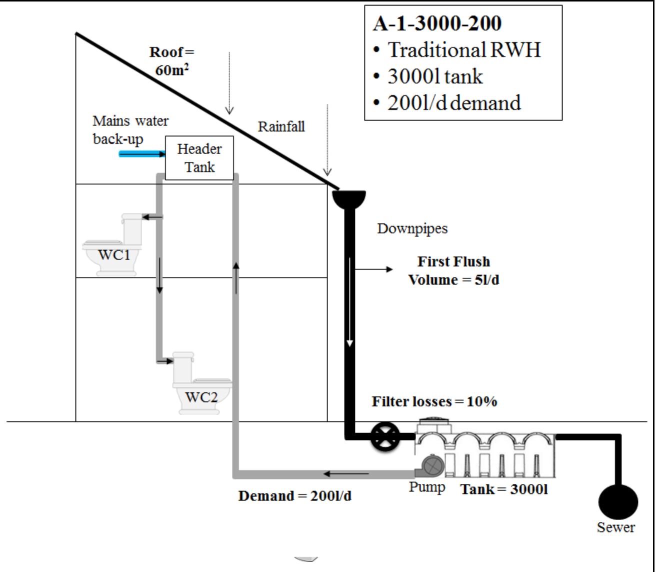
<tr><td>

Traditional RWH
A traditional RWH configuration with a below ground tank that feeds a loft-based header tank via a submersible pump. It has no stormwater control features or water treatment devices.

The system has a 3,000l tank with 3,000l functional storage due to mains water top up entering the header tank within property.

This scenario was tested with rainwater demand for WC usage only.

</td><td>



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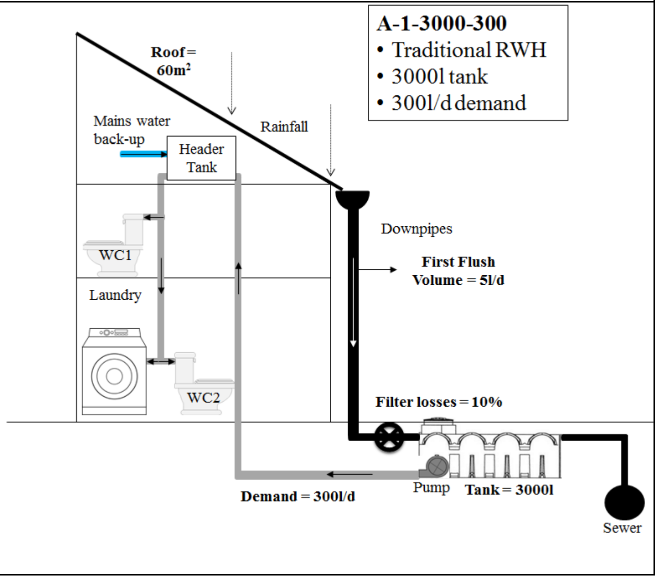
<tr><td>

Traditional RWH
A traditional RWH configuration with a below ground tank that feeds a loft-based header tank via a submersible pump. It has no stormwater control features or water treatment devices.

The system has a 3,000l tank with 3,000l functional storage due to mains water top up entering the header tank within property.

This scenario was tested with rainwater demand for WC+Laundry usage.

</td><td>



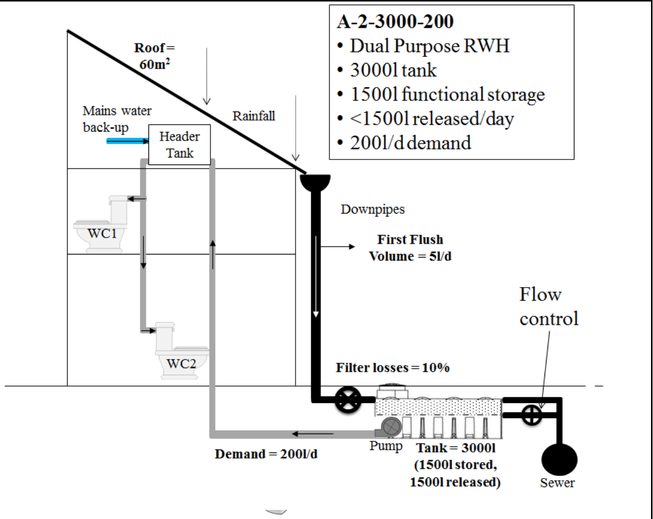
</td></tr>
</table>

Dual Purpose RWH with Passive Control Outlet

A novel RWH configuration with a below ground tank that feeds a loft-based header tank via a submersible pump. It has a passive discharge control device to release stormwater when the tank exceeds 50% full.

The system has a 3,000l tank with 1,500l functional storage. The upper region of the tank comprises a 1,500l source control volume which captures and releases large storm events at a controlled rate on the same day as the storm.

This scenario was tested with rainwater demand for WC usage only.

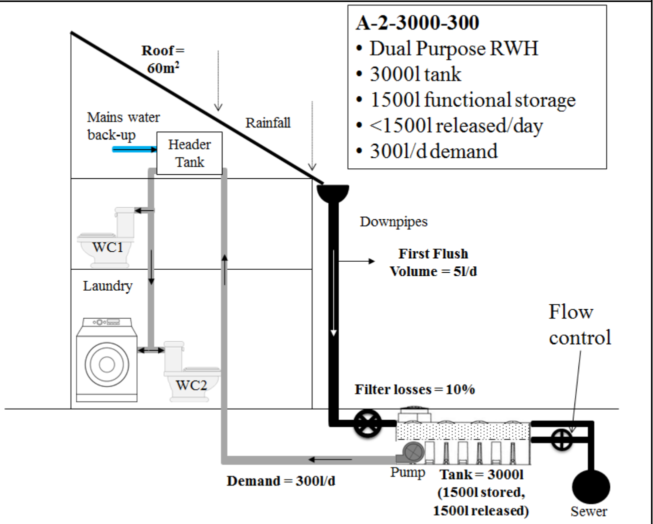


Dual Purpose RWH with Passive Control Outlet

A novel RWH configuration with a below ground tank that feeds a loft-based header tank via a submersible pump. It has a passive discharge control device to release stormwater when the tank exceeds 50% full.

The system has a 3,000l tank with 1,500l functional storage. The upper region of the tank comprises a 1,500l source control volume which captures and releases large storm events at a controlled rate on the same day as the storm.

This scenario was tested with rainwater demand for WC+Laundry usage.



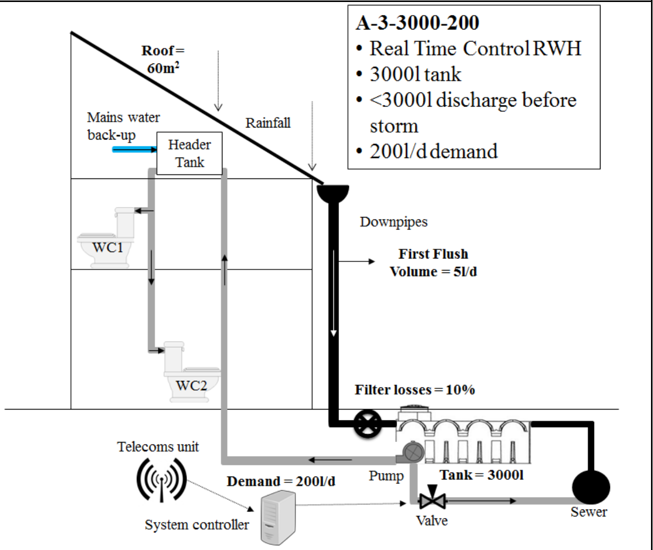
Real Time Control RWH

A novel RWH configuration with a below ground tank that feeds a loft-based header tank via a submersible pump. It has a real time active discharge control to release stormwater the day prior to a storm.

The system has a 3,000l tank with 3,000l functional storage. The real time control system enables rainwater to be released from the tank at the previous time-step to accommodate projected rainfall volume arriving during the current time-step.

The full functional volume is available for source control (up to 3,000l/day). The controller is assumed to have a daily rainfall forecast for the next time step which is 100% accurate.

This scenario was tested with rainwater demand for WC usage only.

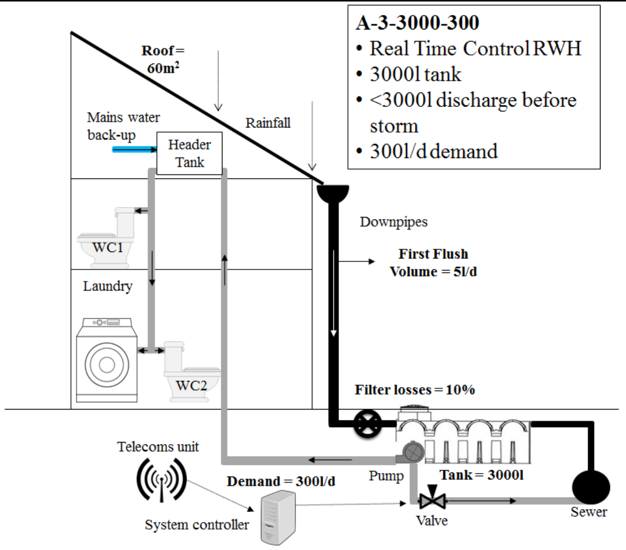


Real Time Control RWH
A novel RWH configuration with a below ground tank that feeds a loft-based header tank via a submersible pump. It has a real time active discharge control to release stormwater the day prior to a storm.

The system has a 3,000l tank with 3,000l functional storage. The real time control system enables rainwater to be released from the tank at the previous time-step to accommodate projected rainfall volume arriving during the current time-step.

The full functional volume is available for source control (up to 3,000l/day). The controller is assumed to have a daily rainfall forecast for the next time step which is 100% accurate.

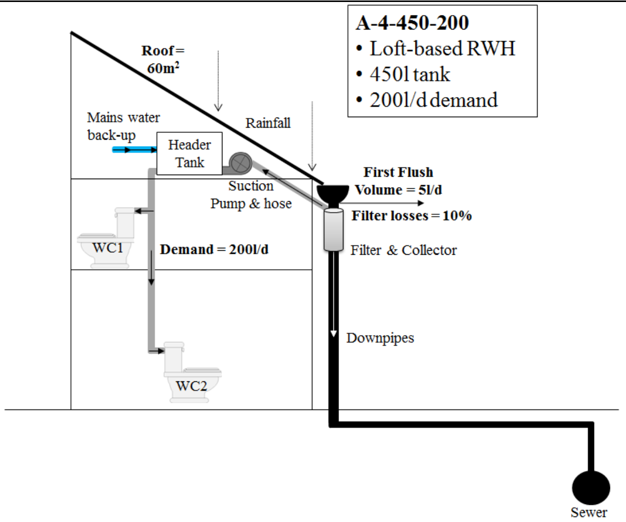
This scenario was tested with rainwater demand for WC+Laundry usage.



Roof Located RWH with Suction Pump
A novel RWH configuration with no external tanks and a small loft-based header tank that is fed from a suction pump within the loft.

The system has a 500l tank with a functional volume of 450l due to mains water top up entering the lower region of the header tank.

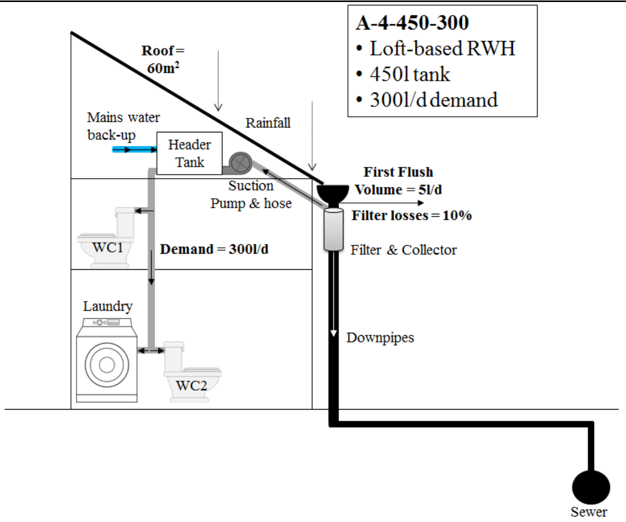
This scenario was tested with rainwater demand for WC usage only.



Roof Located RWH with Suction Pump
A novel RWH configuration with no external tanks and a small loft-based header tank that is fed from a suction pump within the loft.

The system has a 500l tank with a functional volume of 450l due to mains water top up entering the lower region of the header tank.

This scenario was tested with rainwater demand for WC+Laundry usage.



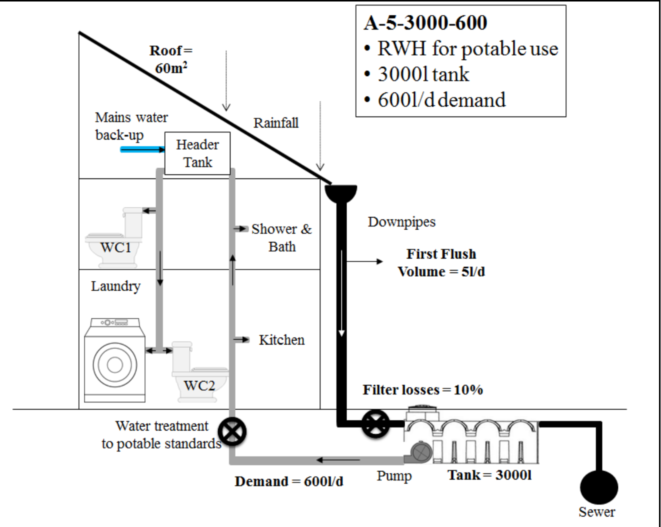
RWH for Potable Use A novel RWH configuration with a below ground tank that feeds a loft-based header tank via a submersible pump. It includes a potable water treatment device. The system has a 3,000l tank with 3,000l functional storage due to mains water top up entering header tank within property. Daily water demand is greater for this configuration as all household uses draw water from the treated rainwater supply. This scenario was tested for rainwater demand for all household water demands.	

Figure 6.2 – Description of the ten RWH configurations tested

6.4 Summary of Simulation Output Metrics

The water demand management and stormwater control benefits of each RWH system were evaluated using the embedded metrics within the RainWET. These are summarised in Table 6.5.

Table 6.5 – Metrics used to evaluate each RWH design scenario

Metric	Description	Details
Yield (l) *i.e. Rainwater demand satisfied*	Maximum, minimum, mean and median values from the twenty annual summaries were calculated.	The simulated annual Yield values define the scale of long term water demand management benefits when compared to the *No RWH scenario*.
Annual Overflow Volume (l) *i.e. Total annual uncontrolled rainwater releases*	Maximum, minimum, mean and median values from the twenty annual summaries were calculated.	The simulated Annual Overflow Volume values define the scale of long term stormwater discharge reductions when compared to the *No RWH scenario*.
Peak Daily Overflow Volume (l) *i.e. Peak uncontrolled rainwater releases*	Maximum, minimum, mean and median values from the twenty annual summaries were calculated.	The simulated Peak Daily Overflow Volume values define the ability of each configuration to limit peak stormwater discharge reductions when compared to the *No RWH scenario*. The largest daily discharge from the twenty year simulation period was compared for each configuration to enable the best performing RWH system (in terms of source control) to be identified.

Metric	Description	Details
		For scenarios which include dual purpose or real time control systems, the discharges associated with the controlled release of rainwater are not reported in these outputs as the controlled discharges are considered to be released at attenuated rates / when no other rainfall is entering the downstream waste water network.

6.5 Results and Discussion

Simulations for the ten RWH configurations described in Table 6.4 were completed for each of the ten locations described in Figure 6.1. One hundred RainWET simulation files were generated, each with twenty annual simulations as illustrated in Figure 6.3. These annual outputs were summarised within the RainWET to produce one hundred summary tables as illustrated in Table 6.6. Finally the data within these summary tables was analysed to investigate the research objectives. A full set of charts and tables comparing RWH performance against locations and design configuration are included in Appendix A. The following sections analyse the results of the simulation outputs.

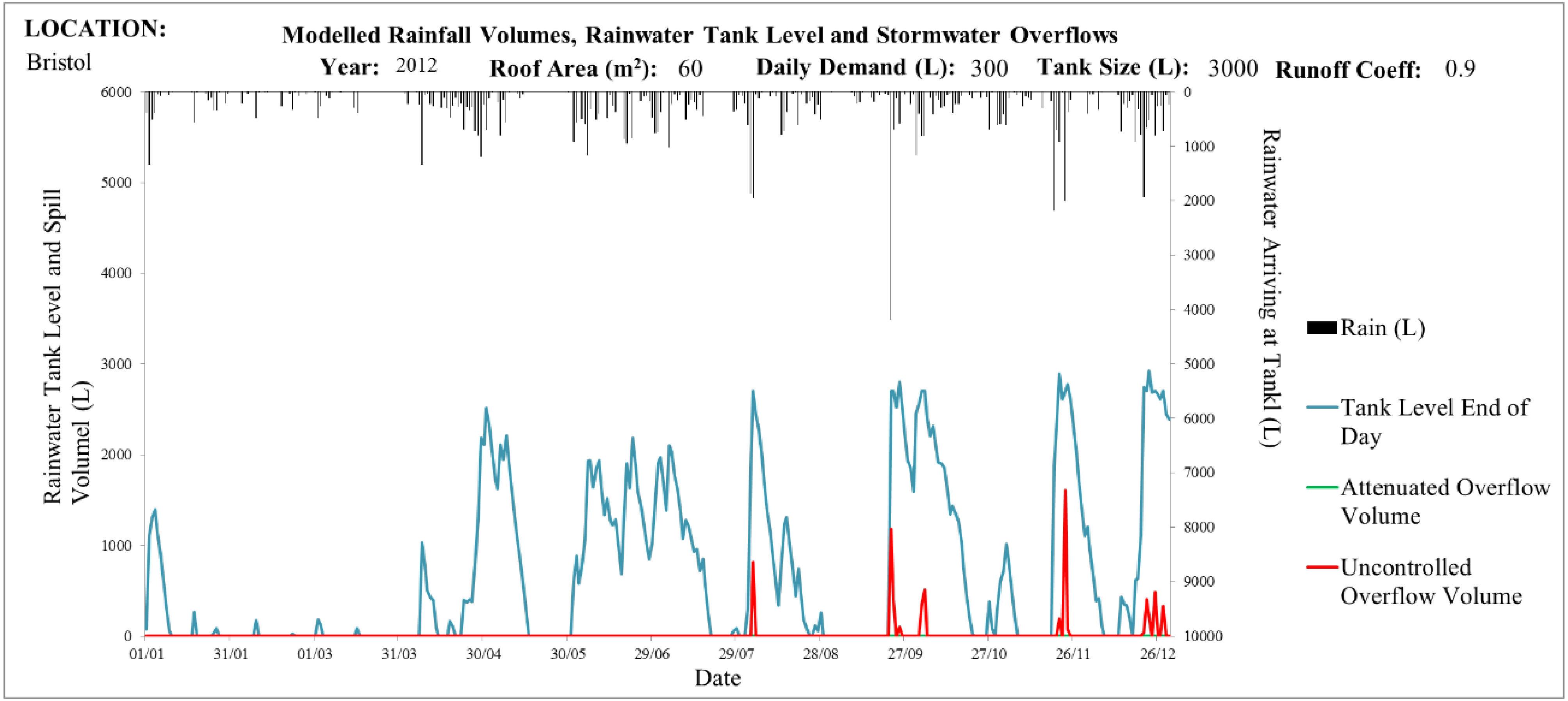


Figure 6.3– RainWET annual output chart for traditional RWH (B-1-3000-300) at Bristol during wettest year (2012)

Table 6.6 – Example of one of the 100 RainWET summary tables produced to summarise twenty annual simulations for each scenario and location evaluated (Example shown is Traditional RWH in Bristol [B1-3000-300])

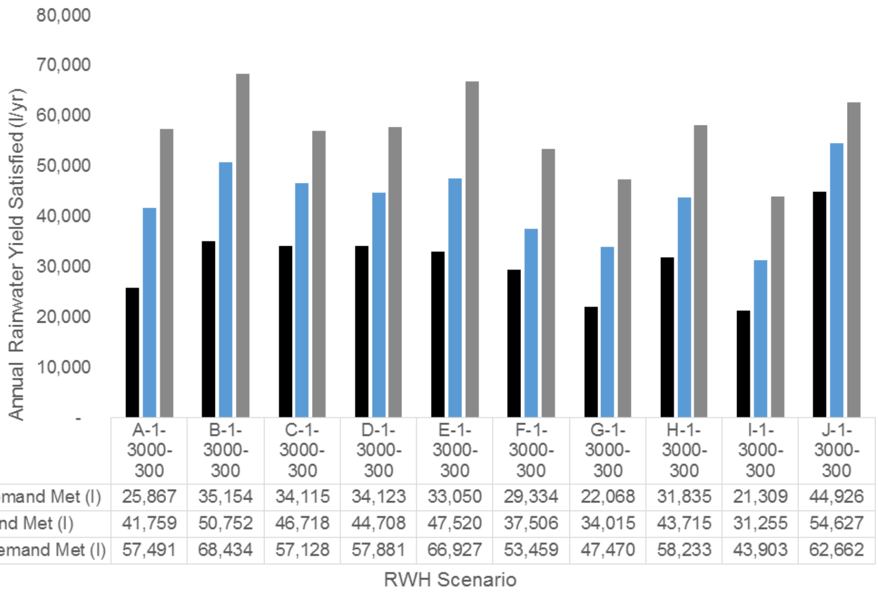
Year	Total Rainfall (mm)	Total Rain (l)	Rain (after losses)(l)	No. of Rain-days	First Flush Volume (l)	Potential RW Demand (l)	RW Demand Met (l)	RW Demand Met (%)	Peak Daily Overflow Volume (l/day)	Annual Overflow Volume (l)
1996	833	49,968	44,971	142	710	109,500	44,260	40.4	0	0
1997	949	56,946	51,251	156	780	109,500	50,412	46.0	0	0
1998	1,048	62,856	56,570	188	940	109,500	53,509	48.9	1130	2,431
1999	1,268	76,074	68,467	178	890	109,500	61,410	56.1	813	4,952
2000	1,307	78,408	70,567	209	1,045	109,500	66,658	60.9	929	2,920
2001	850	51,018	45,916	176	880	109,500	45,035	41.1	0	0
2002	1,164	69,858	62,872	207	1,035	109,500	58,261	53.2	1596	2,438
2003	773	46,368	41,731	169	845	109,500	40,741	37.2	168	333
2004	925	55,482	49,934	216	1,080	109,500	48,848	44.6	0	0
2005	842	50,508	45,457	204	1,020	109,500	43,950	40.1	0	0
2006	889	53,310	47,979	200	1,000	109,500	46,434	42.4	33	33
2007	1,022	61,302	55,172	194	970	109,500	53,572	48.9	624	624
2008	1,072	64,296	57,866	231	1,155	109,500	55,583	50.8	430	1,400
2009	907	54,390	48,951	202	1,010	109,500	47,407	43.3	393	550
2010	667	40,026	36,023	173	865	109,500	35,154	32.1	0	0
2011	846	50,742	45,668	196	980	109,500	44,022	40.2	659	900
2012	1,445	86,712	78,041	229	1,145	109,500	68,434	62.5	1607	6,702
2013	878	52,668	47,401	193	965	109,500	45,124	41.2	184	491
2014	1,117	66,996	60,296	221	1,105	109,500	59,188	54.1	0	0
2015	908	54,492	49,043	188	940	109,500	47,046	43.0	0	0
MAX	**1,445**	**86,712**	**78,041**	**231**	**1,155**	**109,500**	**68,434**	**62**	**1607**	**6,702**
MEAN	*985*	*59,121*	*53,209*	*194*	*968*	*109,500*	*50,752*	*46*	*428*	*1,189*
MEDIAN	917	54,987	49,488	195	975	109,500	48,127	44	176	412
MIN	**667**	**40,026**	**36,023**	**142**	**710**	**109,500**	**35,154**	**32**	**0**	**0**

6.6 How do traditional RWH systems perform when deployed at a range of locations throughout the UK?

The rainfall data analysed in this study reflected the wide variation in rainfall patterns throughout the UK. Consequently, the RWH systems simulated were anticipated to demonstrate a range of performance at the ten study locations.

Traditional RWH systems were simulated using a 3,000l tank with two demand scenarios with of a) 200l/day and b) 300l/day. The performance of the traditional RWH system with a 3,000l tank and 300l/day demand was analysed against the three metrics defined in Table 6.5 in the following Section.

6.6.1 Yield (l/year)



	A-1-3000-300	B-1-3000-300	C-1-3000-300	D-1-3000-300	E-1-3000-300	F-1-3000-300	G-1-3000-300	H-1-3000-300	I-1-3000-300	J-1-3000-300
■ Minimum-RW Demand Met (l)	25,867	35,154	34,115	34,123	33,050	29,334	22,068	31,835	21,309	44,926
■ Mean RW-Demand Met (l)	41,759	50,752	46,718	44,708	47,520	37,506	34,015	43,715	31,255	54,627
■ Maximum RW-Demand Met (l)	57,491	68,434	57,128	57,881	66,927	53,459	47,470	58,233	43,903	62,662

Figure 6.4 – Traditional RWH performance at ten locations: Annual rainwater yield (Demand = 300l/day)

Figure 6.4 describes the minimum recorded annual yield (21,309l/year [19.4% demand satisfied]) from the traditional RWH system was found at location I (London). London also had the lowest mean yield (31,255l/year [28.5%]) and the lowest maximum yield

(43,903l/year [40.1%]). The low yield in London was caused by the relatively low annual rainfall for the London rain gauge (Min=410mm, Mean=597mm, Max=832mm).

The best performing traditional RWH system was at location J (Truro). Truro achieved the best average yield of 54,627l/year. Truro’s worst performing year (44,926l/year) also exceeded the lowest yield for all of the other locations. Furthermore, comparative analysis shows Truro’s *worst yield* actually exceeded London’s *best yield* when the twenty years were evaluated.

Although Truro was found to have the highest mean yield between 1996-2015, the maximum annual yield achieved was found at location B, Bristol with an annual yield of 68,424l/year during 2012. The annual water demand for a typical house with four occupants using 150l/day was calculated as 219,000l/annum. Hence the mean reduction in water demand for the best performing location (Truro) would average 24.9%. The mean saving for the worst performing location (London) was found to be 14.3%.

6.6.2 Annual Overflow Volume (l)

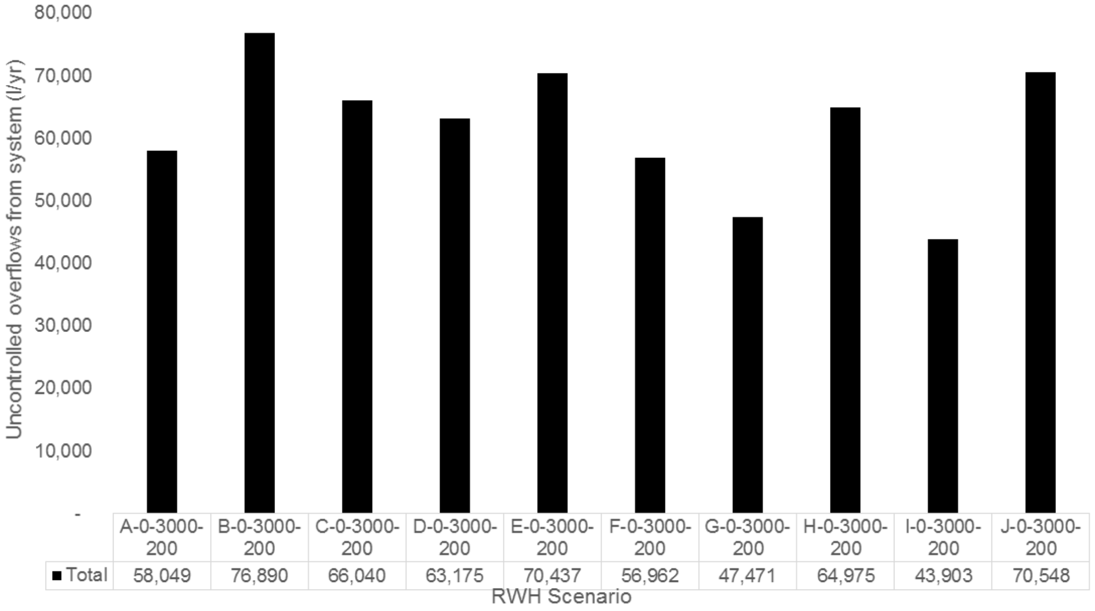


Figure 6.5 – Rainwater discharges for a typical house at ten locations: Maximum annual uncontrolled overflows

The maximum annual overflow volume for each location (assuming no RWH system was installed) is illustrated in Figure 6.5. The largest annual contribution to stormwater runoff was observed at location B, Bristol (76,890l). The location with the smallest annual contribution observed over twenty years was I, London (43,903l).

Figure 6.6 illustrates the highest annual discharges observed at each location with the inclusion of a traditional RWH system (e.g. A1-3000-300). In London, a 100% stormwater discharge reduction was observed (i.e. the 3,000l RWH system fully prevented all rainwater discharges throughout the twenty year simulation period.) The largest annual contribution to stormwater runoff across all of the locations (Bristol) was also significantly reduced by 87% to just 10,309l.

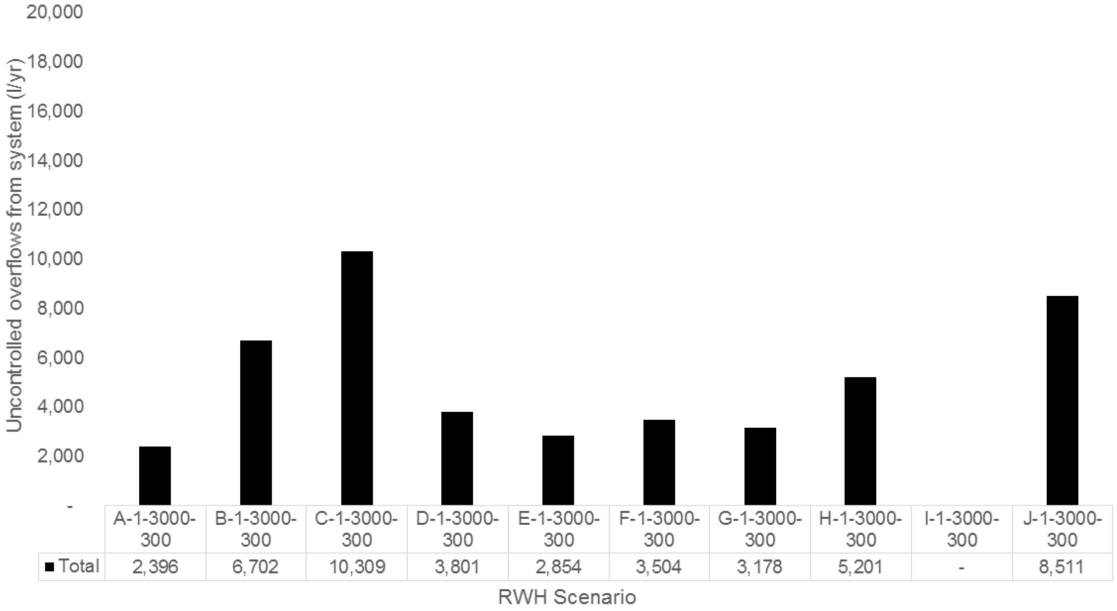
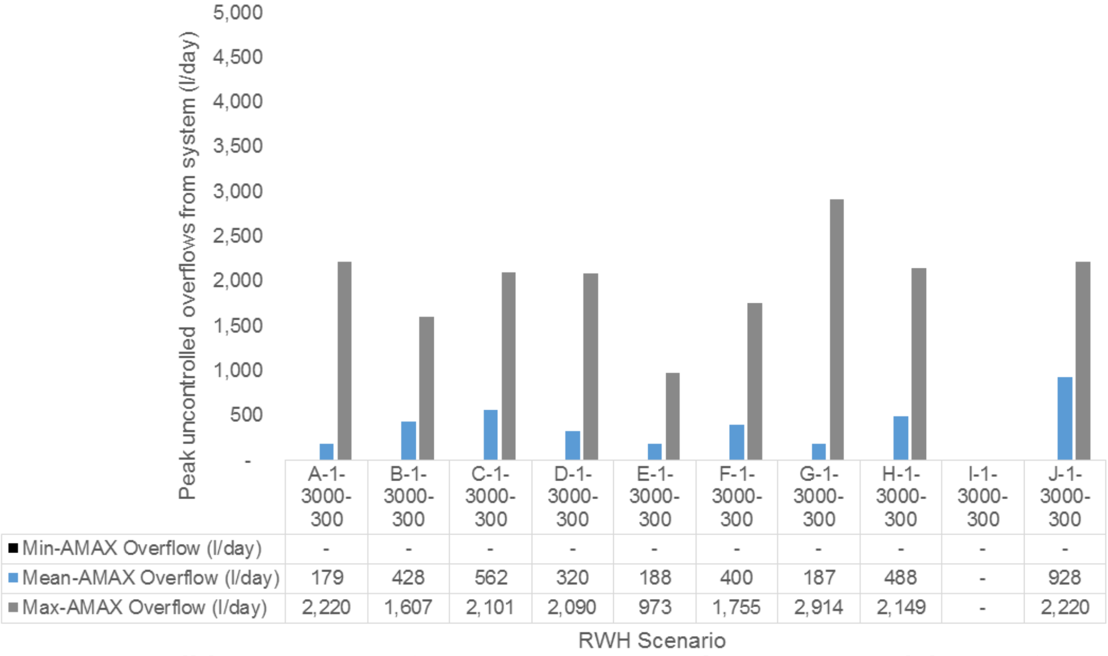


Figure 6.6 – Traditional RWH performance at ten locations: Maximum annual uncontrolled overflows (Demand = 300l/day)

6.6.3 Peak Daily Overflow Volume (l/day)

The peak daily overflow volume was identified by finding the single largest overflow in a given year. The minimum, mean and maximum value for each site was identified as illustrated in Figure 6.8. As observed previously, zero discharges from the RWH system were observed for all storms in London throughout the twenty year analysis, hence location I shows zero values in Figure 6.7.



	A-1-3000-300	B-1-3000-300	C-1-3000-300	D-1-3000-300	E-1-3000-300	F-1-3000-300	G-1-3000-300	H-1-3000-300	I-1-3000-300	J-1-3000-300
■ Min-AMAX Overflow (l/day)	-	-	-	-	-	-	-	-	-	-
■ Mean-AMAX Overflow (l/day)	179	428	562	320	188	400	187	488	-	928
■ Max-AMAX Overflow (l/day)	2,220	1,607	2,101	2,090	973	1,755	2,914	2,149	-	2,220

Figure 6.7 – Traditional RWH performance at ten locations: Largest daily overflow event (Demand = 300l/day)

For all of the remaining locations, the minimum peak daily overflow volume calculated in the analysis was also found to be zero. This illustrates that no stormwater discharge occurred at any of the locations for at least one year from the twenty year simulation. Excluding London, the peak daily discharges ranged from 973l/day (E-Manchester) to 2,914l/day (G-Norwich). For comparison, this is a reduction of 67% in Manchester and only 1% in Norwich. Further investigation of the Norwich data shows that three consecutive days of heavy rainfall occurred in August 1996 which ensured the RWH tank was full at the start of the third day when 54.7mm of rain was observed.

Finally, Figure 6.7 shows the mean peak daily overflows were significantly reduced for all locations. The results illustrate that traditional RWH systems have a strong ability to reduce peak daily overflows for the majority of storms at locations throughout the UK. However, the evidence from the Norwich location demonstrates that storms which last for >2 days can exceed the capacity of traditional RWH systems to provide significant source control. The data supports the design of RWH in a dual purpose configuration with passive control outlets or real time control systems where stormwater control for extreme storm events is a design priority.

6.7 Which RWH configuration and location achieved the greatest rainwater yield?

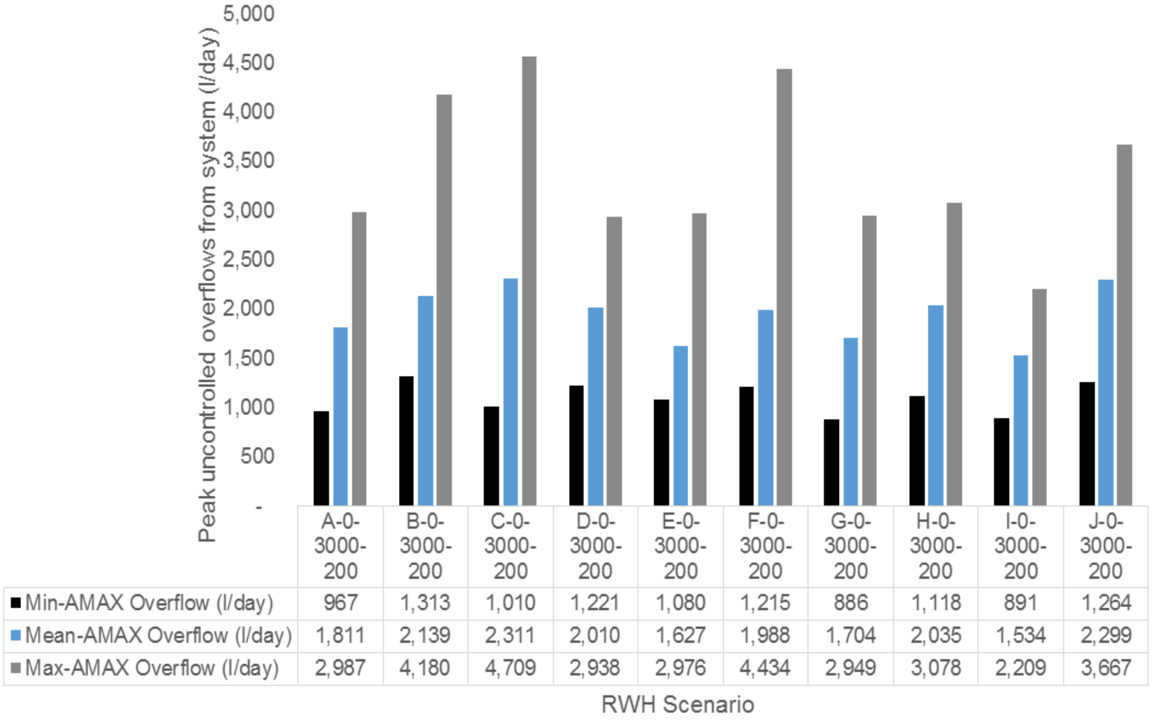
The best performing system, in terms of average yield, was the J-5-3000-600 scenario. This system was located in Truro and included a 3,000l tank and a water treatment device that enabled the rainwater to be used for all applications. The system was therefore modelled with the highest demand, and thus achieved the highest yield in Truro, the wettest location. The average yield over twenty years was 57,699 l/year in Truro. The maximum yield achieved in Truro reached 69,182l/year. This maximum yield was exceeded by the same RWH configuration in Bristol (75,711l/year) however this was an exceptional year and the average yield in Bristol was 11% lower than in Truro (51,119l/year). In contrast the same system achieved an average of only 31,316l/year in London 46% less yield than in Truro.

6.8 Which RWH configuration and location achieved the greatest reduction in peak stormwater discharges?

Two RWH configurations significantly outperformed the traditional RWH systems in terms of reducing the volume of rainwater discharge for the largest event over the twenty year analysis. Figure 6.8 illustrates the peak daily stormwater discharges at ten UK locations without a RWH installation. The dual purpose RWH with passive control outlet (e.g. A-2-3000-300) achieved significant reductions for all the peak storms with mean values tending to be less than 300l/day at all locations as illustrated in

Figure 6.9. The peak discharge rate at location J (Truro, 1,662l/day) was the highest observed for this configuration. When compared against the “No RWH” scenario

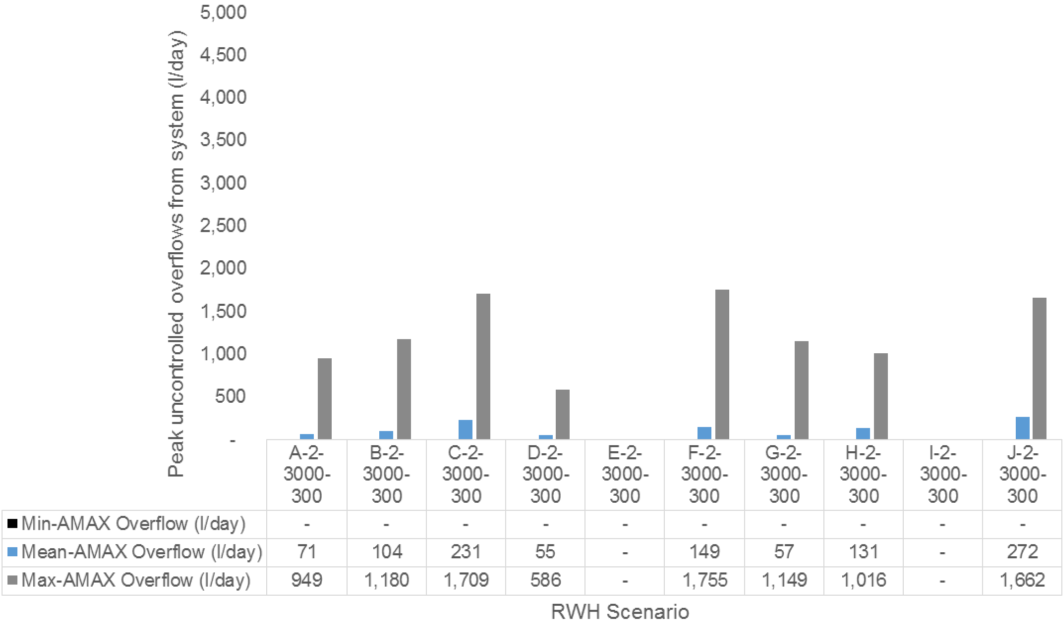
(3,667l/day), the system achieved a 55% reduction in the peak daily discharge for the largest daily storm in the twenty year series (across all ten locations).



	A-0-3000-200	B-0-3000-200	C-0-3000-200	D-0-3000-200	E-0-3000-200	F-0-3000-200	G-0-3000-200	H-0-3000-200	I-0-3000-200	J-0-3000-200
■ Min-AMAX Overflow (l/day)	967	1,313	1,010	1,221	1,080	1,215	886	1,118	891	1,264
■ Mean-AMAX Overflow (l/day)	1,811	2,139	2,311	2,010	1,627	1,988	1,704	2,035	1,534	2,299
■ Max-AMAX Overflow (l/day)	2,987	4,180	4,709	2,938	2,976	4,434	2,949	3,078	2,209	3,667

Figure 6.8 – Rainwater discharges for a typical house at ten locations: Peak daily uncontrolled overflows

A traditional system in the same location (J-1-3000-300) was found to achieve a lower discharge reduction of 25% (2,220l/day). The dual purpose RWH configuration was matched or outperformed (in terms of peak stormwater control) in all locations by the real time control RWH system as illustrated in Figure 6.10. The real time control configuration was able to discharge rainwater the day prior to a storm and thus enable all of the 3,000l tank to be available for stormwater capture during extreme storms.

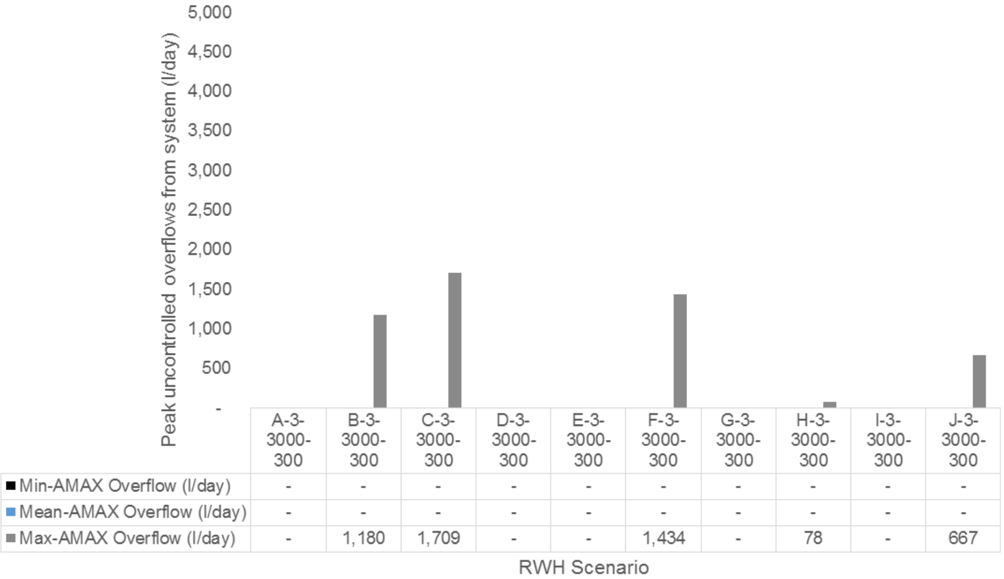


	A-2-3000-300	B-2-3000-300	C-2-3000-300	D-2-3000-300	E-2-3000-300	F-2-3000-300	G-2-3000-300	H-2-3000-300	I-2-3000-300	J-2-3000-300
■ Min-AMAX Overflow (l/day)	-	-	-	-	-	-	-	-	-	-
■ Mean-AMAX Overflow (l/day)	71	104	231	55	-	149	57	131	-	272
■ Max-AMAX Overflow (l/day)	949	1,180	1,709	586	-	1,755	1,149	1,016	-	1,662

Figure 6.9 – Peak stormwater discharges for dual purpose RWH at ten locations: largest daily overflow observed (Demand =300l/day)

This contrasts the dual purpose configuration as only 50% of the tank (1,500l) is available to drain down after each storm, while the remaining 50% is stored for local uses. The dual purpose configuration represents a compromise as the yield is reduced (due to the lower functional storage) and only 50% of the tank is available for stormwater control. In contrast, the real time control system can enable the whole functional storage volume (3,000l) to be available for either storage (drought mitigation) or stormwater control (flood mitigation).

The real time control system reduced the peak storm in location J (Truro) by 82% from 3,667 l/day to 667l/day. Furthermore the system was found to be the only configuration that could prevent all uncontrolled discharges in all locations for the mean annual maximum overflow as illustrated in Figure 6.10.



	A-3-3000-300	B-3-3000-300	C-3-3000-300	D-3-3000-300	E-3-3000-300	F-3-3000-300	G-3-3000-300	H-3-3000-300	I-3-3000-300	J-3-3000-300
■ Min-AMAX Overflow (l/day)	-	-	-	-	-	-	-	-	-	-
■ Mean-AMAX Overflow (l/day)	-	-	-	-	-	-	-	-	-	-
■ Max-AMAX Overflow (l/day)	-	1,180	1,709	-	-	1,434	-	78	-	667

Figure 6.10 – Real time control RWH performance at ten locations: Largest daily overflow observed (Demand = 300l/day)

6.9 Which RWH configuration and location achieved the greatest reduction in annual stormwater discharges?

The analysis demonstrates the ability for RWH systems to reduce stormwater discharges is linked to; the storage capacity of the tank; the ability to intentionally discharge stormwater; and the daily water demand. The year with the largest stormwater discharge was selected and plotted for each location against the best performing configuration in Figure 6.11. This data shows that the high demand (600l/day) associated with the RWH for potable use configuration was able to increase the probability that storage was available prior to a storm occurring. Consequently, the largest annual discharge observed for the configuration (across all the locations and years simulated) was limited to just 2,827l/year, 4% of the largest discharge (66,040l) observed for the same location without RWH installed.

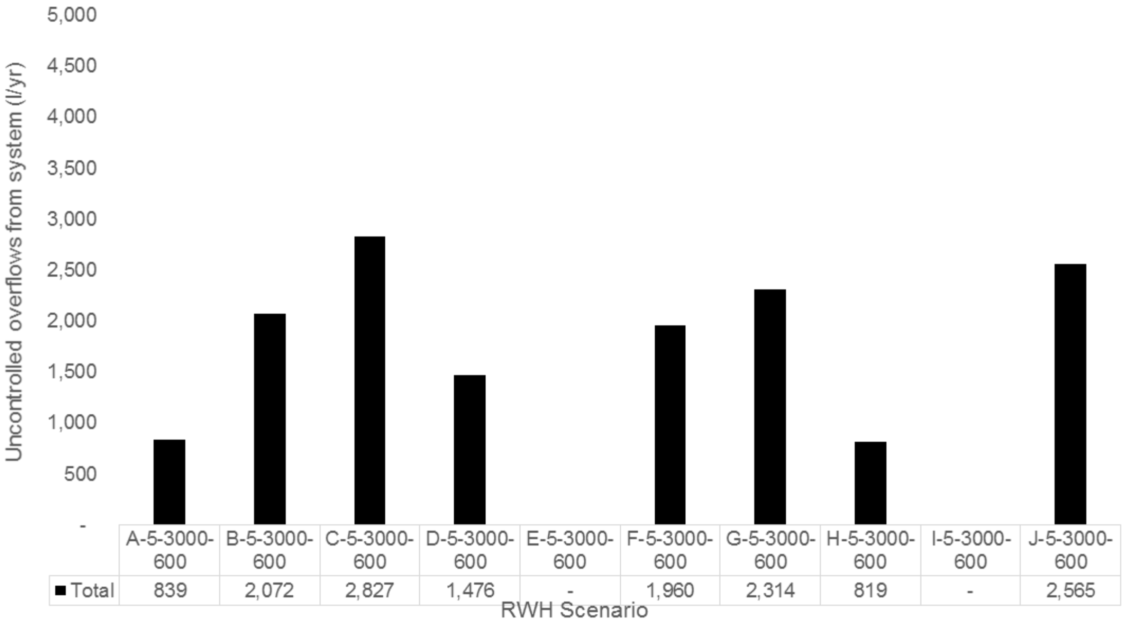


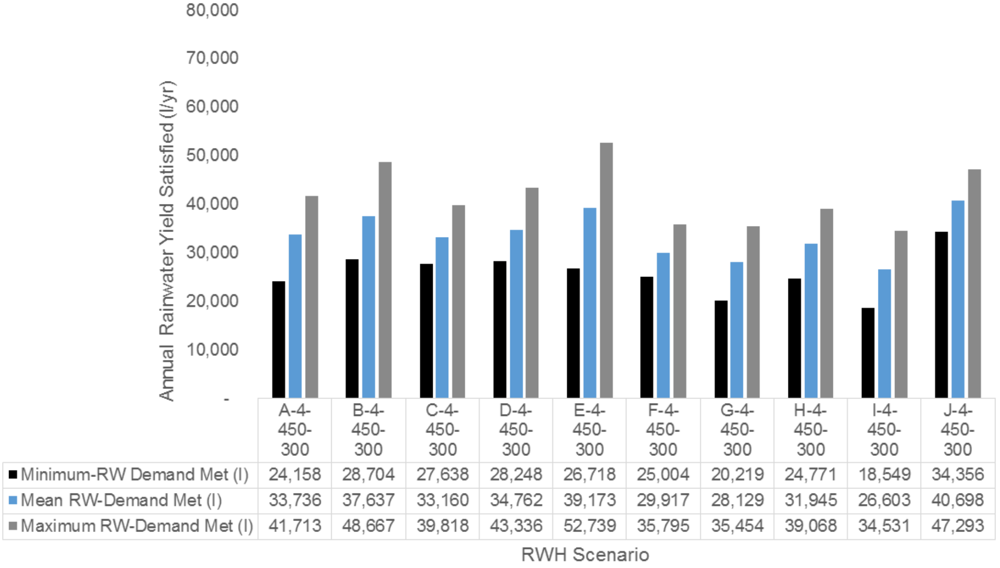
Figure 6.11 – RWH for potable use performance at ten locations: Maximum annual uncontrolled overflows (Demand = 600l/day)

6.10 Can small-scale RWH systems achieve yields that are comparable to traditional design configurations?

Small-scale RWH systems do not usually comply with the key design criteria set out in BS8515's tank sizing methods ((BSI), 2013b). The requirement calls for RWH tanks to have a functional storage capacity of no less than 18 days storage. This poses a potential barrier in the design process for the deployment of small RWH systems as they do not usually comply with this criteria.

The RWH yields for a traditional RWH system (e.g. A1-3000-300) are plotted in Figure 6.4. Minimum yields range from 21,309l/year in London to 44,926l/year in Truro. Mean yields range between 31,255l/year in London and 54,627l/year in Truro. Maximum yields range from 43,903l/year in London to 68,434l/year in Bristol. The average performance of this system in Truro was found to provide 24.9% of total household water demand.

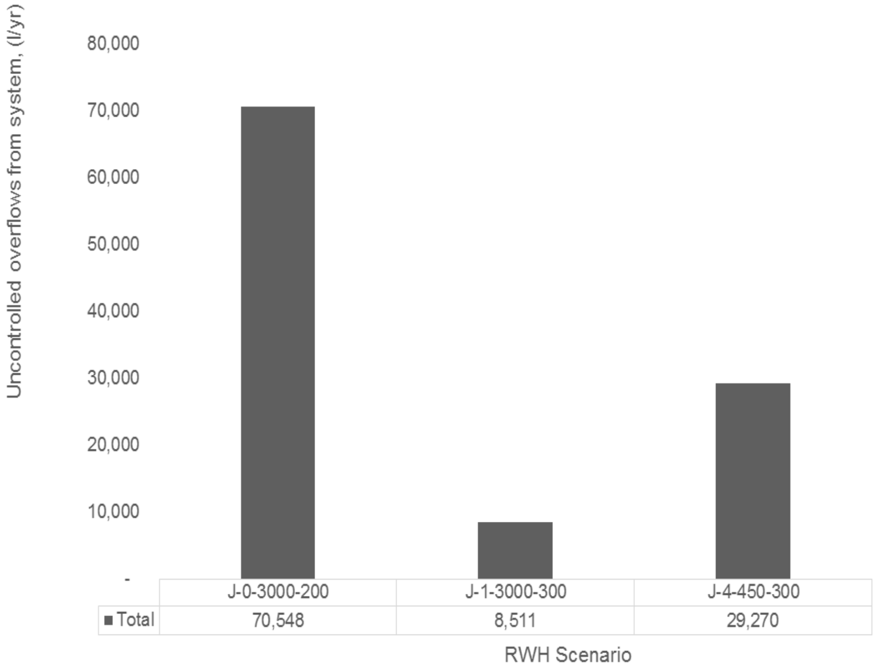
By contrast, scenario A-4-450-300 represents a small loft-based RWH system that can be easier to retrofit than traditional RWH systems as the design does not require external tanks or excavations. Data for this RWH configuration is illustrated for ten locations in Figure 6.12. Minimum yields range from 18,549l/year in London to 34,356l/year in Truro. The average performance of this configuration ranged from 26,603l/year in London to 40,698l/year in Truro. Maximum yields range from 34,068l/year in London to 48,667l/year in Bristol. The system's average performance in the best location (Truro, 40,698l/year) was identified as 18.6% of total household water demand. This value is approximately 2% lower than the yield achieved in the same location with the traditional RWH system (J-1-3000-300). The results support a hypothesis that small-scale RWH systems can provide average yields which are comparable to larger traditional RWH systems. Additionally, the traditional RWH system located in London (I-1-3000-300) achieved an average yield of 31,255l/year. This average yield was exceeded by the small loft-based RWH system (A-4-450-300) at seven of the ten locations (A,B,C,D,E,H,J). This evidence supports a finding that the location of (and rainfall pattern at) a RWH installation can play a bigger role in dictating yield than the overall size of the RWH system's storage tank. Additionally, if drought mitigation was the only design objective then the analysis demonstrates that small scale RWH systems perform better in relatively wet locations (e.g. Truro) than traditional RWH systems in relatively dry regions (e.g. London).



	A-4-450-300	B-4-450-300	C-4-450-300	D-4-450-300	E-4-450-300	F-4-450-300	G-4-450-300	H-4-450-300	I-4-450-300	J-4-450-300
■ Minimum-RW Demand Met (l)	24,158	28,704	27,638	28,248	26,718	25,004	20,219	24,771	18,549	34,356
■ Mean RW-Demand Met (l)	33,736	37,637	33,160	34,762	39,173	29,917	28,129	31,945	26,603	40,698
■ Maximum RW-Demand Met (l)	41,713	48,667	39,818	43,336	52,739	35,795	35,454	39,068	34,531	47,293

Figure 6.12 – Yield for small loft-based RWH at ten locations (Demand = 300l/day)

The analysis has provided evidence that small-scale RWH systems can provide relatively consistent yields, however they perform less favourably in wetter locations in terms of reducing annual stormwater discharges as illustrated in Figure 6.13. The traditional RWH system was found to reduce the largest annual overflow volume recorded in the twenty year study by 88.0%. The smaller 450l RWH system performed also reduced the same annual stormwater volume by 58.5%.



	J-0-3000-200	J-1-3000-300	J-4-450-300
■ Total	70,548	8,511	29,270

Figure 6.13 – Comparison of; No RWH, traditional RWH and small loft-based RWH performance in Truro: Maximum annual uncontrolled overflow event (Demand = 300l/day)

Again the smaller RWH system (J-4-450-300) was found to underperform in comparison to a traditional RWH system (J-1-3000-300) when the largest peak daily uncontrolled overflow was evaluated for the twenty year analysis as illustrated in

Figure 6.14. The traditional RWH system reduced the peak daily stormwater discharge by 39.5%, whereas the smaller 450l RWH system achieved a 12.2% reduction.

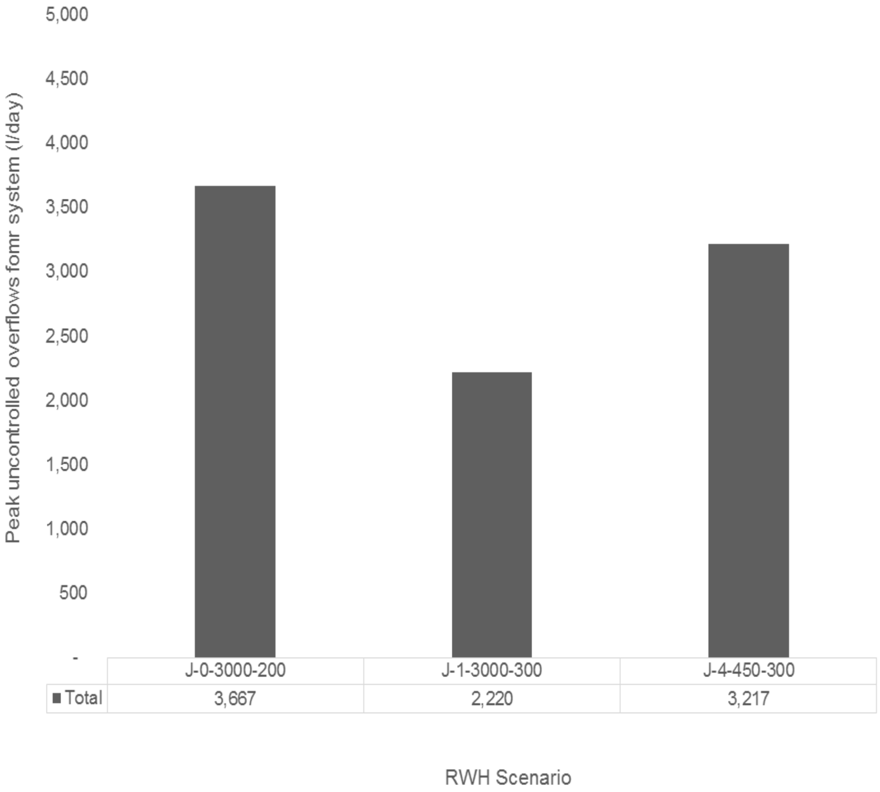


Figure 6.14 – Comparison of; No RWH, traditional RWH and small loft-based RWH performance in Truro: Peak uncontrolled overflow event (Demand = 300l/day)

6.11 Summary and Conclusions

The data analysis conducted in this chapter has demonstrated the functionality of the RainWET as a decision support tool for investigating RWH design scenarios at a range of locations. The methods set out within the tool were successfully deployed to investigate rainfall data for the period of 1996-2015 with over 73,000 time steps across the 10 selected locations. The simulation process solved the 15 Equations described in Chapter 5, giving approximately 1.1m calculation results that fed the summary tables. The data was analysed and the conclusions from the analysis are as follows:

1. The use of RWH systems as a drought mitigation tool has been exemplified and quantified by analysing the yield from a range of RWH configurations at 10 locations throughout the UK. The evidence supports the ability of RWH to be deployed in both high rainfall and low rainfall locations as alternative water supply systems.
2. The mean long-term rainwater yield for a traditional RWH system with a 60m^2 roof feeding a 3,000l tank and 300l/day demand was identified as 43,528l/year when data from across ten UK locations was analysed.
3. Mean long-term rainwater yield from traditional RWH systems (with a 60m^2 roof, 3,000l tank and 300l/day demand) ranged from 31,255l/year in London to 54,627l/year in Truro. These values equate to 14.3% and 24.9% of total household water demand respectively.
4. Average long term rainwater yield for novel loft based RWH technologies with only 450l of storage and 300l/day demand ranged from 26,603l/year in London to 40,698l/year in Truro. These values equate to 12.1% and 18.6% of total household water demand respectively.
5. Small scale RWH systems were found to provide lower yields than traditional systems. However, the reduction in yield was limited to a range of 2.2% of total annual water demand in London (driest location) and 6.3% in Truro (wettest location).

6. Small scale RWH systems do not generally satisfy the BS8515 design rule which requires 18 days of mean rainfall to be stored within the RWH tank ((BSI), 2013b). However, evidence from this analysis suggests that the British Standard's arbitrary allowance for 18 days of storage (based on 5 % of the year) may present an unnecessary barrier to the deployment of small scale RWH systems which have been shown to provide significant yields and stormwater control benefits throughout the UK.
7. The traditional RWH system (60m^2 roof, 3,000l tank and 300l/day demand) was found to prevent all discharges in London for the twenty year simulation period. This data could support a policy for RWH to be deployed as the sole source control measure in regions where demand exceeds yield. The analysis supports the findings of other authors that high demand RWH systems can successfully minimise stormwater discharges (Gerolin *et al.* (2010), Kellagher (2011), DeBusk *et al.* (2013)). Furthermore, this configuration was found to reduce discharges to zero for at least one year at every location analysed, including those in wetter regions.
8. Rainfall availability was shown to be a key factor in satisfying rainwater demands. This was exemplified by the small scale RWH system (60m^2 roof, 450l tank, 300l/day demand) which achieved greater yields at seven locations than the traditional RWH system (60m^2 roof, 3,000l tank, 300l/day demand) achieved in London.
9. Dual purpose RWH systems (with an ability to partially drain down after each storm) were shown to outperform all traditional RWH systems in terms of peak stormwater discharge reduction and annual average stormwater discharges.
10. Real time control RWH systems (with an ability to fully drain down prior to each storm) were able to match or outperform all of the dual purpose RWH systems in terms of peak stormwater discharge reduction and annual average stormwater discharges.

11. High rainwater demand scenarios (e.g. situations where RWH is treated to potable standards and re-used for all potable and non-potable applications) were also found to perform well as stormwater control measures. The peak annual discharge observed from a high rainwater demand scenario (B-5-3000-600) reduced the annual discharges by 97.3% from 76,890l/year to 2,072l/year.

6.12 Limitations and Further Work

This work relies upon the accuracy of rain gauge data to enable the simulations to be completed. It was therefore necessary to make adjustments to the rain fall input data as described in the Methodology. A number of assumptions were necessary as described in Table 6.2. Each of these could potentially introduce errors into the analysis. This is especially true for locations where monthly rainfall values needed to be shared uniformly across the month. Hence the analyses for Bristol, Birmingham, Exeter, Norwich and Truro are based on more reliable input data than those completed for Newcastle, Southampton, Dover, London and Manchester.

Additionally, the RWH analysis was conducted for ten configurations in ten locations. This enabled a UK wide study to be performed. However, it must be acknowledged that the results are based upon the analysis of a single house with a fixed roof area of 60m^2, and a various demand and tank scenarios. Analysis of RWH configurations using the RainWET software can be undertaken for an unlimited range of design configurations by varying site location (rainfall); tank size; rainwater demand; stormwater control features; first flush volumes; loss coefficients and the length of the simulation period (i.e. longer than 20 years). Further work on costs and benefits is warranted in both research and implementation spheres.

Key areas where further simulation and analysis warrant investigation are identified as follows:

1) The demand scenarios simulated assume household demand is uniform throughout the year. Smart metering data is increasingly becoming available at a daily (and sub daily) time step. The use of real world water demand profiles could provide a refinement to the simulation work completed here and an analysis could be conducted to establish the validity of investigating RWH systems using a uniform water demand.

2) Climate change scenario analysis can be completed using projected rainfall data for a future design horizon. The functionality of each RWH under a range of projected scenarios can be tested within the RainWET by manipulating the rainfall data prior to running the tool. UKCP18 (Committee on Climate Change, 2017) data will be generated in the near future and further analysis using the tool could be conducted once that package of climate change outputs is available.

3) All analyses were conducted using a 20 year time series. A long period simulation could be conducted using data that spans for >90 years (e.g. the Manchester rain gauge data). Such an analysis would enable a further assessment of RWH system performance during extreme storm events, and peak over threshold methods could be used to define system performance in the 1 in 100 year storm event (Crooks and Kay, 2015).

4) The RainWET was used to evaluate rainfall at a daily time step. However, rain gauge data can be obtained at a 15 minute time step. Simulating RWH performance at a sub-daily resolution poses an opportunity for further development of the methods and analyses reported herein as exemplified in recent research studies (Campisano and Modica, 2014).

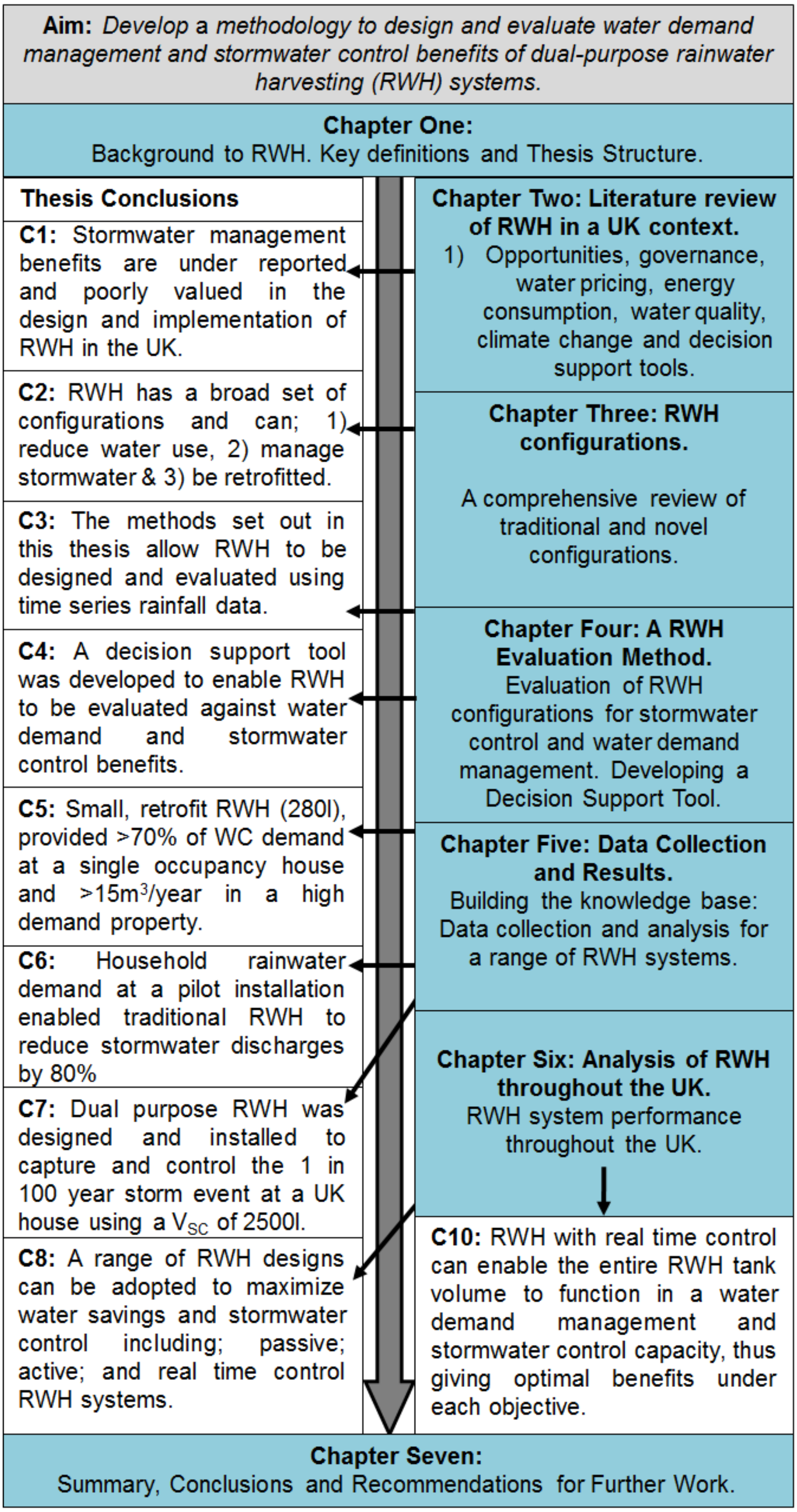
Chapter 7: Conclusions and Recommendations for Further Work

7.1 Chapter Summary

This chapter describes conclusions of research, original contributions, investigates opportunities for further research and provides recommendations for next steps and impact generation associated with the thesis.

7.2 Summary of Conclusions

The following section examines the broad conclusions derived from each chapter as described in Figure 7.1.



Aim: *Develop a methodology to design and evaluate water demand management and stormwater control benefits of dual-purpose rainwater harvesting (RWH) systems.*

Chapter One:
Background to RWH. Key definitions and Thesis Structure.

Thesis Conclusions

C1: Stormwater management benefits are under reported and poorly valued in the design and implementation of RWH in the UK.

C2: RWH has a broad set of configurations and can; 1) reduce water use, 2) manage stormwater & 3) be retrofitted.

C3: The methods set out in this thesis allow RWH to be designed and evaluated using time series rainfall data.

C4: A decision support tool was developed to enable RWH to be evaluated against water demand and stormwater control benefits.

C5: Small, retrofit RWH (280l), provided >70% of WC demand at a single occupancy house and >15m^3/year in a high demand property.

C6: Household rainwater demand at a pilot installation enabled traditional RWH to reduce stormwater discharges by 80%

C7: Dual purpose RWH was designed and installed to capture and control the 1 in 100 year storm event at a UK house using a V_{SC} of 2500l.

C8: A range of RWH designs can be adopted to maximize water savings and stormwater control including; passive; active; and real time control RWH systems.

Chapter Two: Literature review of RWH in a UK context.
1) Opportunities, governance, water pricing, energy consumption, water quality, climate change and decision support tools.

Chapter Three: RWH configurations.
A comprehensive review of traditional and novel configurations.

Chapter Four: A RWH Evaluation Method.
Evaluation of RWH configurations for stormwater control and water demand management. Developing a Decision Support Tool.

Chapter Five: Data Collection and Results.
Building the knowledge base: Data collection and analysis for a range of RWH systems.

Chapter Six: Analysis of RWH throughout the UK.
RWH system performance throughout the UK.

C10: RWH with real time control can enable the entire RWH tank volume to function in a water demand management and stormwater control capacity, thus giving optimal benefits under each objective.

Chapter Seven:
Summary, Conclusions and Recommendations for Further Work.

Figure 7.1 – Summary of key conclusions

C1: Stormwater management benefits are under reported and poorly valued in the design and implementation of RWH in the UK.

The literature reviewed in Chapter 2 steered the development of the research completed in this thesis. The conclusions from the review enabled the research objectives for the thesis to be formed. The key value from the literature review was the evidence from emerging literature that stormwater management objectives could offer potential in the overall valuation of a RWH system's performance. In addition the literature review provided evidence of existing research studies and methods which influenced the development of the methods set out in this thesis. Existing literature provided evidence that the quantification of stormwater control benefits is lacking in UK policy and practice. It was concluded that quantification of these benefits is necessary (in parallel with water demand management benefits) to enable a wider, more holistic view of RWH objectives to be included at the design stage. It was hypothesised that such an approach was necessary to enable the dual purpose benefits of RWH systems to be truly valued. Chapter 2 also contributed a new conceptual model to underscore the potential for wide-scale RWH uptake in the context of the UK's climate change adaptation plan. The conceptual model is provided in Figure 7.2 to illustrate the potential for RWH to reduce droughts and floods as part of an increasingly water sensitive design paradigm.

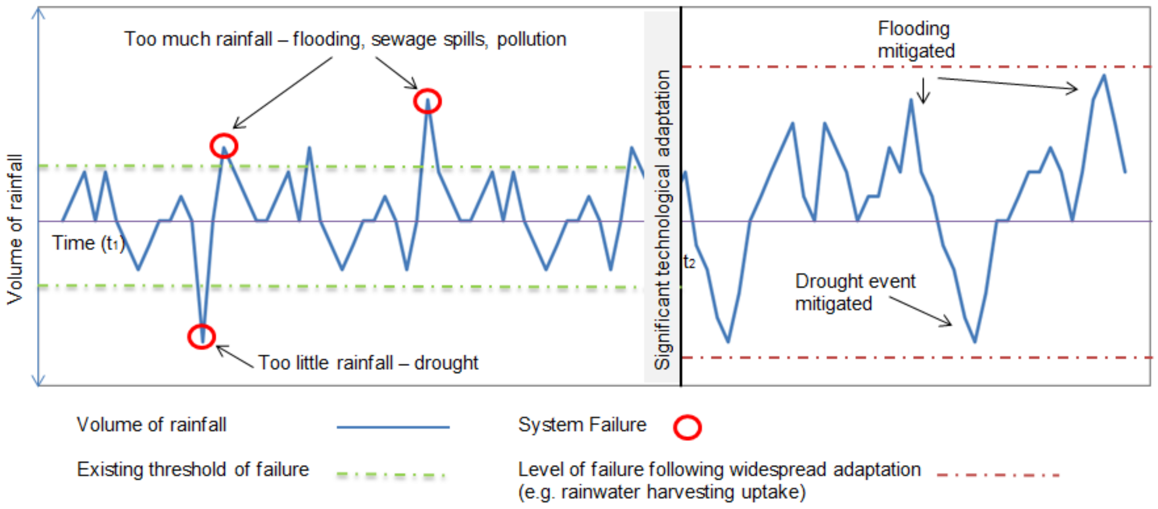


Figure 7.2 – A conceptual model for reduced system failure through implementation of dual purpose RWH as a technological adaptation tool

C2: RWH has a broad set of configurations and can; 1) reduce water use, 2) manage stormwater & 3) be retrofitted.

The literature review of existing RWH systems provided strong evidence that water savings can be generated when suitable RWH systems are installed. However, the work conducted in Chapter 3 concluded that further niches for RWH can be identified. The identification of RWH systems as a multi-functional technology was exemplified in this chapter. The work described a range of novel RWH configurations which are not widely-used in the UK and concluded that those with stormwater management features, or which were easy to retrofit, show potential for application at UK houses. The chapter revealed the opportunity for RWH to be designed to meet more than one objective, and challenged the conventional view that RWH technologies should be seen as “off the shelf” systems.

It was argued that such an approach broadens the decision space and increases the opportunity for RWH systems to have higher benefits and lower whole life costs as illustrated in Figure 7.3.

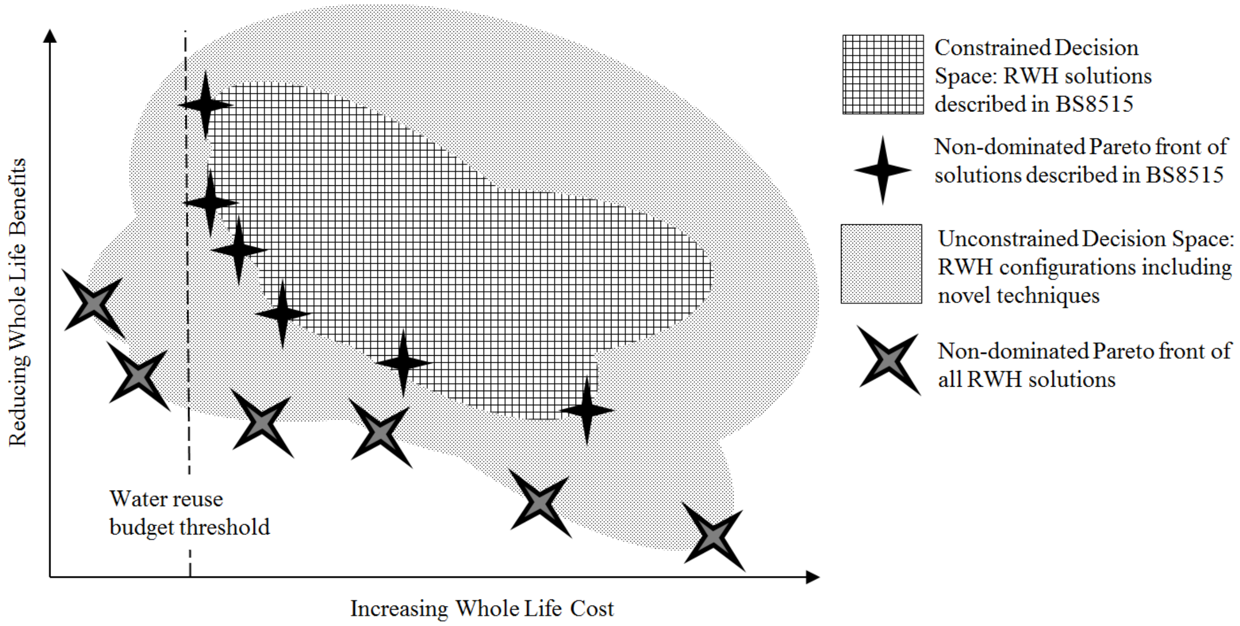


Figure 7.3 – Conceptualising the benefits of novel RWH system configurations (adapted from Coombes, 2002)

C3: The methods set out in this thesis allow RWH to be designed and evaluated using time series rainfall data.

Prior to the development's set out in this thesis, existing UK RWH modelling tools had been developed to investigate single year datasets at a regional scale without focusing on stormwater management benefits (Roebuck, 2008, Fewkes and Butler, 2000). In addition, the modelling tools failed to allow stormwater control devices (e.g. passive release) to be included in the analyses. Chapter 2 included a review of the state of the art for RWH decision support tools to identify key works that could be further developed in the thesis. Existing models described by a set of international researchers were interrogated to inform the development of the RWH Evaluation Method developed in Chapter 4. This Chapter described the development of a new methodology and associated software interface to overcome current limitations. The work made five steps from the current state of the art in the form of original contributions as follows. The methods enable; (1) a range of RWH configurations to be analysed using; (2) high resolution data from; (3) long-term datasets and compared at (4) locations and (5) building typologies throughout the UK.

C4: A decision support tool was developed to enable RWH to be evaluated against water demand and stormwater control benefits.

In order to facilitate the iterative analyses necessary to design or evaluate RWH systems, the methodology described in Chapter 4 was developed into a software tool (The RainWET). This tool was utilised successfully to undertake analyses of RWH systems throughout the UK enabling the conclusions described in Chapter 6 to be derived. Building on existing equations, new methods were defined to enable an extended methodology to be developed and accessed in a decision support interface. Calculation methods from existing studies were extended through the inclusion of new parameters which enable stormwater control benefits to be defined for a range of RWH configurations. New parameters were contributed as follows:

4. $RV_{t.}$. Maximum (Active or Passive) Release Volume for a given time step.
5. $PRVD_t$. Passive Release Volume of Discharge for a given time step.
6. $ARVD_t$. Active Release Volume of Discharge for a given time step.

C5: Small, retrofit RWH (280l) provided >70% of WC demand at a single occupancy house and >15m^3/year in a high demand property.

Chapter 5 described analysis and data collection activities to obtain original data sets associated with traditional and novel RWH systems. The findings from the studies improve our understanding of the true performance of such systems. The FlushRain RWH system was analysed in two laboratory studies and at a further three pilot installations at houses in Exeter, UK. The system stores significantly less water than advised in the British Standard's ((BSI), 2013b) design methods due to its loft-based location. However, the system was found to be straightforward to retrofit and generated savings of 15m^3/year at the best performing location. Furthermore, the largest annual storm event observed at a nearby rain gauge was reduced by 15% at the pilot installation. Mean monthly tank water temperatures were observed in the range of 11.5-20.6^{o}C over 12 months. Where occupancy was low (single occupancy) the tenant satisfied >70% of their WC demand during a yearlong study. The evidence from this study contributes to the supplier's claims that small-scale RWH systems can be retrofitted, whilst generating financial savings (up to £83/year) and also reducing stormwater discharges during intense storm events.

C6: Household rainwater demand at a pilot installation enabled traditional RWH to reduce stormwater discharges by 80%.

The traditional RWH system monitored during the course of this study saw 80% of the rainwater arriving at the tank used in the WC and laundry. The system was located in a relatively wet location (SAAR=1200mm), had a large tank (5,000l) and a household occupancy of 4 people. The ability of traditional RWH systems to significantly reduce stormwater discharges on an annual basis was exemplified by this installation, however, the largest rainfall event of the year was still projected to cause a spill from the RWH tank. The study illustrated the need for RWH to be "intentionally designed" for stormwater control where peak discharge rates from the system are a key design objective.

C7: Dual purpose RWH was designed and installed to capture and control the 1 in 100 year storm event at a UK house using a V_{SC} of 2500l.

The study of a pilot installation which included a 5,000l tank with a source control volume (V_{SC}) of 2500l demonstrated the ability of passive RWH systems to provide water savings and limit peak discharge rates during intense storms. Data loggers at the site were analysed and the largest 30 minute outflow from the tank was reduced by 93% when compared to the inflow rate of the same storm. This evidence, alongside modelling studies associated with the pilot installation supports a conclusion that passive RWH systems can be implemented which capture and control the 1 in 100 year rainfall event from the roofs of UK houses.

C8: A range of RWH designs can be adopted to maximize water savings and stormwater control including; passive; active; and real time control RWH systems. Chapter 6 examined the use of the RWH Evaluation Method to investigate the water demand management and stormwater control characteristics of ten RWH configurations installed a houses located throughout the UK. This represented two original contributions as it (1) included the first UK-wide time series analysis into the deployment of RWH systems, and (2) interrogated the performance of 10 different design configurations. This chapter generated a wide set of conclusions which are summarized as follows:

1. The evidence supported the ability of RWH to be deployed in both high rainfall and low rainfall locations as alternative water supply systems.
2. The mean long-term rainwater yield for a traditional RWH system with a 60m^2 roof feeding a 3,000l tank and 300l/day demand was identified as 43,528l/year when data from across ten UK locations was analysed.
3. Mean long-term rainwater yield from traditional RWH systems (with a 60m^2 roof, 3,000l tank and 300l/day demand) ranged from 31,255l/year in London to 54,627l/year in Truro. These values equate to 14.3% and 24.9% of total household water demand respectively.
4. Average long term rainwater yield for novel loft based RWH technologies with only 450l of storage and 300l/day demand ranged from 26,603l/year in London to 40,698l/year in Truro. These values equate to 12.1% and 18.6% of total household water demand respectively.

5. Small scale RWH systems (480l storage) were found to provide lower yields than traditional systems (3,000l). However, the reduction in yield was limited to 2.2% of total annual water demand in London (driest location) and 6.3% in Truro (wettest location).
6. Small scale RWH systems do not generally satisfy the BS8515 design rule which requires 18 days of mean rainfall to be stored within the RWH tank ((BSI), 2013b). However, evidence from this analysis suggests that the British Standard's arbitrary allowance for 18 days of storage (based on 5 % of the year) may present an unnecessary barrier to the deployment of small scale RWH systems which have been shown to provide significant yields and stormwater control benefits throughout the UK.
7. The traditional RWH system (60m^2 roof, 3,000l tank and 300l/day demand) was found to prevent all discharges in London for the twenty year simulation period. This data could support a policy for RWH to be deployed as the sole source control measure in regions where demand exceeds yield. The analysis supports the findings of other authors that high demand RWH systems can successfully minimise stormwater discharges (Gerolin *et al.* (2010), Kellagher (2011), DeBusk *et al.* (2013)). Furthermore, this configuration was found to reduce discharges to zero for at least one year at every location analysed, including those in wetter regions.
8. Rainfall availability was shown to be a key factor in satisfying rainwater demands. This was exemplified by the small scale RWH system (60m^2 roof, 450l tank, 300l/day demand) which achieved greater yields at seven out of ten locations than the traditional RWH system (60m^2 roof, 3,000l tank, 300l/day demand) achieved in London.

9. Dual purpose RWH systems (with an ability to partially drain down after each storm) were shown to outperform all traditional RWH systems in terms of peak stormwater discharge reduction and annual average stormwater discharges.
10. Real time control RWH systems (with an ability to fully drain down prior to each storm) were able to match or outperform all of the dual purpose RWH systems in terms of peak stormwater discharge reduction and annual average stormwater discharges.
11. High rainwater demand scenarios (e.g. situations where RWH is treated to potable standards and re-used for all potable and non-potable applications) were also found to perform well as stormwater control measures. The peak annual discharge observed from a high rainwater demand scenario (3,000l tank and 600l daily demand) reduced the annual discharges by 97.3% from 76,890l/year to 2,072l/year.

7.3 Recommendations

The following recommendations reflect on the conclusions evidenced in the work completed during the engineering doctorate to set out next steps from both an academic and industrial perspective to build on the research described herein.

R1: RWH Configuration Selection

RWH designers and system providers should consider a wide set of RWH configurations prior to selecting a preferred design. Evidence from the work completed in Chapters 2 and 3 demonstrated that RWH systems in the UK are almost solely designed with below ground tanks and without consideration of the stormwater control potential. A range of RWH configurations were described in Chapter 3 and it is proposed that RWH designers should investigate each of these systems prior to selecting a preferred configuration at a given site.

Recommendation 1: RWH designers should evaluate a wide set of RWH configurations prior to selecting a preferred design.

R2: Utilising time series analysis for site-specific RWH design

The work conducted in Chapters 4 and 6 of this thesis sets out and tests a method for a long-term (20 years) time series analysis method to enable water demand management benefits to be more accurately interrogated. Evidence from this tool showed that traditional RWH systems at a house in London can fully mitigate stormwater discharges.

Recommendation 2: Detailed time series simulations can be completed using site specific demand and rainfall data when deriving design estimates pertaining to the long term water saving / stormwater control benefits of RWH systems.

R3: Small scale RWH can be effective as AWRs

Historically RWH systems have focussed on “full-scale” RWH systems being designed that satisfy BS8515’s design methods ((BSI), 2013b). The laboratory and site monitoring studies completed in this thesis showed small scale RWH systems such as the FlushRain configuration (280l functional storage) have strong ability to provide alternative water resources (15m^3/annum from the site monitoring data). However, they typically fail to satisfy the “18 day storage requirement” set out in BS8515 and consequently. It is recommended that future revisions to BS8515 recognise the opportunity posed by small RWH systems, even where they fail to provide 95% of the non-potable water demand for a given site. Evidence from the UK wide modelling study also showed that small-scale (450l) RWH systems installed in wet regions (Truro) performed better (in terms of providing non-potable water supplies) than large-scale (3,000l) RWH systems installed in dry regions (London).

Recommendation 4: Design requirements in BS8515 could be relaxed to allow small-scale RWH systems which fail to achieve 18 days of storage to be promoted when appropriate. Design methods should focus on whole life benefit and value stormwater management alongside rainwater demand metrics.

R5: Designing for stormwater control using dual purpose RWH configurations

Historically, RWH systems were not acknowledged as stormwater control systems as they are conservatively assumed to be full when the design storm event occurs. However, work conducted in this thesis demonstrated that there are a range of RWH configurations which can be effective as source control measures:

Traditional RWH: Evidence from Chapter 6 illustrated that the passive attenuation achieved simply by relying on demand to free space within the RWH tank can be highly effective in regions with low rainfall (e.g. London where the traditional 3,000l RWH system was simulated with zero overflow spills over a 20 year simulation).

Passive discharge control: Dual purpose RWH configurations with small orifices (5-10mm) located below a source control zone were described in Chapters 2 and 3, and evaluated in Chapters 5.4 and 6. Evidence from literature, hydraulic modelling simulations and the UK wide simulation outputs included in Chapter 6 all demonstrate the ability of dual purpose RWH systems to capture and attenuate storm events up to the 1 in 100 year design event. Further work investigating the real world performance of such systems should focus on the ability of rainwater downpipes and filters to successfully deliver rainwater to the storage tanks during intense rainfall events. Monitoring studies are now warranted to investigate their performance in a real world setting.

Active discharge control: Actively controlled systems which drain a source control volume from the tank on a regular basis were demonstrated to perform well as dual purpose RWH systems which can capture and attenuate storm events up to the 1 in 100 year design event.

Smart RWH: RWH systems with real time control systems that can fully drain prior to a storm were found to offer the strongest ability to capture rainwater for given RWH tank size. Monitoring studies are now warranted to investigate their performance in real world settings.

Recommendation 5: The design of RWH systems should include stormwater management features to reduce rainwater runoff (volumes and rates) entering downstream drainage systems. In the absence of existing design thresholds, such systems could be designed to match the current design guidance for soakaway systems i.e. to control the 1 in 10 year storm event (BRE, 2007).

Further work could be undertaken to optimally define the level of service from such devices. Such systems also show potential for retrofit as stormwater management solutions within SuDS retrofit schemes.

R6: Review of terminology describing RWH technologies

The literature reviewed in Chapter 2 demonstrated the use of the term “RWH” has a wide range of meanings. Through the work completed in this thesis, the term “dual purpose rainwater harvesting” was assigned to RWH systems which include stormwater management features. It is proposed that further clarification of terminology is needed.

Recommendation 6. A sub-group of installations can be defined under the heading “rainwater management systems (RMS)”. It is proposed that future research relating to plot-scale RMS could use the nomenclature set out in Figure 7.4 and the terms RMS and Rainwater Control Systems (RCS) can be introduced to future studies. In the proposed hierarchy of RMS; RWH systems focus on rainwater yields; dual purpose RWH seek to balance rainwater use and rainwater control; whilst RCS seek to solely achieve plot scale rainwater control.

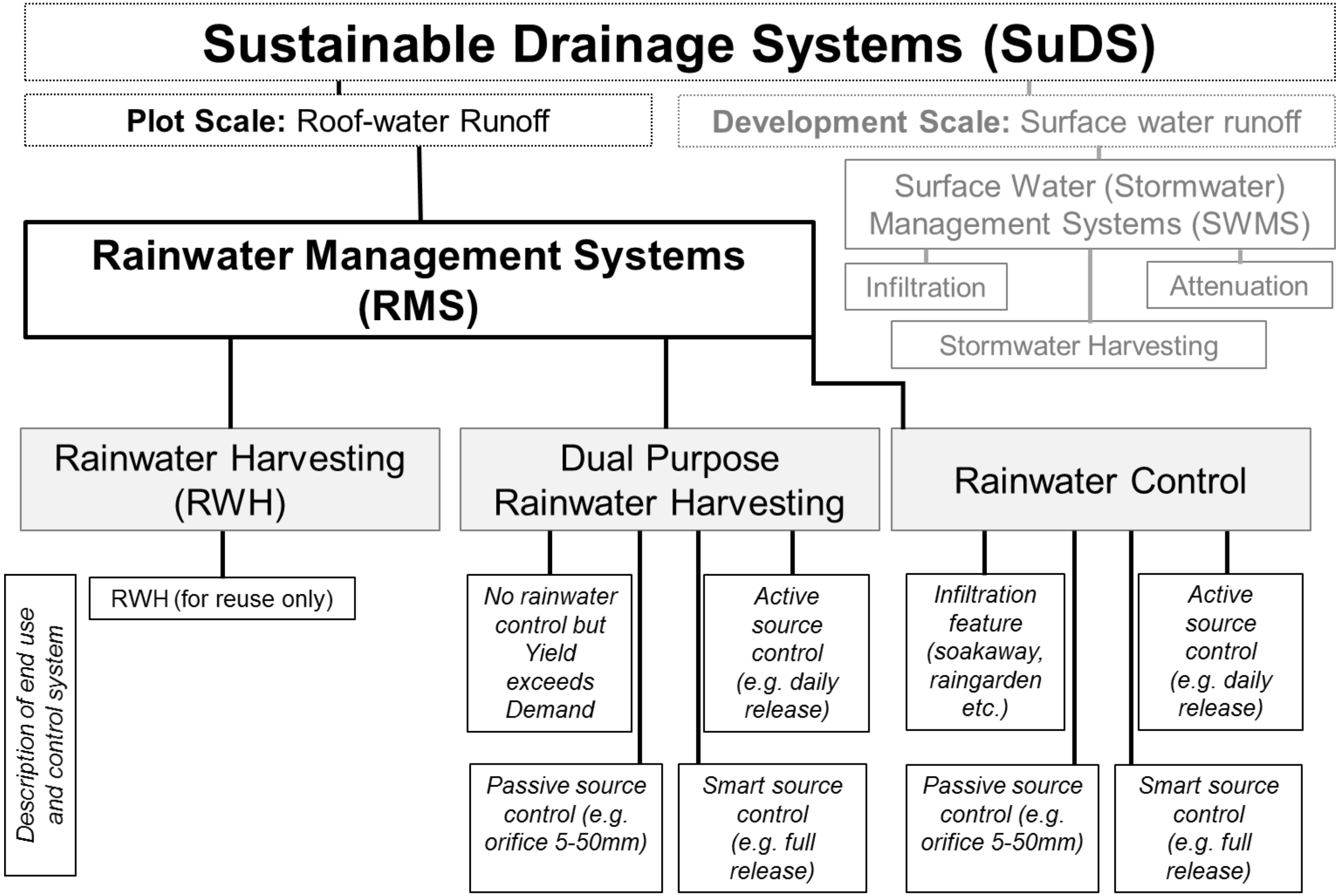


Figure 7.4 – Proposed nomenclature for Rainwater Management Systems (RMS)

R7. The design of RMS should take into account the opportunity for dual purpose benefits before a single purpose (e.g. RWH system or RCS) is selected

The evidence provided by the nationwide analysis of RWH systems as dual purpose assets has demonstrated that multiple benefits can be achieved. Designers should take these into account when developing alternative water resources and SuDS strategies.

Recommendation 7. Where appropriate, RMS should be designed to manage rainwater under the dual design goals of: 1) maximise non-potable water use and 2) minimise downstream discharges (in terms of peak rates and total volumes).

R8. Smart RMS

Further work is necessary to investigate the effectiveness of smart RMSs configured with real time controls. The field shows great promise for both research and industrial application.

Recommendation 8. Further research activities are needed to investigate the costs and benefits of smart RMS. In addition, pilot installations should be completed and monitored to investigate the opportunity posed by smart RMS. Evidence from such work may be beneficial to inform updates to design standards applied to UK drainage design. It is suggested that Sewers for Adoption, the SuDS Manual, Building Regulations Part H and wider drainage guidance documents will need to recognise the opportunity for smart RMS to manage stormwater using real time controls. For example at small residential developments, discharge rates during the 1 in 100 year rainfall event are frequently limited to 5l/s (as this represents a feasible design for current passive control technology e.g. vortex flow controls). Such designs can result in SuDS which are designed to operate (on average) once every 100 years. It is suggested that a revised design criteria based on the following could be developed to enable uptake of smart RMS:

1) Zero rainfall discharge to downstream systems during days with storms up to the 1 in 10 year rainfall event.

2) Uncontrolled discharge on days without rainfall (subject to local catchment characteristics).

3) Intentional discharges to irrigation fields and watercourses to support environmental water demands during dry weather periods.

R10: Gathering datasets and evidence

RMS should be installed and monitored to develop a long term understanding of their performance. Little evidence has been identified which illustrates the long-term performance of RWH and RC systems in a real world setting. Plot scale RMS show great promise in supporting a shift towards source control being retrofitted within catchments and further research studies are needed to interrogate their performance and maintenance needs.

Recommendation 10: RWH standards and SuDS standards should support and encourage monitoring and data collection as part of the operational phase of RMS deployment. Research communities should collaborate with system providers to maximise monitoring of RMS to support improved design and deployment of these technologies whilst developing further understanding of economic models for installation.

R11: RMS performance in a changing climate

A key feature of the work conducted in this thesis was to utilise site specific rainfall data to drive simulations (i.e. historic performance analyses). However, a key limitation to this approach is the unpredictable nature of future rainfall patterns. Updated climate change projections will be available from UKCP18 in 2018.

Recommendation 11: Further modelling of the performance of RMS investigated in this thesis should be completed using the RainWET to provide whole life benefit assessments using high resolution data available from the forthcoming UKCP18 project.

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