Rainwater harvesting

An investigation into the potential for rainwater harvesting in Bradford

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Summary

This report provides a brief review of rainwater harvesting and rainwater harvesting tools, which are then used in case study examples for domestic, office block and warehouse rain water harvesting scenarios.

Rainwater harvesting is placed in an historical context as a source of water supply and in a modern context as being complementary to centralised water distribution networks with benefits for wider water management including flood risk treatment as well as providing environmental and economic benefits.

A range of readily available rainwater harvesting tools are presented and compared using data supplied by the City of Bradford Metropolitan District Council (CBMDC). Rainwater harvesting is discussed in the context of applicable British Standards, from which formula for assessing rainwater harvesting potential and requirements, such as maximum storage tank sizes, are given.

Using data from 2008 to 2010 and provided by CBMDC, case study examples are given for rainwater harvesting potential and reductions in rainfall run-off volumes. These include city centre office blocks, domestic properties and estates, and large commercial warehouses:

Offices in Bradford are assessed for water demand and rainwater harvesting potential using the 'RainCycle' rainwater harvesting tool. The report identifies that whilst reducing demand at source the most effective way of reducing water use, rainwater harvesting can also contribute to reductions in water demand and rainfall run-off even from office buildings with low roof area to occupancy ratios.

The report considers rainwater harvesting from individual domestic properties and from a small urban estate using rainfall data, roof area data and alternative methods of determining dwelling occupancy numbers (occupants verses roof area and statistical occupant numbers). Using roof yield coefficients identified in literature and acknowledging the difficulties in determining occupancy numbers (and therefore water demand), the report notes that individual domestic properties can contribute to surface water management though reducing rainfall run-off via rainwater harvesting. This potential is increased as greater numbers of domestic dwellings use rainwater harvesting.

Using the same simplistic method of determining rainwater harvesting potential, the report considers rainwater harvesting from large, warehouse-type buildings, firstly by only considering available rainfall collected from a large warehouse, and secondly in considering a large warehouse with comparatively low occupancy rates but high water demand (through vehicle maintenance). Both example detail volumes of rainfall that could be captured, thus reducing run-off, whilst the second example also details potential reductions in mains supplied water through comparing mains water supply volumes with potential volumes of harvested rainwater.

As an illustrative example, the report considers the potential for reducing rainfall run-off from a city centre area, and therefore contributing to flood management, should all roof areas be connected to a rainwater harvesting system and disconnected from urban drainage systems. This illustration details the potential volumes of rainfall that could be collected from roofs within a two kilometre square city centre area, detailing an approximate reduction in run-off of 23%. This compensates for the anticipated increase in runoff that will be generated by climate change by the end of the 21st Century.

The report briefly discusses and gives examples of the potential benefits associated with rainwater harvesting (reduced energy costs associated with unnecessary cleaning and transporting of potable water supplies, increased capacity in drainage networks, less water abstraction, and potentially reduced demand for reservoir capacity) and uses for harvested rainwater (vehicle and road gully cleaning, urban irrigation schemes, toilet flushing and industrial cleaning operations). Additional benefits include urban flood management and less tangible benefits to the wider environment such as groundwater recharge and reduced water abstraction from rivers.

Constraints on rainwater harvesting such as cost factors and uncertainty of economic gains are noted along with uptake by businesses and the public. The report concludes that rainwater harvesting has potential for non-potable water use and wider water management through reductions in run-off, particularly so if implemented within urban areas and on a larger, city wide scale, but that this is unlikely to happen unless an appropriate degree of leadership and coordination is provided.

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Contents

1 Introduction

In light of increasing energy and water treatment costs, the supply and use of potable water to flush toilets, wash cars and undertake laundry is becoming less tenable as an effective use of resources and finances. Increasing water use is also placing demands and constraints on the natural environment as water resources become depleted (Anand and Apul, 2011; Li *et al*., 2010). In parallel with this, the need to better manage rainfall and surface flows with respect to flood risk have taken on a new impetus following recent, severe flood incidents within the UK and worldwide. In these contexts, rainwater harvesting (RWH) offers potential as a means to reduce the demand for potable water in non-consumptive use. Potential benefits associated with this include reduced energy consumption and emissions associated with unnecessarily purifying and pumping water and reduced requirements to abstract water from rivers and aquifers, thereby compensating for anticipated demographic changes and benefiting the wider environment. Additionally, RWH has the potential to assist in attenuating and reducing rainfall flows to drains and water courses, thereby reducing flood risk associated with surface runoff. Although not without costs and requiring careful consideration with regards installation, maintenance and potential contamination issues, RWH is one of a suite of tools that together could provide improved water management in the context of increasing urbanisation and predicted, climate change related variations in rainfall patterns.

Using case study examples for domestic, office block and warehouse rain water harvesting scenarios, this report considers the potential of RWH as a means to reduce potable water consumption whilst potentially contributing to flood risk management within Bradford.

1.1 Project Aim;

To investigate the potential benefits of rainwater harvesting from roof surfaces for property owners, flood risk managers, local authorities and water supply organisations.

1.2 Project Objectives

1. To investigate and identify the individual and joint benefits of rainwater harvesting from an office block roof to;
    a. the building owner
    b. local flood risk managers
2. To upscale and assess the findings with respect to a city centre area.
3. To investigate and identify the individual and joint benefits of rainwater harvesting from a domestic building to:
    a. the building owner
    b. local flood risk managers
4. To upscale and assess the findings to city scale.
5. To investigate the benefits of rainwater harvesting from a large warehouse for ground maintenance and street, gulley and sewer cleaning etc.
6. To upscale the findings to city scale
7. To assess the potential benefits in meeting future water demand at city scale

2 Background and review

The comparative 'newness' in a UK context of RWH as a parallel and alternative to centralised water supplies gives rise to uncertainty as to its application, benefits and constraints; there is little historical information with which to inform decision making. Given the fine balance that often exists in deciding on economic grounds alone whether a project is viable or not, the uncertainty of costs and savings associated with RWH compared to more predictable costs of mains supplied water make it difficult to justify RWH installation. This is compounded by demand and rainfall variations; modern society has come to rely on 'on-demand' water supplies, and is unlikely to tolerate breaks in supply. Given this context of 'limitless' water supply, a review of rainwater harvesting and its potential within current water management issues was undertaken, including reviewing British Standards for rainwater harvesting. Internet-based rainwater harvesting tools were investigated and used for comparative purposes to give an indication of rainwater harvesting potential.

Rainwater harvesting is not a new idea. Practised by ancient civilisations before the development of centralised water distribution network in more recent periods, RWH is still widely used in more remote and arid areas of the world such as Australia and Africa. In its simplest form consisting of a surface to catch rainfall on and a container to store rainwater in, RWH is increasingly presented as an alternative, decentralised water supply in more water-stressed regions of the world. In this respect 'water-stressed regions' include more temperate locations where water stress is caused by demand exceeding supply rather than an absence of water, be it rainfall, ground water, riverine or otherwise. In such locations, water security is an increasing concern. Additionally, RWH has gained increased public awareness worldwide in line with increased environmental awareness and rising water costs for the consumer (Farreny *et al*., 2011; Domènech and Saurí, 2011).

The increased interest in environmental concerns within the public has been mirrored within national and international legislation. With respect to water and water management, the preeminent legislation aimed at protecting water resources and governing water management within the European Union are the Water Framework Directive (2000/60/EC) and the Floods Directive (2007/60/EC). These Directives place greater responsibilities on European Union countries to manage their water resources in a responsible, sustainable manner.

Following the transposition of the Water Framework Directive (2000/60/EC) and the Floods Directive (2007/60/EC) into UK legislation, increased responsibility for water management has been placed on local authorities and the Environment Agency. In addition to aspects such as pollution and water quality control, the management of water to prevent, reduce and manage flood risk forms a central component of local authority and Environment Agency work. With respect to local authorities and their responsibility for ordinary and smaller water courses, historical legacies associated with culverted water courses and uncharted drainage networks complicate an already complicated system of water management. This is particularly so in urban areas where many miles of often unidentified drains interconnect and ultimately flow into watercourses that may be unable to accommodate increases in water flow.

Combined with surface flow over impermeable urban surfaces, increased urbanisation and more rapid drainage into urban watercourses have resulted in flooding with often severe impacts for those flooded. Given that rainfall and urbanisation are expected to increase following climate change and population increases respectively, it is likely that flood risk will also increase (Lhomme *et al*., 2010). Considering these factors, drainage systems that attenuate and or allow water to drain and disperse more naturally have taken on a greater impetus as a method of managing rainfall and surface water flows. Frequently grouped under the collective banners of SUDS (Sustainable Urban Drainage Systems) or LID (Low Impact Development), such drainage systems are being increasingly used worldwide as a means of attenuating rainfall and surface water flows (Heal *et al*., 2009). This has the potential to not only reduce flood risk, but also allow the infiltration of water into the ground in a more natural manner with benefits for the wider environment. Given its rainfall attenuation potential, RWH could contribute to water and flood management through reducing peak flows following rainfall (ARUP, 2011).

In addition to flood risk reduction, increasing costs in treating and supplying potable water have encouraged the consideration of rainwater as a source of non-potable water supply. Such water can be used for watering gardens, washing cars, toilet flushing and laundry (Environment Agency, 2010). In doing so, potable water treatment and supply costs are reduced, along with associated carbon emissions. Additionally and important for water-stressed regions, the use of rainwater for non-potable use may lead to less extraction from dwindling ground water supplies and rivers already at risk from low water levels. Concurrently, the capture of rainwater may also counter the demand for new reservoir supply capacity associated with changes in annual rainfall patterns and predicted climate change, and increased demand associated with growing populations. Although there are issues associated with contamination and pollutants within harvested rainfall (Ahmed *et al*., 2010; Lye, 2009), there is limited evidence from the UK on pathogen levels within harvested rainwater (ARUP, 2011).

Rainwater harvesting therefore has the potential to reduce the energy demand associated with treating and distributing potable water, to reduce consumer costs and also contribute to flood risk management. Countering these benefits are factors such as installation and maintenance costs, size and placement of storage tanks, filtering and treating rainwater, energy used to pump stored water to outlets in non-gravity fed systems, and the risks of illness caused by contamination of potable water supplies through incorrectly installed and poorly maintained RWH systems.

2.1 Rainwater harvesting tools

Depending on requirements and intent (e.g. water supply and/or flood mitigation), available rainfall and storage space, the potential gains of rainwater harvesting should be compared with cost factors, short and long-term, and expected demand. It may be that demand sufficiently outstrips rain water supply that installing a RWH system is not worthwhile on economic grounds relative to water supply costs. Installing a RWH system for water attenuation and flood control may, however, offer benefits in addition to supply cost savings.

Determining the benefits or otherwise of rainwater harvesting is difficult. The variables in equipment, installation and maintenance costs are more easily quantified, where as future demand, rainfall volumes and long-term maintenance costs are much more difficult to determine. Numerous internet-based tools are available that provide information on potential water use from RWH systems. These range from tools that are aimed at capturing rainwater for growing crops to meet growing demand for food, to tools designed to illustrate the cost savings of RWH systems in domestic situations.

Using algorithms to calculate water use and water saved, such tools use inputs such as building occupancy numbers, annual rainfall, roof area and roof type to calculate rainfall collected, water demand and potential savings. As these tools are often used by companies in the business of selling RWH equipment, optimum storage tanks sizes are often given. Using data applicable to a typical, multi-story office block located in Bradford, UK, and associated rainfall data sourced from local authority operated rainfall gauges, Table 1 details examples of simple, internet-sourced RWH tools and their outputs with respect to rainfall collected.

Table 1; Examples of simple rainwater harvesting tool output

<table>
<tr><th>RWH tool</th><th>Roof area m^2</th><th>Rainfall mm</th><th colspan="2">Roof yield coefficient/roof type</th><th>Water collected/yield (m^3)</th></tr>
<tr><td>Save-the-rain.com[i]</td><td>1321.8</td><td>900[*]</td><td colspan="2">Not required</td><td>1189.6</td></tr>
<tr><td>Waterscan[ii]</td><td>1353</td><td>Not required[**]</td><td colspan="2">Flat roof</td><td>690.9</td></tr>
<tr><td>AJ Design Software[iii]</td><td>1353</td><td>775[+]</td><td colspan="2">60%</td><td>629.1</td></tr>
<tr><td>harvestyourrain.com[iv]</td><td>1353</td><td>775[+]</td><td colspan="2">60%</td><td>629.1</td></tr>
<tr><td colspan="6">Bradford average annual rainfall 1911 - 2010; 868mm[v]</td></tr>
<tr><td colspan="3">Source (accessed 20/1/2012);
[i]www.save-the-rain.com/world-bank
[ii]http://www.waterscan.com/rainwater-calculator.asp?page=1
[iii]http://www.ajdesigner.com/phprainwaterharvest/rain_fall_harvest.php</td><td colspan="3">[iv]http://www.harvestyourrain.com/calc.htm
[*]determined by Save-the-rain.com RWH tool
[**]Believed to be around 850mm/yr through comparisons with AJ Design & harvestyourain.com output @ 850mm/yr
[+]Rainfall data supplied by City of Bradford Metropolitan District Council. Mean average 2008 - 2010 rainfall data</td></tr>
<tr><td colspan="6">[v]Rain gauge location; Lister Park, Bradford. Source; Met Office.
http://www.metoffice.gov.uk/climate/uk/stationdata/bradforddata.txt Accessed 3/11/2011</td></tr>
</table>

2.2 Rainfall harvesting & British Standards

RWH systems must comply with British Standard 8515 2009. This includes storage tank sizes, which must not be oversize due to the risk of bacterial infection (e.g. Legionnaires Disease). To ensure sufficient use of stored water to reduce the likelihood of bacterial infection, the size of rainwater harvesting tanks is limited to the lower capacity of either 5% of annual rainwater yield, or 5% of annual rainwater demand, i.e. whichever is the least.

BS 8515 2009 (BSI, 2009) provides three approaches for determining rainwater yield and storage tank sizes. It is also noted that calculations for residential properties will differ from those for larger, commercial properties. The latter will require more detailed calculations to ensure cost effectiveness and regular use of stored water to account for potential greater variations in use than within domestic systems.

For smaller and simpler RWH systems, calculations for annual rainfall yield can be calculated by;

$$Y_R = A \times e \times h \times \eta \times 0.05$$

Y_R = annual rainwater yield (l)

A = collecting or roof area (m2)

e = yield coefficient (%)

h = annual rainfall (mm)

η = hydraulic filter efficiency (if filter used)

Similarly, annual demand for non-potable water can be calculated by;

$$D_N = P_D \times n \times 365 \times 0.05$$

D_N = annual non-potable water demand

P_D = daily requirement per person

n = number of persons

(BSI, 2009)

For the office block example detailed in Table 1, and excluding any hydraulic filter efficiency, a simplistic annual rainfall yield equates to;

@ 775mm/yr $\quad$ 1353 x 0.6 x 775 = 629.1m^3

@ 850mm/yr $\quad$ 1353 x 0.6 x 850 = 690.0m^3

(Note, the roof collection coefficient, or yield coefficient, will vary depending on roof material and roof slope. 0.6 equates to the roof collection coefficient for a smooth, flat roof (SUDS Solutions, 2005) frequently found on multi-story office blocks and as used in this example).

The figures of 629.1m^3 and 690.0m^{3}compare with those detailed in Table 1 as determined via internet-sourced RWH tools. However, the simplistic nature of the calculations and RWW tools detailed in Table 1,along with Codes of Practice within BS 8515 2009, necessitate a more detailed approach to RWH for commercial buildings. This is to account fully for the size of the building, its commercial use and occupancy numbers. Such an approach is given by the RainCycle RWH tool (SUDS Solutions, 2005). This tool allows a wide range of data to be input, and thus outputs can be tailored to suit large, commercial buildings.

3 Case studies and examples

3.1 Case study 1: the city centre office block

3.1.1 Methodology

Case Study 1 considers the potential benefits of rainwater harvesting for an office block in the centre of the City of Bradford (Jacobs Well; See Figure 3). To achieve this, the following data was required and has been supplied by the City of Bradford MDC;

- Rainfall data (2008 - 2010).
- Building occupancy numbers (2008 - 2011)
- Water demand and costs (2008 - 2009)

This data was refined to account for incomplete annual datasets and data discrepancies.

The RainCycle RWH tool was used to assess rainwater harvesting potential of the case study office block. Using data supplied by CBMDC, the operation of this tool and its outputs (costs, water demand met, optimum storage tank sizes etc.) are discussed in the Appendices and compared to the output of a simple, Excel based volume-balance spreadsheet. The Appendices also detail issues associated with the use of average rainfall data, along with roof yield coefficients and their effect on potential run-off collected.

3.1.2 Results; Jacobs Well RWH

Table 2,

Table 3 and Table 4 detail the output results for RWH from Jacobs Well using the RainCycle RWH tool. Full results are detailed in the Appendices.

It should be noted that the toilet cisterns within Jacobs Well have recently been reduced from 13.5 litre capacity to 6 litre capacity. This clearly has an impact on water demand. Comparative tables illustrating the difference this has made to water demand and RWH potential are provided in the Appendices.

Table 2; RWH system performance

Annual performance of Jacobs Well RWH system	
Using 6 litre cisterns	
Rainfall to storage tank	567m^3/yr
Storage tank overflow	8m^3/yr
Number of overflows	7 per year
Water demand (urinals & toilets only)	1,875^{3}m/yr
Water supplied by RWH	557m^3/yr
Demand met by RWH	29.7%
Mains top-up required	1,319m^3/yr

Table 3; Water costs

	6 litre cisterns
Average cost of mains water per m^3	£1.21
Average cost of harvested water per m^3	£0.93

Table 4; RWH savings and pay-back periods

RainCycle Optimise Savings output					
Storage tank size; 10,000 litres. Capital costs; £7,337(All prices are 2010 prices) *Analysis runtime; 50 years. Does not include any maintenance schedule* *Gravity fed supply - no pump costs.* *6 litre cisterns; Mains water cost @ £1.21m³. Demand 1875m³/year*					
Cistern capacity	**Savings over 50 years**		**Pay-back period (years)**		**Demand met (%)**
	0% Discount Rate	3% Discount rate[1]	0% Discount Rate	3% Discount rate[4]	
6 litre	£26,250	£10,465	11	13	29.7

Discussed further in the Appendices, the results detailed illustrate that around 30% of water demand could be met through rainwater harvesting for the Jacobs Well office block. Although installation and maintenance costs require considering, savings on water bills have been identified. Additionally, RWH would provide a modest reduction in run-off from the office block, with benefits for surface water and flood risk management.

3.2 Case Study 2: Rainwater harvesting from domestic buildings - individual dwellings

Domestic buildings provide opportunity for individual householders to install RWH systems, although the uptake of this will greatly depend on financial demands, occupancy type (owner occupied, private or public sector rented) and house type (detached/semi-detached, terrace, flat), some house types being more suited to RWH than others. Whilst it is possible to fit RWH harvesting systems to older houses, it is perhaps new-build houses that will RWH will become predominate, particularly if planning conditions stipulate run-off limitations from development sites; RWH could be used to meet such planning conditions.

[1] The Green Book. (TSO, 2011).

In considering new-build properties, additional factors come into play which negate previously used assumptions with respect to domestic water demand and building roof areas. Firstly, modern domestic appliances, candidates for using non-potable water from RWH, use less water than previous generation of appliances. Secondly, building regulations limit the capacity of newly installed toilet cisterns to 6 litres maximum (TSO, 1999). Thirdly, trends towards greater housing density, including flats and three story houses, potentially give a greater occupancy to roof area ratio thereby affecting the mains water/RWH supply ratio (although there is no direct link between roof area and occupancy numbers). Consequently, whilst modern appliances reduce water demand, new-build properties are likely to have reduced roof areas and therefore reduced catchment areas (Wallingford, 2011; Roebuck, 2007).

3.2.1 Methodology and results

In considering factors discussed above and using occupancy versus roof area data detailed in Roebuck (2007), Table 5 and Table 6 detail household, non-potable water consumption data, potential RWH volumes and reductions in run-off. Non-potable water consumption data is limited to toilet and washing machine use only. Examples are given using both SUDS Solutions (2005) and Wallingford (2011) run-off loss coefficient methodology[2]. Additional information and examples are provided in the Appendices (TableA3.1 and Table A3.2).

Table 5; Occupancy numbers, roof area, RWH potential and non-potable consumption volumes

Number of household occupants	Average roof area (m^2)	Available annual rainfall (m^3) after losses				Annual household non-potable consumption (m3)
		Using Wallingford (2011) loss methodology	Using SUDS Solutions (2005) yield coefficients			
			High	Expected	Low	
1	57	32.0	35.8	33.8	29.8	14.6
2	76	42.7	47.7	45.1	39.7	29.2
3	69	38.8	43.3	40.9	36.1	43.8
4	76	42.7	47.7	45.1	39.7	58.4
5	72	40.5	45.2	42.7	37.7	73
		Available rainfall; 562mm/year	Available rainfall; 628mm/ year	Available rainfall; 593mm/year	Available rainfall; 523mm/ye ar	Non-potable consumption; 40 litres/person/day
Rainfall data based on 775mm/year total rainfall (CBMDC data, 2008 - 2010 annual average). Occupancy and roof area data; Roebuck, 2007. Non-potable water consumption; toilet and washing machine use only, (Wallingford, 2011). Dwelling roof types presumed to be pitched roof using concrete roofing tiles; 93% of English dwellings have pitched roofs, with roof tiles being predominantly of concrete manufacture. Regional and local variations exist in						

[2]See Roebuck (2007) for further discussion on the methodology used for determining occupancy versus roof area data. Additionally and in following Roebuck (2007), calculations are undertaken using whole occupancy numbers, rather than fractional numbers. Non-potable water consumption data is based on modern, water efficient household appliances as detailed in Wallingford (2011).

construction types and materials (DCLG. (2010). English Housing Survey). See Table for details of loss and yield coefficients. DOES NOT ACCOUNT FOR SPILLAGE FROM FULL RWH STORAGE TANKS.

Table 6; RWH and reductions in run-off compared to occupancy numbers and roof areas

Number of household occupants	Average roof area (m^2)	Percentage reduction in run-off using RWH for non potable, domestic use				Annual household non-potable consumption (m3)
		Using Wallingford (2011) loss methodology	Using SUDS Solutions (2005) yield coefficients			
			High	Expected	Low	
1	57	46%	41%	43%	49%	14.6
2	76	68%	61%	65%	73%	29.2
3	69	Demand exceeds supply (113%)	101%	Demand exceeds supply (107%)	Demand exceeds supply (121%)	43.8
4	76	Demand exceeds supply (137%)	Demand exceeds supply (122%)	Demand exceeds supply (130%)	Demand exceeds supply (147%)	58.4
5	72	Demand exceeds supply (180%)	Demand exceeds supply (161%)	Demand exceeds supply (171%)	Demand exceeds supply (194%)	73

Occupancy and roof area data; Roebuck, 2007.

Non-potable water consumption; toilet and washing machine use only, (Wallingford, 2011).

See Table for details of loss and yield coefficients.

DOES NOT ACCOUNT FOR SPILLAGE FROM FULL RWH STORAGE TANKS.

The values detailed in Table 5 and Table 6 are indications only of RWH and potential reductions in run-off. Whether using whole or fractional occupancy numbers (Roebuck, 2007 and Wallingford, 2011, respectively) in calculations, there is little correlation between roof area and occupancy numbers. Wallingford notes that the majority of UK dwellings, 90%, comprise of two to four bedroom houses, with approximately half of houses in a given estate being three bedrooms. Few one bedroom houses are built. However, bedroom numbers do not necessarily relate to occupancy numbers, thus assumptions and categorisations are necessary. Additionally, the timing and duration of rainfall in conjunction with the timing of occupancy and demand will also affect the volume of rainwater that can be stored. Whilst these caveats introduce uncertainty into calculations of RWH and run-off reductions, nonetheless the potential of RWH from domestic properties is demonstrated, and thus the contributions of domestic dwellings to surface water and flood management are also demonstrated.

3.3 Case study 3: Example of RWH from a housing estate

Whereas Roebuck (2007) used whole occupancy numbers linked to average roof areas in calculations, Wallingford (2011) use dwelling bedroom numbers and statistical occupancy rates, i.e. fractional occupancy numbers. Both methodologies contain generalisations as actual occupancy rates are difficult to obtain. As an alternative to Roebucks approach, the following example uses statistical, fractional occupancy numbers as identified in Wallingford (2011).

3.3.1 Methodology

A discrete housing estate within the CBMDC area was chosen using ArcMap GIS. The estate in question contains 35 dwellings, has one entry and exit road and is 'contained' within its own development boundaries (Figure 1).

Figure 1; Example housing estate for RWH; Google image (left), OS MasterMap (right)

Using ArcMap, roof areas of the dwellings was established (stand-alone garages, sheds and greenhouses were excluded from the analysis). It was assumed that the dwellings were two to four bedroom houses, with the greater proportion (approximately 50%) being three bedroom (Wallingford, 2011). The remainder were split between two and four bedroom dwellings. Occupancy numbers were set at statistical rates identified by Wallingford (2011).

Occupancy rates;

Two bedroom (8 dwellings); 1.74 occupants (13.92 occupants)

Three bedroom (18 dwellings); 2.41 occupants (43.38 occupants)

Four bedroom (9 dwellings); 3.02 occupants (27.18 occupants)

Total number of occupants for all 35 dwellings; 84.48

Non-potable water consumption (toilets and washing machines) was deemed 40 litres/person/day, as identified in Wallingford (2011). Non-potable water demand for all 35 dwellings totalled 3,379 litres per day, equating to 1,233m^3/year.

Total roof area for all dwellings; 2,844m^2, which represents 21% of the total area within the development

Following the 2008 English housing stock report, roof type was presumed pitched with concrete tiles (DCLG, 2010).

Rainfall before losses was set at 775mm/year, using CBMDC data.

3.3.2 Results

Using rainfall, roof area and non-potable water demand data, potential reductions in run-off were calculated. This was done using both Wallingford (2011) and SUDS Solutions (2005) roof yield coefficients. Table 7 details volumes of available rainfall after accounting for losses.

Table 8 details reductions in run-off following RWH. As the roof area form 21% of the total area of the estate, the expected yield reduces the total possible runoff by some 15%, assuming total saturation of gardens, and the reduction of rapid runoff is even greater

Table 7; Example housing estate - available rainfall volumes after accounting for losses

Total housing estate roof area (m^2)	Annual rainfall falling on roof areas before losses (m^3)	Available annual rainfall (m^3) after losses			
		Using Wallingford (2011) loss methodology	Using SUDS Solutions (2005) yield coefficients		
			High	Expected	Low
2,844	2,204.1	1,598	1,786	1,686	1,487
		Available rainfall; 562mm/year	Available rainfall; 628mm/year	Available rainfall; 593mm/year	Available rainfall; 523mm/year
Rainfall data based on 775mm/year total rainfall (CBMDC data, 2008 - 2010 annual average). Dwelling roof types presumed pitched roof using concrete roofing tiles; 93% of English dwellings have pitched roofs. Roof tiles predominantly of concrete manufacture (DCLG, 2010. English Housing Survey. Housing Stock Report 2008). See Table for details of loss and yield coefficients. DOES NOT ACCOUNT FOR SPILLAGE FROM FULL RWH STORAGE TANKS.					

Table 8; Example housing estate - run-off reductions through RWH non-potable consumption

<table>
<tr><th rowspan="3">Total, annual non-potable consumption (m3)</th><th colspan="8">Available rainfall after losses, plus percentage run-off reductions via RWH consumption</th></tr>
<tr><th colspan="2" rowspan="2">Wallingford (2011) loss methodology</th><th colspan="6">SUDS Solutions (2005) yield coefficients</th></tr>
<tr><th colspan="2">High</th><th colspan="2">Expected</th><th colspan="2">Low</th></tr>
<tr><th></th><th>Available annual rainfall (m^3)</th><th>% run-off reduction via RWH consumption</th><th>Available RWH (m^3)</th><th>% run-off reduction via RWH consumption</th><th>Available RWH (m^3)</th><th>% run-off reduction via RWH consumption</th><th>Available RWH (m^3)</th><th>% run-off reduction via RWH consumption</th></tr>
<tr><td>1,233</td><td>1,598</td><td>77%</td><td>1,786</td><td>69%</td><td>1,686</td><td>73%</td><td>1,487</td><td>83%</td></tr>
<tr><td colspan="9">Original rainfall data based on 775mm/year total rainfall (CBMDC data, 2008 - 2010 annual average).
Non-potable consumption data; Toilet & washing machine use only. Does not consider outside water use, e.g. garden watering. Non-potable water consumption based on 40 litre/person/day (Wallingford, 2011).
Non-potable consumption demand based on 84.48 occupants in 35 dwellings.
See Table for details of loss and yield coefficients.
SPILLAGE FROM FULL RWH STORAGE TANKS NOT ACCOUNTED FOR</td></tr>
</table>

3.4 Case Study 4: Rainwater harvesting and large, warehouse-type buildings

Case study 1 illustrates that the installation of a RWH system for an office block (CBMDCs Jacobs Well offices) with a low roof area to occupancy ratio, could reduce toilet and urinal water demand by approximately 30% with additional benefits for reductions in rainfall run-off. For larger buildings with proportionally lower occupant numbers, RWH offers greater potential for reducing mains supplied water and rainfall run-off. Case study 4 gives two examples;

1. example of potential rainwater capture and reductions in run-off from a large warehouse of unknown water demand
2. example of rainwater capture and potential reductions in run-off and mains supplied water from a large warehouse structure of known water demand

3.4.1 Example 1; RWH from a large warehouse of unknown water demand

As an example of the potential for RWH from large buildings, a distribution warehouse in Bradford was selected to illustrate the quantities of rainfall that could be collected. The building in question is located 1.6km to the northwest of CBMDCs Jacobs Well offices.

3.4.1.1 Methodology

Due to lack of occupancy and demand data, the following example simply details potential harvested rainfall volumes, and is based on annual average rainfall volumes multiplied by roof area and factored for run-off yield coefficients as identified by the RainCycle RWH tool (SUDS Solutions, 2005). Table A4.1 (Appendices), details calculations used in this example.

Approximate roof area of the warehouse; 70,000m^2

Roof type; multiple pitched roofs, coated, steel sheeting

Rainfall; 775mm/year

Total rainfall falling on warehouse; 54250m^3/year

RainCycle yield coefficients;

0.9 ('High' coefficient for a pitched roof)

0.85 ('Expected' coefficient for a pitched roof)

0.75 ('Low' coefficient for a pitched roof)

3.4.1.2 Results; large warehouse RWH

Potential collected rainfall (without any filtering or first flush devices);

Using 0.9 yield coefficient; 48825m^3/year

Using 0.85 yield coefficient; 46113m^3/year

Using 0.75 yield coefficient; 40688m^3/year

As with any RWH system, the volume of rainfall collected will depend on rainfall, roof type and structure. Additional factors such as filtering and first flush devises will also affect volumes of useable rainfall collected. Nonetheless, the example above illustrates that the quantity of rainfall collected from large warehouses and similar buildings could be considerable.

3.4.2 Example 2; RWH and water consumption from a low occupancy, large commercial warehouse

The above example gives a generic indication of potential water savings from RWH using large, warehouse-type buildings with unknown consumption. Relative to an office building, occupancy numbers for such buildings are likely to be low. However, this does not mean that such buildings have a low water demand; data supplied by CBMDC show that such buildings used for vehicle maintenance and washing, or as waste transfer stations, have high water use. The following example details RWH potential and associated mains-supplied water savings for CBMDCs fleet maintenance depot in Bradford (Figure 2).

Figure 2; CBMDCs fleet depot - Google image (left), OS MasterMap (right)

3.4.2.1 Methodology

Rainfall and water consumption data was supplied by CBMDC. The roof area of the maintenance depot was determined using ArcMap GIS. Whilst a predominantly corrugated pitched roof, the office section of the building complex consisted of flat or gently sloping asphalt roof. Roof yield/run-off and filter coefficients were determined using methodologies in Wallingford (2011) and SUDS Solutions (2005). Occupancy numbers are unknown; therefore this example simply considers total water use.

Annual rainfall; 775mm/year (2008 - 2010 average annual)

Roof area;

pitched corrugated roof; 3,721m^2

flat, asphalt roof (presumed smooth surface); 880m^2

(Total roof area; 4,601m^2)

Average annual water demand (CBMDC data, 2008 - 2010);

4226m^3/year

Average annual water supply costs (CBMDC data, £1.21/m^3);

£5113.year

3.4.2.2 Results

Using roof yield coefficients identified by both Wallingford (2011) and SUDS Solutions (2005) in conjunction with total rainfall and annual water demand values, available annual rainfall volumes and potential reductions in run-off through RWH were calculated (Table 9 and Table 10).

Table 9; CBMDCs fleet depot - Annual available run-off

Roof type & area (m^2)		Annual rainfall falling on roof areas before losses (m^3)	Available annual rainfall (m^3) after losses			
			Using Wallingford (2011) loss methodology	Using SUDS Solutions (2005) yield coefficients		
				High	Expected	Low
Pitched, corrugated	3,721	2884	2,091	2,336	2,206	1,947
Flat, asphalt	880	682	494	368	338	307
Total roof	4,601	3566	2585	2704	2544	2254

Rainfall data based on 775mm/year total rainfall (CBMDC data, 2008 - 2010 annual average).

See Table A2.7 for details of Wallingford (2011) & SUDS Solutions (2005) roof loss and yield coefficients, except SUDS Solutions (2005) flat roof yield coefficients including 10% filter loss; High - 0.54; Expected - 0.495; Low - 0.45.

DOES NOT ACCOUNT FOR SPILLAGE FROM FULL RWH STORAGE TANKS.

Table 10; CBMDCs fleet depot - reductions in run -off

Total, average annual water use (m3) (includes un-quantified drinking and similar water use. 2008-2010 average)	Available rainfall after losses (m^3), plus percentage run-off reductions via RWH consumption							
	Wallingford (2011) loss methodology		SUDS Solutions (2005) yield coefficients					
			High		Expected		Low	
	Available annual rainfall (m^3)	*% run-off reduction via RWH consumption*	Available RWH (m^3)	*% run-off reduction via RWH consumption*	Available RWH (m^3)	*% run-off reduction via RWH consumption*	Available annual rainfall (m^3)	*% run-off reduction via RWH consumption*
4226	2585	*Demand exceeds supply (163%)*	2704	*Demand exceeds supply (156%)*	2544	*Demand exceeds supply (166%)*	2254	*Demand exceeds supply (187%)*

Original rainfall data based on 775mm/year total rainfall (CBMDC data, 2008 - 2010 annual average).

See Table A2.7A2.7 for details of Wallingford (2011) & SUDS Solutions (2005) roof loss and yield coefficients, except SUDS Solutions (2005) flat roof yield coefficients including 10% filter loss; High - 0.54; Expected - 0.495; Low - 0.45.

SPILLAGE FROM FULL RWH STORAGE TANKS NOT ACCOUNTED FOR

Figures in Table 10 show water demand within CBMDCs fleet depot exceeds available rainfall run-off irrespective of roof yield coefficients used. Although this example does include un-quantified demand for potable water (meaning that not all water demand can be met by RWH), nonetheless the example illustrates that RWH from large, low occupancy, high water demand buildings can be an important contributor in reducing both run-off volumes and in supplying water for non-potable use such as vehicle cleaning. Installation and maintenance costs notwithstanding, RWH could also provide significant savings in water supply costs for these same buildings; these being approximated to £5,113 per year[3] for CBMDCs fleet depot.

3.5 Case Study 5: City centre-scale rainwater harvesting and disconnection

The potential for RWH to contribute to wider surface water management and reductions in flood risk is illustrated by considering reductions in run-off volumes should all roofs in a given area be disconnected from drainage systems. Theoretically, this could be achieved by installing rainwater harvesting systems for non-consumable use including toilet flushing, garden use and vehicle cleaning. Such an approach is discussed by Wallingford (2011) in considering RWH from a residential development as a means to manage stormwater run-off.

3.5.1 Rainfall run-off management using RWH in Bradford city centre; an example

Simply using annual average rainfall data and total roof area within a 2km x 2km square area of Bradford city centre, the following example illustrates the potential for RWH to contribute to rainfall run-off management and an associated reduction in flood risk.

Figure 3 details the centre of Bradford encompassed by a 2 kilometre square. For the purposes of this example, all roofs within or intersecting the 2km square have been 'disconnected' from the surface water drainage system by a RWH device. No account has been taken of roof pitch or construction type and materials.

Table 11 details run-off, i.e. rainfall available for harvesting, based on UK average rainfall and assumed losses expected using procedures outlined in Wallingford (2011).

Table 12 places these losses in the context of annual rainfall for Bradford, detailing total rainfall and potential rainfall available for harvesting (run-off reduced) through the use of RWH being based on roof area within the city centre 2km square.

Table 13 details potential reductions (as a percentage) in rainfall run-off from Bradford city centre through the implementation of RWH and disconnection of run-off from surface drainage.

(See Table A5.1 and

Table A5.2 for calculations).

[3] Based on 2010 prices of £1.21/m^3, and using 2008 - 2010 average, annual water demand of 4226m^3/year.

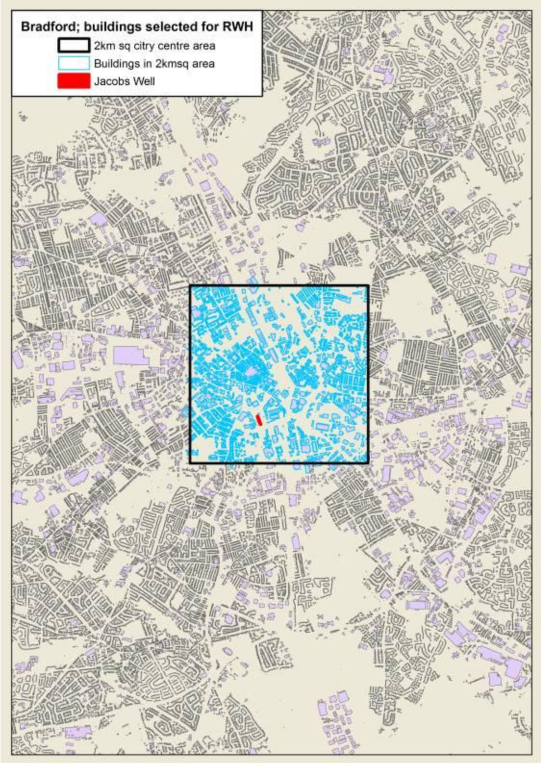

Figure 3; Selected roof areas for RWH within Bradford city centre

Table 11; UK rainfall, assumed RWH losses and run-off proportion

UK average rainfall	713mm/year
Assumed losses due to roof wetting	0.5mm per event (75mm/year)
Assumed losses after wetting (presumed evaporation, spillage, wind blow etc.)	10%
Assumed losses due to rainwater filter	10%
Overall run-off proportion for post-wetting losses & filtering	0.81 (81%)
Resultant run-off depth for UK	517mm/year (72.5% of UK average annual rainfall)
	Source; Wallingford, 2011.

Table 12; Rainfall harvesting potential based on annual, average Bradford rainfall

Bradford average annual rainfall (2008 - 2012)	775mm/year
Bradford average annual rainfall factored for losses	562mm/year
Total rainfall volume falling within city centre 2kmsq	3,100,000m^3
Total rainfall volume falling within city centre 2kmsq & factored for losses	2,248,000m^3
Roof area within city centre 2kmsq (derived using ArcMap)	1,039,739m^2
Total volume of rain falling on 2kmsq selected roof area	805,798m^3
Potential volume of rain available for harvesting from 2kmsq selected roof area	584,333m^3
Source; after Wallingford, 2011. Rainfall data from CBMDC.	

Table 13; Potential reductions in run-off following RWH in Bradford city centre

Bradford rainfall factored for losses except rainwater filter loss (10%)	624mm/year
Volume of rainfall falling within 2kmsq city centre area factored for losses except filter loss	2,496,000m^3
% rainfall run-off reduction following RWH from buildings and disconnection from surface drainage	23%
Source; after Wallingford, 2011. Rainfall data from CBMDC DOES NOT ACCOUNT FOR SPILLAGE FROM FULL RWH STORAGE TANKS..	

The above example shows that a reduction in rainfall run-off volumes of approximately 23% could be achieved through RWH and roof disconnection within Bradford city centre. This in turn provides potential for improved surface water management and a reduction in flood risk through greater spare capacity in drainage networks and water courses. However, there are caveats to this; the example assumes that all RWH devices work as designed and that there is storage capacity available. In reality, some RWH devices will not work to their full potential, whilst some rainfall will by-pass RWH devices. Additionally, available storage capacity will depend on antecedent demand and rainfall volumes.

The volume of run-off available from roofs in a given area will depend on the density of buildings; less dense development affords less opportunity for RWH, more dense development afford greater opportunity for RWH and reductions in rainfall run-off from roofs. Therefore the benefits to be gained from using RWH harvesting for stormwater management will greatly depend on the available roof area and density of buildings in conjunction with flood risk and flood damage costs to local residents, businesses and therefore local economies.

4 Discussion; Rainwater harvesting - uses and benefits

Many uncertainties exist with respect to RWH (Wallingford, 2011). Factors of yield, demand, optimum storage tank size and variations in rainfall patterns all conspire to make definitive quantifications of RWH potential difficult to determine, both in terms of water supply and economic justification. Nonetheless, that RWH has been and is part of past and current societies indicates that there is a use for such systems, even in modern, western societies. The difficulty for more widespread installation of RWH systems lies not in the benefits demonstrated through individual, small scale harvesting systems, but in justifying on economic grounds wider installation of RWH systems in a society that is used to relatively cheap, readily available water from a centralised mains supply system.

Water supply savings related to RWH encompass more than simply water supply costs. Reduced demand for mains supplied, i.e. potable water, would also reduce demand for;

- water treatment and associated energy costs
- pumping costs associated with mains supply
- disposal costs through less rainwater entering sewers and being unnecessarily treated in sewerage treatment works
- Reduction in frequency and volume of discharges from Combined sewer overflows
- water extraction from rivers and groundwater and their subsequent recharge
- costs associated with supply and sewer network infrastructure through reduced capacity requirements

Although issues of contamination exist with RWH, first flush diversion and simple filters can remove larger particles and reduce contamination risk. Additionally, given the non-potable uses that rainwater can be put to contamination becomes less of an issue. Examples of uses for untreated rainfall from large, low occupancy warehouses include;

- plant and garden irrigation
- gully and drain cleaning
- vehicle and building exterior cleaning
- road washing
- toilet and urinal flushing
- industrial cleansing operations

The benefits of the capture of rainwater by RWH will be to provide spare capacity in sewers, drainage systems and watercourses during storm events, although once full, rainwater storage tanks provide no contribution to the management of subsequent flows. However, RWH reduces the need to manage surface water at ground level and is capable of compensating for a significant portion of the anticipated increase in rainfall that will come with climate change. Studies suggest that this is possible, with RWH storage tanks providing capacity to store rainfall (ARUP, 2011). RWH could therefore be used as a component of flood risk management.

Ultimately and if implemented on a large scale, RWH could reduce the requirement for additional reservoir capacity[4]. If rainfall can be captured where it falls and used for non-potable purposes, then the volume of water required to be impounded in reservoirs to supply all uses is less; reservoir impounded water could then become predominantly for potable use. Given expected increases in populations and

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[4] Currently, there are 2,126 'large raised reservoirs' (over 25,000m3 capacity above natural ground level) within England and Wales (Defra, 2012). In 2007, plans existed to build five new reservoirs (and extend three existing reservoirs) (GWI, 2007). These plans have reportedly been cancelled or rejected by the UK Government (Booker, 2012)

uncertainties in future rainfall associated with climate change, minimising unnecessary water treatment but maximising untreated water use would likely provide economic and environmental benefits, with associated gains for Society.

All the factors highlighted add an incremental benefit to RWH. Importantly, an economic aspect can be applied to many of the benefits through reduced mains water supply, infrastructure and energy costs; these having benefits for both public sector organisations such as local authorities and private businesses looking to reduce water supply costs. Additional benefits, such as environmental benefits associated with less river extraction and falling water tables, are harder to quantify but nonetheless are a benefit. Reduced flood risk, difficult to quantify, would enable more targeted application of flood defence schemes with benefits for property values and business confidence in areas deemed at less of a flood risk. Although becoming further removed from the simple task of RWH, the costs of flooding to society, property values and businesses are better understood (Pitt, 2008). If these costs can be reduced through RWH, this then gives more economic weight to RWH schemes.

Clearly, to achieve such aims, RWH would need to be implemented on a wide scale. Whilst this might prove problematic for existing dwellings and commercial buildings with limited space for storage tanks and multiple occupancy, for new and redevelopments, installing RWH systems could be a condition of planning permission without which development restrictions could apply. Equally so, incentives to install RWH systems could include a reduction in domestic and business rates, savings being made in reduced requirements for drainage networks and flood defences, although if adopted as a flood management strategy there would be a requirement for capacity in RWH storage tanks at all times.

The implementation of a city-wide RWH policy would require careful thought and the engagement of a wide range of stakeholders; ensuring that stakeholders understand the reasons for and benefits of RWH would be critical to long-term operation. Given the relatively low cost of mains water supply and immediate, up-front costs of installing RWH systems, financial or legislative incentives may be necessary to encourage uptake of RWH systems, from which the wider Society would benefit.

5 Conclusions

The examples detailed illustrate that RWH, whilst containing inherent uncertainties with regards to supply and demand, nonetheless is able to offer benefits to wider water management. In terms of water demand, the example of CBMDCs Jacobs Well offices reducing water demand through replacing large capacity toilet cisterns with smaller, more efficient cisterns demonstrates that reducing demand at source is the most effective method of reducing water use. Nonetheless, following this and within a building with a low roof area to occupancy ratio, RWH has been shown to have benefits for water demand and cost savings. This is also true of domestic dwellings where, depending on occupancy numbers, RWH can contribute to high proportions of domestic water demand.

Perhaps the most beneficial gains from rainwater harvesting can be seen when applied to large, warehouse type buildings or when encompassing multi-property RWH systems in more dense urban areas. Irrespective of water demand from within buildings, the volume of rainfall potentially harvested for non-potable use elsewhere is considerable. The potential for potable water use to be replaced by untreated water where appropriate, the gains for water and flood risk management, particularly in urban areas with large impermeable areas, and associated savings in pumping, network infrastructure and reductions in drain and sewer surcharging, suggest RWH at a larger scale has many positives. Used in conjunction with other SuDS infrastructure, RWH has potential to contribute wider water management with the added benefit of annual water cost savings for those who install such systems.

The need to seek multiple benefits to maximise the rate of return, means that there is a need for positive action to achieve the necessary degree of leadership and coordination. Unless this happens, it is likely that the potential benefits will be lost

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Appendices

Appendix 1: RainCycle RWH tool

Appendix 2: Case Study 1: the city centre office block

Appendix 3: Case Study 2: Rainwater harvesting from domestic buildings - data

Appendix 4: Case Study 3: Rainwater harvesting and large, warehouse-type buildings - calculations

Appendix 5: Bradford city centre; reductions in rainfall run-off through RWH

Appendix 6: Roof yield coefficients, rainfall events and wetting losses

Appendix 1: RainCycle RWH tool

Whilst internet-sourced RWH tools are easy to use, their simplistic data requirements limit the detail of information obtained. This is particularly so in respect of variations in water demand and total costs, i.e. whole life costs of installing RWH systems. These issues are magnified when considering large commercial and industrial buildings and RWH potential.

In contrast, the RainCycle RWH tool enables a wide range of data to be input, which enables a greater range of scenarios to be investigated, and thus more detailed data to be produced. In enabling a wide range of variables to be considered, the RainCvcle RWH tool aims to remove much of the uncertainty associated with the whole life costs of RWH systems and variations in demand. As such, the RainCycle RWH tool can be used as an aid to decision making (SUDS Solutions, 2005).

Examples of the type of data that can be input to the RainCycle RWH tool include;

- roof catchment area and type
- water demand, e.g. week days verses weekend demand in commercial buildings
- numbers of male and females within a building
- building type; domestic, commercial and school buildings
- capacity and power demand of pumps
- Ultra Violet water purification power demand and flow rates

Examples of output tables include;

- whole life costs of RWH systems
- long-term financial and hydraulic analysis outputs including graphs
- optimisation outputs for costs and storage tank sizes

Figure 4, Figure 5 and Figure 6 detail examples the system map, data input and data output tables within the RainCycle RWH tool. It is not necessary, however, to input data for all fields within the RainCycle tool. Rainfall yield can be determined without filter, pump and UV Unit information, for example. The tool also contains default data that can be used if actual data is lacking, although use of default data will produce less specific output.

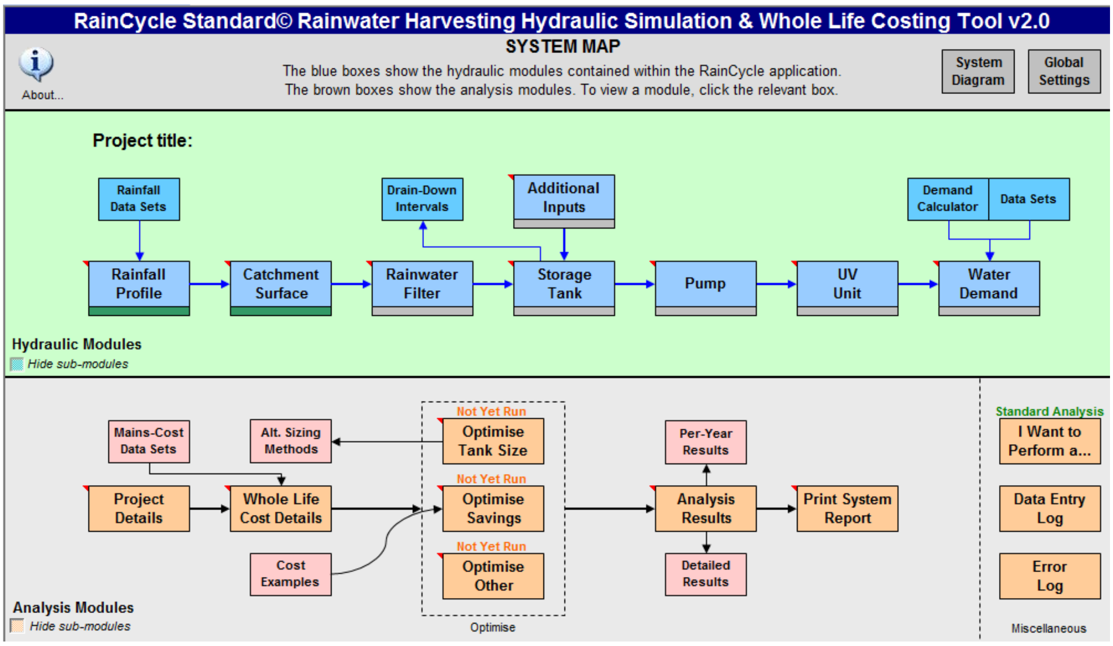


Figure 4; RainCycle front page

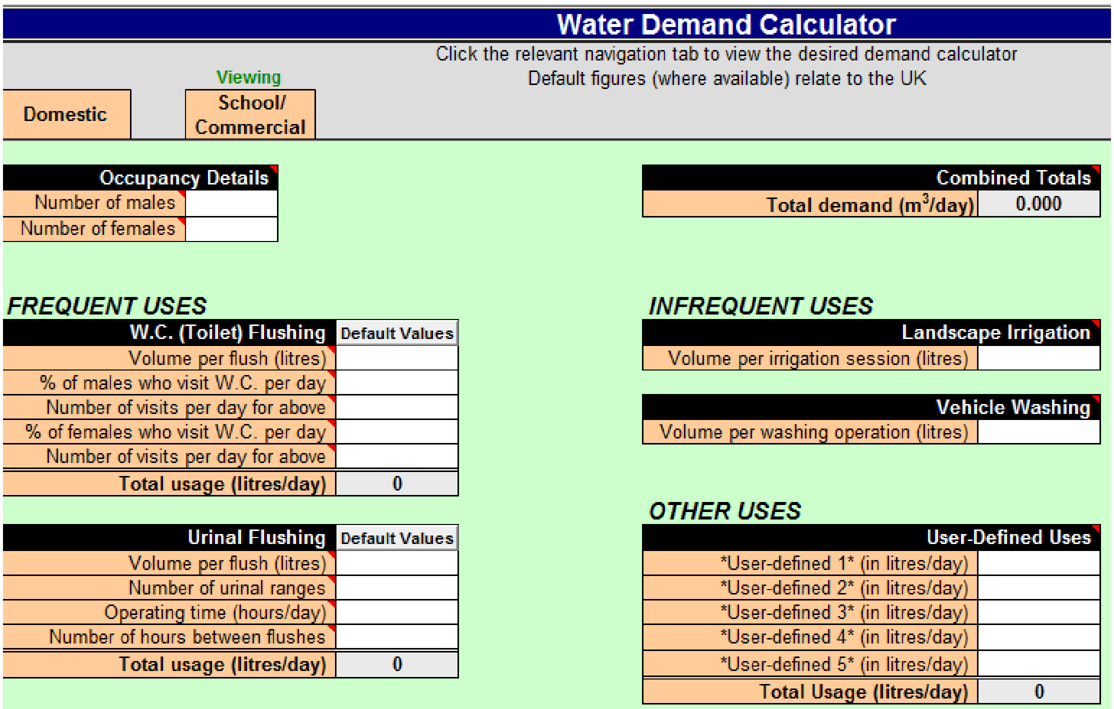


Figure 5; RainCycle Water Demand Calculator

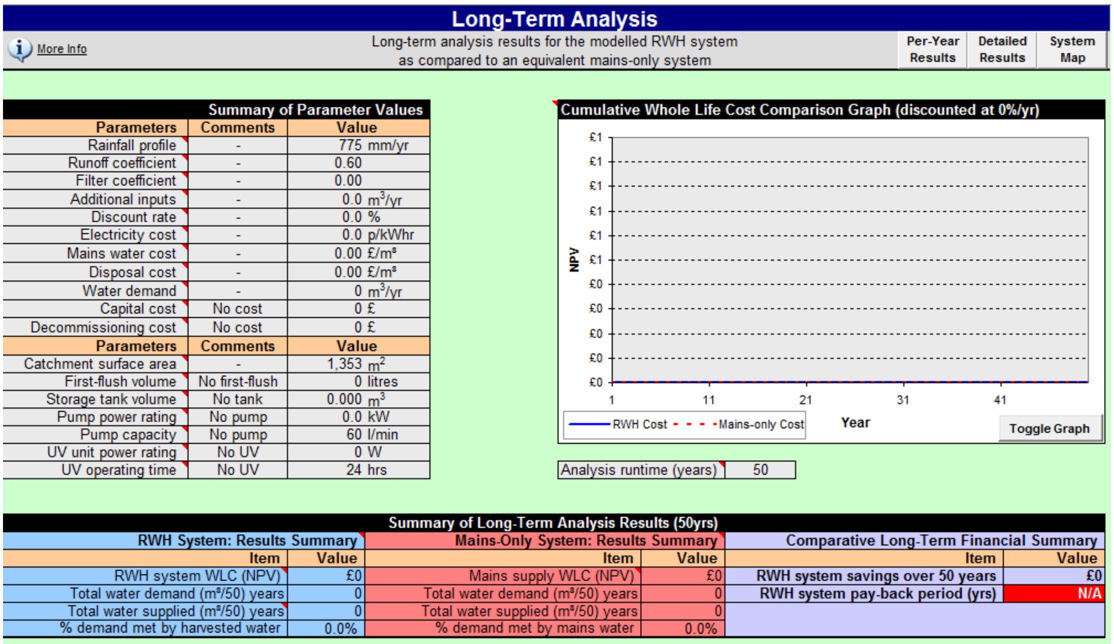


Figure 6; RainCycle Long-Term Analysis page

Rainwater storage tanks sizes

As well as being able to input an actual or desired size of storage tank, the RainCycle RWH tool enables the optimum size of storage tank to be determined. However, there are caveats to this. RainCycle gives alternative methods of determining the optimum storage tank size;

- as a % of annual demand/supply

or

- as 'X' days supply.

Due to the different water demand requirements of domestic and commercial buildings, the RainCycle tool suggests that for commercial use, the 'X' days supply option should be used. The '% of annual demand' option has been noted to over-estimate the required storage tank size for large, commercial buildings, and thus is considered suitable for domestic and small scale systems only (SUDS Solutions, 2005).

In addition to the above, it should also be noted that these options are available in RainCycle via the 'Alternative Sizing Option' tag within the 'Optimise Tank Size' analysis. Using mean average water demand and the number of days supply required, this option simply gives a recommended storage tank volume. However, this 'Alternative Sizing Option' tool is not recommended for use with large, commercial buildings as it has been shown to give inaccurate data with respect to calculated storage tank volumes (SUDS Solutions, 2005). As an example of this and using Jacobs Well water demand, the 'Optimise Storage Tank' tool suggests a 15m^3 tank would suffice, where as the more simplistic 'Alternative Sizing

Option' (using a requirement of six days supply[5] and a daily toilet and urinal flush demand of 5.137m^3), recommends a 30.8m^3 storage tank. This is calculated simply as;

$$6 \times 5.137 = 30.8$$

It should be noted that in calculating optimum storage tank sizes using the 'Alternative Sizing Option', the RainCycle tool assumes that any storage tank is full before the start of a dry period and that water demand is the same for all days of the year, i.e. weekends are considered the same as weekdays. For determining optimum storage tank size, daily water demand is therefore calculated as;

$$\text{Daily annual water demand} = \frac{\text{Total annual water demand}}{365}$$

This approach does not allow for differences in water demand between weekdays and weekends, important for commercial buildings, and does not allow for storage tanks to be partially full at the start of a dry period, and thus giving less days supply.

In complying with British Standards, the rainwater storage tank for Jacobs Well should be no larger than 31.5m^3. This equates to 5% of the rainwater yield of 629m^3 (the lesser of yield and water demand) and adheres to maximum storage tank size requirements as detailed within British Standard 8515 2009 (BSI, 2009).

[5] Recommended number of days supply according to current practice, (SUDS Solutions, 2005).

Appendix 2: Case Study 1: the city centre office block

Section A: Jacobs Well data

Data provided by the City of Bradford Metropolitan Council (CBMDC) and used in the RainCycle RWH tool included;

- occupancy numbers (2008 - 2011)
- rainfall data (from rain gauge situated on Jacobs Well, 2008 - 2010)
- water demand and costs (2008 - 2009)

Daily rainfall data for the period 2008 - 2010 were averaged for mean values to account for annual variations in rainfall data. Occupancy numbers within Jacobs Well were also averaged for mean values for the period 2008 - 2011; staff reorganisation within CBMDC increased the number of staff within Jacobs Well temporarily. Using the mean average for staff data helped account for this. Water demand was compared and averaged for the mean value on a monthly basis to account for incomplete annual data and to account for changes in occupancy numbers. A2.1, Table and Table A2.3 in Appendix 2 detail data for rainfall, occupancy and water demand.

The roof area of Jacobs Well was determined using ArcMap (version 9.3) GIS software; this was estimated to be 1353m^2.

The roof collection (or yield) coefficient was set at 60% (0.6), as within parameters detailed in the RainCycle RWH tool for a smooth, flat roof (SUDS Solutions, 2005).

A filter coefficient was set at 90% (0.9), as detailed in SUDS Solutions (2005).

The Jacobs Well toilet cisterns are currently being replaced. The capacity of the old cisterns was 13.5 litres, with the new cistern capacity being six litres as required by current legislation (TSO, 1999). Toilet flush volumes do not take into account differing flush volumes for urinals. Due to lack of data on urinal flush volumes, default values within the RainCycle software have been used.

Given the eight floors to Jacobs Well, the number of urinal ranges requiring flushing is set at one range per floor, i.e. eight urinal ranges. RainCycle does require the actual number of urinals.

No account is taken of external maintenance teams, temporary staff, visitors to Jacobs Well, nor staff holidays (public holidays are taken account of).

The proportions of male and female occupants within Jacobs Well are unknown. RainCycle allows such data to be entered. For this example, male/female ratios are deemed 50-50.

A drain-down schedule for storage tank maintenance and cleaning has been set at once per year (December 31st).

RainCycle allows 'Domestic' and 'School/Commercial' settings to be used. These enable different parameters to be set within the tool that better represent water demand within the buildings being investigated. For this project, the 'School/Commercial' setting has been used.

Due to the 'first flush' of rainwater off a roof often being contaminated with debris, bird droppings and other pollutants, rainwater harvesting systems often contain devises that allow this first flush to be diverted to drainage systems. This can reduce contamination risk and improve the quality of harvested rainwater (Farreny *et al*, 2011; Lye, 2009). RainCycle contains an option to include a first flush device in rainwater yield calculations. However, due to lack of data on first flush volumes from Jacobs Well, this has been given a zero value.

Cost and power consumption data for pumps and UV filters can also be taken into account in RainCycle. Due to lack of data, these values have been set at '0' or left blank. Other data not thought applicable to

Jacobs Well, e.g. clothes and vehicle washing demand, garden irrigation, have also been left blank or given a '0' value.

Table A2.1; Jacobs Well data for the RainCycle RWH tool

Roof area	1353m^2
Roof collection (yield) coefficient	0.6 (60%)
Filter coefficient	0.9 (90%)
'First flush' diversion volume	0 litres
Flush toilet cistern capacity; old cisterns	13.5 litres
Flush toilet cistern capacity; new cisterns	6 litres
Number of urinal ranges	8
Ratio of men to women	50/50
Maintenance and cleaning drain-down schedule	Once per year

Table A2.2; Jacobs Well annual rainfall and occupancy data

Year	Annual Rainfall (mm)	Number of Occupants
2008	984.2*	611
2009	733.8	621
2010	609.2	729
2011	no data	647
Mean average	775.7mm/yr	652

*Less 29th February for rainfall data

Table A2.3: Jacobs Well water demand

Year	Water use (m^3)	Total months data available	Mean average water use/month (m^3)

2008	3868	12 months	322.3
2009	3810	12 months	317.5
2010	3591	9 months	399
Total demand, all years	11269	33 months	341.5

The mean average total monthly water use of 341.5m^3 per month equates to;

- 4098m^3 per year
- 11.23m^3 per day (@ 365 days/year)
- 16.2m^3 per working day (@ 253 working days/year)

(These values encompass all water use and include the use of 13.5 litre capacity toilet cisterns).

Jacobs Well; potable and non-potable water demand

Given that water demand figures detailed above comprise of all water use, it is important to separate water use that requires mains water supply, i.e. drinking water, and water uses that could be met by rainwater harvesting, such as toilet use. This can be done by using the RainCycle Water Demand calculator. This tool provides water demand values for uses that do not require mains water supply, such as toilet flushing, washing machines and garden irrigation. For Jacobs Well and based on CBMDC supplied occupancy numbers, water use that could be met by rainwater harvesting, i.e. urinal and toilet use, equates to;

- old, 13.5 litre toilet cisterns;
  - 15.483m^3 per working day
  - 3917m^3 per year
- new, six litre toilet cisterns;
  - 7.415m^3 per working day
  - 1875m^3 per year

These values are based on toilet and urinal water use alone, and it can be clearly seen that considerably less water, 48% less, is required using the new, six litre toilet cisterns.

It should also be noted that the urinal and toilet working day demand of 15.483m^3 for the 13.5 litre cisterns is close to the total working day water use of 16.2m^3. In conjunction with staff holidays not being accounted for (thereby increasing daily calculated demand) and the inclusion of default values, it is thought that RainCycle may over-estimate water demand. Due to a lack of more detailed water use information and data, and the change to six litre cisterns, the default values used in these calculations have not been altered. Output using 13.5 litre cisterns is presented for comparative purposes alongside output for six litre cisterns.

RainCycle default data for Jacobs Well

In the event of missing or incomplete data, RainCycle enables the use of default data. For this study, default values have been used for;

- Proportion of men who use flush toilets per day; 30%
- Number of visits for the above men; 1
- Proportion of women who use flush toilets per day; 100%
- Number of visits for the above women; 3
- Urinals - volume per flush; 7.5 litres
- Urinal flushing - hours of operation per day; 8
- Urinal flushing - flushes per hour; 2

Water demand profile for Jacobs Well

For establishing water demand patterns in relation to building use, RainCycle uses a Daily Water Demand Profile and Demand Wizard, with options for Schools and Commercial buildings. For commercial buildings, RainCycle uses the following demand profile;

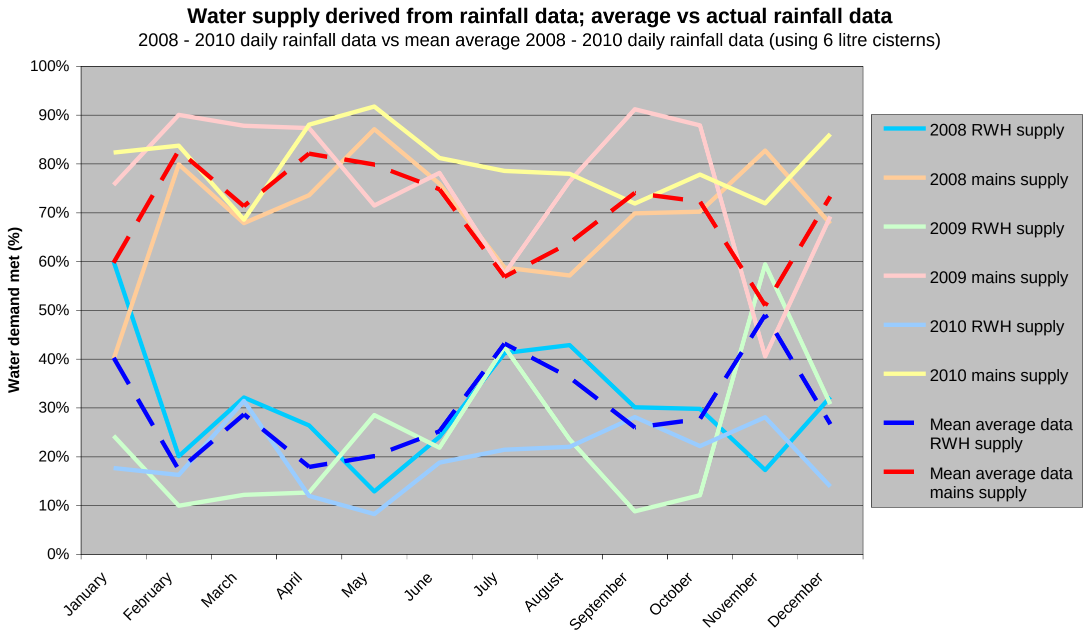
- Working days per year; 253 (Monday to Friday)
- Saturdays; 52
- Sundays; 52
- Bank holidays; 8

For the purposes of this study, a nil water demand is presumed for weekends and bank holidays.

Case Study 1; Rainfall data; the use of average data

Use of monthly or annual rainfall volumes can have the effect of giving ambiguous information. Although the use of such rainfall data comprised of many years of data and then averaged may provide more accurate information, this may not reflect actual daily rainfall volumes, nor rainfall variation season to season. How rainfall falls on a day to day basis is critical to how much rainfall can be harvested when considered with water demand profiles and storage tank sizes. To obtain more viable outcomes from the RainCycle RWH tool, daily and seasonal rainfall variations require accounting for. Therefore the use of the most accurate rainfall data is necessary to produce viable results. To this end, the use of daily rainfall data is recommended. The least accurate data, and therefore not recommended for use, is annual rainfall data (SUDS Solutions, 2005).

The smoothing effect of average data is also apparent within rainfall data used to determine volumes of harvested rainwater and proportionate water demand for Jacobs Well. Graph A2.1A2.1 details water supply data derived from actual rainfall data for 2008 - 2010, and mean averaged rainfall for the same period. It can be seen that the peaks and troughs within the actual data have been reduced following averaging. Whilst using a greater time period of data to create average data may produce more representative average figures, nonetheless, the use of average data creates a margin for error that requires considering when interpreting results and deciding on action to take.



Graph A2.1; Use of actual rainfall data verses averaged rainfall data

Case Study 1; Supply and demand spreadsheets

In addition to RainCycle output, a volume-balance spreadsheet was constructed in Excel as a means of comparing RainCycle output information for potential water demand met by RWH. This was done using mean average daily rainfall data for the years 2008, 2009 and 2010. Findings using this process are presented alongside findings from RainCycle simulation output. Figure A2.1A2.1 shows an example of the volume-balance spreadsheet.

runoff coef	filter coef	roof area		weekday demand	Tank vol	Initial vol					Total used	% from rainwater					
0.6	0.9	1353		7.415	15	0		sum	566.76629	1309.22871	1875.995	30.2%					
Day of Month	Date (date arbitary for this example)	Weekday	Month	Rainfall (mm/day)	Runoff to tank	Demand	vol stored at end of day	% full	Demand supplied from tank & runoff	Supply met by water co	Month	Month	Demand supplied from tank & runoff	Supply met by water co	Total dermand	% from harvesting	% from Water co
1	01/01/2011	6	1	2.47	1.80	0	1.80	12%	0.00		January	1	65.65838	97.47162	163.13	40.2%	59.8%
2	02/01/2011	7	1	1.13	0.83	7.415	0.00	0%	2.63	4.78	February	2	25.62041	122.6796	148.3	17.3%	82.7%
3	03/01/2011	1	1	0.20	0.15	7.415	0.00	0%	0.15	7.27	March	3	46.75968	116.3703	163.13	28.7%	71.3%
4	04/01/2011	2	1	3.27	2.39	7.415	0.00	0%	2.39	5.03	April	4	25.24213	115.6429	140.885	17.9%	82.1%
5	05/01/2011	3	1	0.73	0.54	7.415	0.00	0%	0.54	6.88	May	5	31.35657	124.3584	155.715	20.1%	79.9%
6	06/01/2011	4	1	0.93	0.68	0	0.68	5%	0.00	0.00	June	6	39.25865	116.4564	155.715	25.2%	74.8%
7	07/01/2011	5	1	2.73	2.00	0	2.68	18%	0.00	0.00	July	7	70.43177	92.69823	163.13	43.2%	56.8%
8	08/01/2011	6	1	1.40	1.02	7.415	0.00	0%	3.70	3.71	August	8	59.0341	104.0959	163.13	36.2%	63.8%
9	09/01/2011	7	1	4.00	2.92	7.415	0.00	0%	2.92	4.49	Septembe	9	38.52803	109.772	148.3	26.0%	74.0%
10	10/01/2011	1	1	7.40	5.41	7.415	0.00	0%	5.41	2.01	October	10	47.34418	123.2008	170.545	27.8%	72.2%
11	11/01/2011	2	1	2.47	1.80	7.415	0.00	0%	1.80	5.61	November	11	79.97854	83.15146	163.13	49.0%	51.0%
12	12/01/2011	3	1	4.67	3.41	7.415	0.00	0%	3.41	4.01	December	12	37.55387	103.3311	140.885	26.7%	73.3%

Figure A2.1; Example of the volume-balance spreadsheet

Section B; Jacobs Well - Results and Findings

Optimum storage tank size and demand met

Having placed the relevant data into the RainCycle tool, simulations were then run to optimum size of storage tank. Additionally, the same data and parameters were placed within volume-balance spreadsheet. The volume-balance spreadsheet used storage tank volumes as from RainCycle tank optimisation output and enabled a check with RainCycle demand met was done for both six and 13.5 litre capacity toilet cisterns.

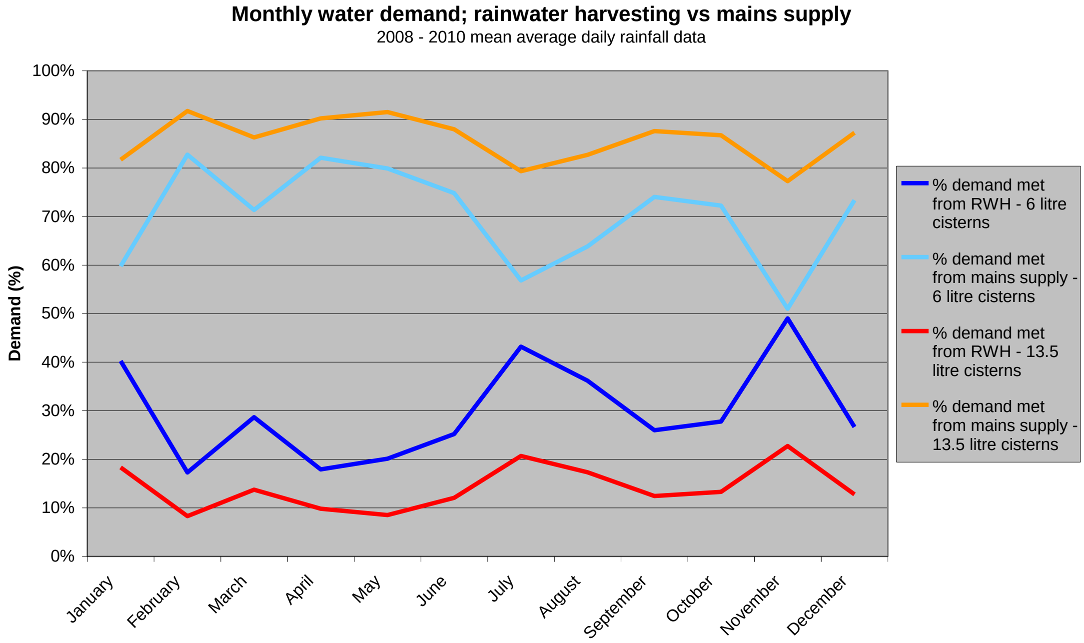
TableA2.4 details the findings for both these approaches, comparing storage tank sizes and water demand met, whilst Graph 1.2 details monthly water demand met for six and 13.5 litre cisterns from the volume-balance spreadsheet output.

NOTE; the values of water demand met relate to toilet and urinal water demand only.

TableA2.4; Storage tank volumes and demand met; RainCycle & Volume-balance sheet outputs

Rainfall 2008 - 2010 mean average daily data. Total rainfall 775mm/year New, 6 litre cisterns; Water demand 1875m^3/year, mean averaged at 7.415m^3/working day Old, 13.5 litre cisterns; Water demand 3917m^3/year, mean averaged at 15.483m^3/working day				
RainCycle determined storage tank size (m^3)	RainCycle demand met (%)		Volume-balance sheet demand met (%)	
	6 litre toilet cisterns	*13.5 litre toilet cisterns*	6 litre toilet cisterns	*13.5 litre toilet cisterns*
1	9.5	*4.6*	23.8	*11.4*
2	15.6	*7.5*	26.0	*12.5*
3	20.1	*9.6*	27.5	*13.2*
4	23.1	*11.1*	28.5	*13.6*
5	25.3	*12.1*	29.2	*14.0*
6	27.1	*13.0*	29.6	*14.2*
7	28.2	*13.5*	29.8	*14.3*
8	28.9	*13.8*	29.9	*14.3*
9	29.3	*14.0*	30.0	*14.4*
10	29.7	*14.2*	30.1	*14.4*
11	29.9	*14.3*	30.2	*14.5*
12	30.0	*14.4*	30.2	*14.5*
13	30.1	*14.4*	30.2	*14.5*
14	30.1	*14.4*	30.2	*14.5*
RainCycle maximum	30.1	*14.4*	30.2	*14.5*

simulated tank size; 15m^3				



Graph 1: Monthly water demand met; RWH verses mains supply

RainCycle tank optimisation and demand met output

From

TableA2.4, it can be seen that the maximum storage tank size required as determined by RainCycle for six litre cisterns is 13m^3, which would meet 30.1% of water demand, and for 13.5 litre cisterns 12m^3 at 14.4% demand met.

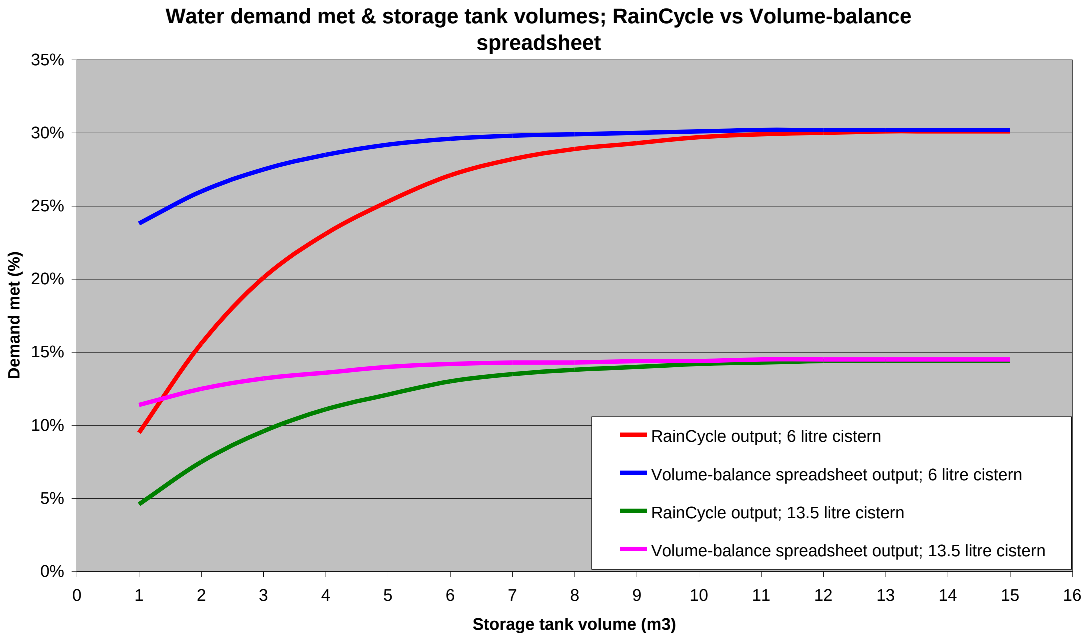
Viewing the RainCycle output data graphically (Graph A2.2), it can be seen that there is little to gain from installing a storage tank greater than 7m^3 using six litre cisterns. This would enable 28.2% of water demand to be met, the maximum available being 30.1%. Using the old, 13.5 litre cisterns, a smaller storage tank could be used; a 4m^3 storage tank would allow 11.1% of water demand to be met out of a possible 14.5%. Beyond these tank sizes, the rate of demand met using harvested rainfall levels off, and the likely higher costs of installing a larger tank would reduce savings gained through reductions in mains water supply.

Volume-balance sheet demand met output

Given the unknown calculation process within RainCyle, it is difficult to make a detailed However, the volume-balance spreadsheet suggests that greater demand can be met using storage tanks (

Table and Graph A2.2). For six litre cisterns, a 5m^3 storage tank would meet 29.2% of demand out of a maximum of 30.2%. For the older, 13.5 litre cisterns, there is much less variation in potential demand met volumes; from 11.4% to 14.5%. From the data obtained, there would be little to be gained from installing a tank larger than $2m^3$, equating to 12.5% of demand met, if using 13.5 litre cisterns.

In considering demand met output using both methods of calculation and either six or 13.5 litre cisterns, the limited rainwater harvesting potential of Jacobs Well can be attributed to the relatively small roof area in relation to the number of occupants. If the occupant numbers were less, this would give a much more favourable rainwater verses mains water supply demand ratio. However, what is apparent from the data is that replacing 13.5 litre cisterns with six litre cisterns reduces toilet water demand considerably, thereby reducing mains water supply costs. The six litre cisterns also enable a greater proportion of toilet water demand to be met by rainwater harvesting, with associated benefits for reduced mains water supply.



Graph A2.2; Comparison of water demand met and storage tank volume -

RainCycle and Volume-balance spreadsheet outputs, using 6 and 13.5 litre cisterns

Differences in accounting for rainfall capture and demand met calculations

The two approaches used to determine RWH potential vary in the way rainfall is accounted for relative to the working day and the storage or not of harvested rainwater. The volume-balance spreadsheet operates on the premise that rainfall that falls on any given day can be used that day, i.e. there is always space available within the storage tank for rainwater to be collected. This gives an optimistic approach to the findings, and hence a greater proportion of demand met when using smaller storage tank volumes.

It is believed that within RainCycle calculations, rainfall that falls on a given day is stored until day, but that the volume stored is based on the available storage capacity at the end of the day; i.e. if at the end of the previous day the storage tank is full, no further rainfall can be it is 25% full, then there is 75% capacity available. Thus RainCycle uses a very conservative the re-filling of storage tanks. This results in the lower demand met quantities within the

output compared to the volume-balance spreadsheet output, particularly when using smaller storage tanks, as detailed in

Table. As such, the RainCycle output could be considered more a pessimistic approach. Figure details a stylised illustration of the different approaches within calculations used by RainCycle and the volume-balance method.

It is important to remember that whilst neither approach used in determining rainfall yield is wrong, both contain assumptions that may or may not be accurate. The assumptions made highlight the inaccuracies due to carrying out calculations on a daily basis. If calculations were carried out at an hourly or better resolution, then assumptions based on inflow to and outflow from the storage tank would be less significant. Using RainCycle and the described volume-balance approach effectively gives an envelope of the likely performance of the RWH system.

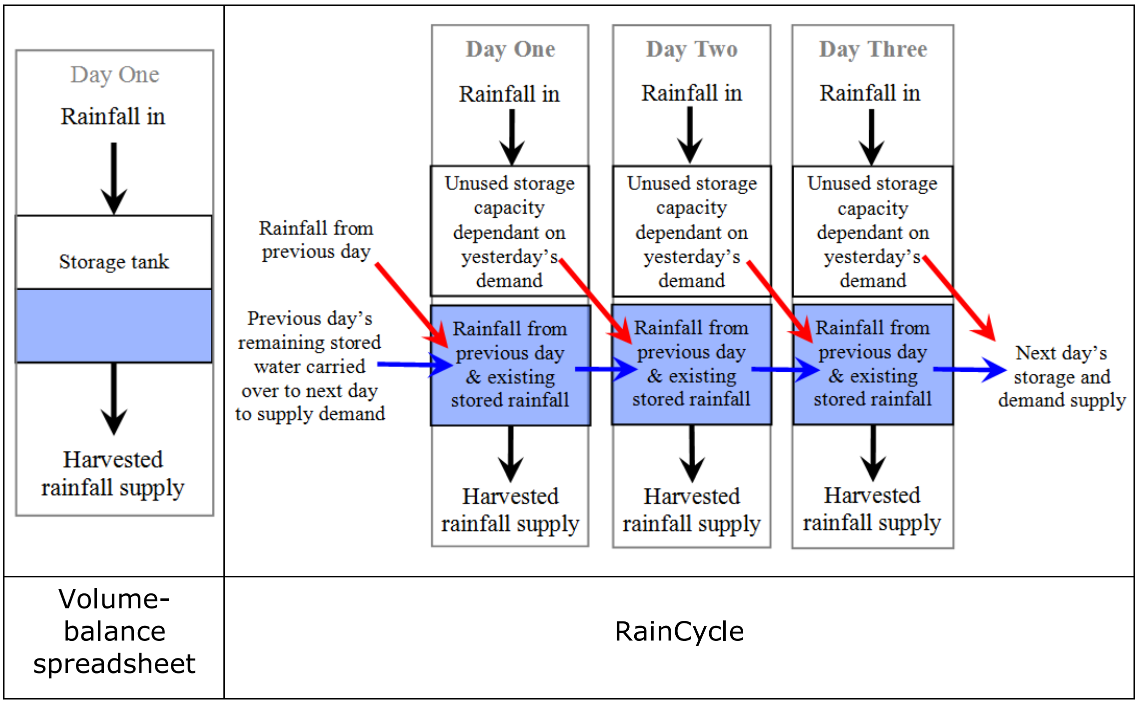


Figure A2.2: Comparison of rainfall capture, storage and use processes;

Volume-balance spreadsheet verses RainCycle

Case Study 1; Costs

The installation of rainwater harvestings systems will depend greatly on requirements and site specific factors. The more equipment required, such as pipes, pumps and water treatment devises, the higher the cost. Additionally and aside from storage tanks costs, installation costs for storage tanks increases rapidly as the size of storage tanks increase (SUDS Solutions, 2005). Thus careful consideration of all cost factors is necessary to determine the viability of RWH systems, particularly if costs savings alone are the reason for installing a RWH system.

An alternative to excavating and placing storage tanks in the ground is to mount them on walls, as detailed for small buildings in ARUP (2011) or on building roofs. Assuming building structures are able to withstand the weight of water storage tanks, such placement may enable gravity fed systems to be installed for water use. This would reduce the requirements for pumps and associated running costs.

If the aim of harvesting rainwater is primarily for attenuation and flood management, then different factors become applicable which may allow the use of larger storage tanks. Additionally, if the aim is not to supply buildings with water for toilet flushing, but to supply untreated water for use in town centre plant irrigation, road and gully cleaning and similar operations i.e. to reduce potable mains water use in non-potable requirements and so reduce potable water supply costs, installation of above ground storage tanks at ground level with water tanker access is an option. Clearly, the intended aim of harvesting rainwater is critical when considering cost factors, and thus should be established at the outset of a RWH project.

Jacobs Well water costs and savings

For the purposes of this project, it is assumed storage tanks are placed on the roof of Jacobs Well, with gravity fed delivery systems. The RainCycle Optimise Savings tool has been used to calculate costs using default values and calculation methods with one exception; default capital costs have been adjusted for inflation to 2010 values.

The actual components of RainCycle default capital costs are unknown, excepting that a range of storage tank sizes can be input. Due to the limited potential of rainwater capture, only one storage tank size is considered; 10,000 litre. Capital costs and potential savings are provided for this size of storage tank only.

For the 10,000 litre tank, capital costs are given as £6,300. As these are 2005 values, capital costs have been adjusted for inflation up to 2010, this being the most recent date of available Jacobs Well water cost charges. As adjusted for inflation, £6,300 at 2005 prices equates to £7,336 at 2010 prices[6].

Table and Table detail RainCycle output for both six and 13.5 litre cisterns. It can be seen from these that whilst the different cistern capacities affect proportions of water demand met, savings over 50 years and pay-back periods, at 11 years, are similar for both cistern capacities. The savings of £26,250 and £10,465 over 50 years (at 0% and 3% discount[7] rates respectively), add to the benefits of RWH, although in this example they give a small return on investment; the annual savings averaging at £525 and £209 per year over 50 years for each discount rate respectively. (Note, due to limited data, annual maintenance and running costs are unaccounted for).

Table A2.7 illustrates potential savings in 2010 water prices from installing a RWH system for Jacobs Well. It can be seen that greater savings are made, i.e. the cost of harvested water is less, when using six litre capacity cisterns. This is due to the reduced water demand of these cisterns and the greater ability of rainfall to meet this demand.

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[6] Average inflation at 3% per annum. Bank of England.
http://www.bankofengland.co.uk/education/inflation/calculator/flash/index.htm

[7] Discount rates as detailed in TSO (2011); The Green Book, HM Treasury.

(*Due to assumptions made in water use, calculations, adjustments for inflation, limited operational cost data and discount rate applications, values shown are indicative only, and should be viewed with some caution. No operational or maintenance costs are included in cost and savings values*).

Table A2.5; RWH savings & pay-back periods (Comparative table; 6 & 13.5 litre cisterns)

RainCycle Optimise Savings output *Storage tank size; 10,000 litres. Capital costs; £7,337(All prices are 2010 prices)* *Analysis runtime; 50 years. Does not include any maintenance schedule* *Gravity fed supply - no pump costs.* *6 litre cisterns; Mains water cost @ £1.21m^3. Demand 1875m^3/year* *13.5 litre cisterns; Mains water cost @ £1.21m^3. Demand 3917m^3/year*					
Cistern capacity	**Savings over 50 years**		**Pay-back period (years)**		**Demand met (%)**
	0% Discount Rate	3% Discount rate[8]	0% Discount Rate	3% Discount rate[4]	
6 litre	£26,250	£10,465	11	13	29.7
13.5 litre	£26,251	£10,466	11	13	14.2

Table A2.6; RWH system performance (Comparative table; 6 & 13.5 litre cisterns)

Annual performance of RWH system		
	6 litre cisterns	**13.5 litre cisterns**
Water to tank	567m^3/yr	567m^3/yr
Tank overflow	8m^3/yr	8m^3/yr
Number of overflows	7 per year	7 per year
Water demand (urinals & toilets only)	1,875^{3}m/yr	3,917m^3/yr
Water supplied	557m^3/yr	557m^3/yr
Demand met	29.7%	14.2%
Mains top-up required	1,319m^3/yr	3,360m^3/yr

[8] The Green Book. (TSO, 2011).

Table A2.7; Water costs (Comparative table; 6 & 13.5 litre cisterns)

	6 litre cisterns	13.5 litre cisterns
Average cost of mains water per m^3	£1.21	£1.21
Average cost of harvested water per m^3	£0.93	£1.07

If cost values within Table A2.7 are considered in terms of annual, mean average water demand for Jacobs Well detailed in Table A2.3, then the savings potential of RWH become more apparent. Following Waggett and Arotsky (2006), water use for urinals and toilets within offices is estimated at 63% of total water demand; 43% toilet flushing and 20% urinal flushing. Given a mean average, 2008 - 2010 total annual water use of 4098m^3 in Jacobs Well, 63% of this equates to 2582m^3 for urinal and toilet use. Using 2010 prices for water of £1.21/m^3, mains supplied water use for urinals and toilets cost £3124 per annum using 13.5 litre capacity cisterns (2010 prices).

Using the same ratios as Waggett and Arotsky (2006), supplied water costs of £1.21/m^3 and installing six litre cisterns, the annual cost of mains supplied urinal and toilet water would reduce to £1938 per annum, a cost reduction of 62%. By adding a RWH system and reducing mains water supply by 29.7% (Table A2.6), mains water supply costs could be further reduced to £1362 per annum. Given allowances for assumptions and uncertainties in both methods of calculation, this figure compares with that determined by RainCycle output at £1596 for mains supplied top-up water for urinal and toilet flushing (values in Table and Table A2.7). This data is summarised in Table which illustrates potential savings associated with RWH for non-potable water use within Jacobs Well.

Table A2.8; Jacobs Well water demand & costs summary (Comparative table; 6 & 13.5 litre cisterns)

Jacobs Well water demand (2010)		**Water demand** (m^3)	**Annual mains supply water cost** (@ £1.21/m^3 . 2010 prices)
All water use	Total water demand using 13.5lt cisterns	4098	£4959
Toilet & urinal use at 63% of all water use (Waggett and Arotsky, 2006)	Toilet & urinal demand; 13.5lt cisterns	2583	£3124
	Toilet & urinal water demand; 6lt cisterns	1601	£1938
	Toilet & urinal water demand; 6lt cisterns less 29.7% RWH	1126	£1362

	supply		
RainCycle output using calculated water demand	Toilet and urinal water demand; 6lt cisterns	1875	£2269
	Toilet and urinal water demand; 6lt cisterns less 29.7% RWH supply	1319	£1596

Run-off from Jacobs Well

In addition to cost and water supply savings, it is also important to note that of the potential available rainfall falling on Jacobs Well roof per year, 629 m^3/year using a 0.6 yield coefficient (reduced from 1049m^3), 577m^3 of this is supplied to toilets and urinals for flushing (see Table 1 and Table). This equates to a calculated 89% reduction in runoff. Factored up for larger buildings or multiple smaller buildings, this '*distributed attenuation system*' (ARUP, 2011) theoretically provides a considerable reduction in building run-off and thus rainfall entering drainage and sewer systems.

Case Study 1; Cost calculations

Using old, 13.5 litre cisterns;

Average 2008 - 2010 water use; 4098m

Predominant cost water/m^3 in 2010 for Jacobs Well; £1.206 (to £1.21)

Waggett and Arotsky (2006); toilet & urinal flushing = 63% of office water use (43% toilets, 20% urinals)

63% of all water use (4098m^3) = 2582m^3

Cost of 2582m^3 of water for toilet & urinal flushing @£1.21/m^3 = £3124/year (based on old, 13.5 litre toilet cisterns)

Urinal use @ 20% of all use (4098m^3) = 820m^3

Toilet use @ 43% of all use (4098m^3) = 1762m^3 using 13.5 litre cisterns

Using new, 6 litre cisterns;

6/13.5 = 44.4%

44.4% of 1762m^3 = 782m^3 used to flush toilets

Urinal & toilet use = 820m^3 + 782m^3 = 1602m^3 using 6 litre toilet cisterns

@ £1.21/m^3, 1602m_3/year = £1938/year toilet & urinal flushing water costs

£1938/£3124x100 = 62%. £1938 = a 62% cost reduction in toilet & urinal water charges from converting to 6 litre cisterns from 13.5 litre cisterns

Including RWH contributions in Waggett and Arotsky (2006) 63% estimates;

RainCycle demand met proportion; 29.7%

29.7% of £1938 = £576

£1938-£576 = £1362 water supply cost/year for urinal & toilet flushing

RainCycle output water supply costs;

Total annual demand for toilet & urinal flushing; 1875m^3

RWH supply/year; 557m^3 @ 29.7% demand met

RWH water costs per m^3; £0.93.

557m^3 RWH supply equates to £518 per annum saved through RWH supplied water

Mains supplied top-up required/year; 1319m^3

Mains supply water costs m^3; £1.21.

1319m^3 mains supply equates to £1596 per annum cost to top-up supplies to flush toilets & urinals per year.

Calculations contain assumptions, rounding of values and uncertainties. Approximate values only.

£ values at 2010 prices.

Appendix 3: Case Study 2: Rainwater harvesting from domestic buildings - data

TableA3.1; RWH and run-off reductions from domestic properties (a)

Domestic dwellings; available annual rainfall after accounting for losses					
Number of household occupants	Average roof area (m^2)	Available annual rainfall (m^3) after losses			
		Using Wallingford (2011) loss methodology	Using SUDS Solutions (2005) yield coefficients		
			High	Expected	Low
1	57	32.0	35.8	33.8	29.8
2	76	42.7	47.7	45.1	39.7
3	69	38.8	43.3	40.9	36.1
4	76	42.7	47.7	45.1	39.7
5	72	40.5	45.2	42.7	37.7

Domestic dwellings; occupancy numbers, roof area and annual, non-potable water consumption				
Occupants	Average roof area (m^2)	Daily household non-potable consumption (lt)	Annual household non-potable consumption (lt)	Annual household non-potable consumption (m3)
1	57	40	14600	14.6
2	76	80	29200	29.2
3	69	120	43800	43.8
4	76	160	58400	58.4
5	72	200	73000	73

Domestic dwellings; reductions in run-off following RWH - Wallingford loss methodology				
Occupants	Average roof area (m^2)	Annual household non-potable	Available annual rainfall Wallingford	% run-off reduction via RWH consumption

		consumption (m3)	(m^3)	
1	57	14.6	32.0	46
2	76	29.2	42.7	68
3	69	43.8	38.8	113
4	76	58.4	42.7	137
5	72	73	40.5	180

Source data;

Rainfall; 775mm/year. CBMDC data, 2008 - 2010 average annual rainfall data.

Loss methodology/yield coefficient data; Wallingford (2011); 0.5mm wetting loss for all rainfall events, plus additional coefficient losses (ponding, filter etc.) of 0.81. Available rainfall after losses; 562mm (annual). Equates to a 0.725 (72.5%) yield coefficient.

Loss methodology/yield coefficients; SUDS Solutions (2005); available rainfall after roof & 10% filter losses (annual) - High; 0.81 yield coefficient; 628mm; Expected; 0.765 yield coefficient; 593mm; Low; 0.675 yield coefficient; 523mm.

Occupancy & roof area data; Roebuck, 2007.

Non-potable consumption data; Wallingford (2011); Non-potable consumption litres/person/day; 40 (14.6m^3/person/year). Non-potable consumption data; Toilet & washing machine use only. Does not consider outside water use, e.g. garden watering.

Dwelling roof types; presumed pitched roof using concrete roofing tiles; 93% of English dwellings have pitched roofs, roof tiles predominantly of concrete manufacture (DCLG, 2010. English Housing Survey. Housing Stock Report 2008).

DOES NOT ACCOUNT FOR SPILLAGE FROM FULL RWH STORAGE TANKS.

Table A3.2; RWH and run-off reductions from domestic properties (b)

Domestic dwellings; reductions in run-off following RWH - SUDS Solutions '*High*' yield coefficient				
Occupants	Average roof area (m^2)	Annual household non-potable consumption (m3)	Available RWH 'High'; m3/year	% run-off reduction via RWH consumption; 'High'
1	57	14.6	35.8	41
2	76	29.2	47.7	61
3	69	43.8	43.3	101
4	76	58.4	47.7	122
5	72	73	45.2	161

Domestic dwellings; reductions in run-off following RWH - SUDS Solutions '*Expected*' yield coefficient				
Occupants	Average roof area (m^2)	Annual household non-potable consumption (m3)	Available RWH 'Expected'; m3/year	% run-off reduction via RWH consumption; 'Expected'
1	57	14.6	33.8	43
2	76	29.2	45.1	65
3	69	43.8	40.9	107
4	76	58.4	45.1	130
5	72	73	42.7	171

Domestic dwellings; reductions in run-off following RWH - SUDS Solutions '*Low*' yield coefficient				
Occupants	Average roof area (m^2)	Annual household non-potable consumption (m3)	Available RWH 'Low'; m3/year	% run-off reduction via RWH consumption; 'Low'

1	57	14.6	29.8	49
2	76	29.2	39.7	73
3	69	43.8	36.1	121
4	76	58.4	39.7	147
5	72	73	37.7	194

Source data;

Rainfall; 775mm/year. CBMDC data, 2008 - 2010 average annual rainfall data.

Loss methodology/yield coefficient data; Wallingford (2011); 0.5mm wetting loss for all rainfall events, plus additional coefficient losses (ponding, filter etc.) of 0.81. Available rainfall after losses; 562mm (annual). Equates to a 0.725 (72.5%) yield coefficient.

Loss methodology/yield coefficients; SUDS Solutions (2005); available rainfall after roof & 10% filter losses (annual) - High; 0.81 yield coefficient; 628mm; Expected; 0.765 yield coefficient; 593mm; Low; 0.675 yield coefficient; 523mm.

Occupancy & roof area data; Roebuck, 2007.

Non-potable consumption data; Wallingford (2011); Non-potable consumption litres/person/day; 40 (14.6m^3/person/year). Non-potable consumption data; Toilet & washing machine use only. Does not consider outside water use, e.g. garden watering.

Dwelling roof types; presumed pitched roof using concrete roofing tiles; 93% of English dwellings have pitched roofs, roof tiles predominantly of concrete manufacture (DCLG, 2010. English Housing Survey. Housing Stock Report 2008).

DOES NOT ACCOUNT FOR SPILLAGE FROM FULL RWH STORAGE TANKS.

Appendix 4: Case Study 3: Rainwater harvesting and large, warehouse-type buildings - calculations

Table A4.1; RWH from large, warehouse-type buildings - calculations

Annual rainfall	**Warehouse roof area**	**Total annual rainfall falling on warehouse**	**Roof run-off coefficients** (High; 0.9. Expected; 0.85. Low; 0.75)	**Potential collected rainfall per annum** (without accounting for any first flush or filtering losses)
775mm/year	70,000m^2	.775×70000=5,4250m^3	0.9×5,4250	48825m^3/year
			0.85×5,4250	46113m^3/year
			0.75×5,4250	40688m^3/year

Rainfall data supplied by CBMDC. Mean average data for 2008 - 2010

Roof run-off coefficients; SUDS Solutions, 2005.

Roof area determined using ArcMap GIS

DOES NOT ACCOUNT FOR SPILLAGE FROM FULL RWH STORAGE TANKS.

Appendix 5: Bradford city centre; reductions in rainfall run-off through RWH

Table A5.1; UK rainfall, losses and run-off depths

Rainfall based on 100 year rainfall series	Average UK rainfall 713mm/year
Assumed losses due to wetting for every event	0.5mm (75mm per annum. 10.5% of UK average annual rainfall)
Assumed subsequent run-off losses after wetting	10% (presumed to be evaporation, wind blow, rain missing collection devices, ponding etc. Not specified in Wallingford (2011))
Assumed losses due to rainwater filter	10%
Overall run-off proportion for post-wetting losses & filtering	0.81 (81%)
Resultant run-off depth for the UK	517mm/pa (72.5% of UK annual average rainfall)
Source; Wallingford. (2011). *Stormwater Management Using Rainwater Harvesting; Testing the Kellagher/Gerolin methodology on a pilot study*. Report SR736, Release 1.0. July 2011. HR Wallingford.	

Table A5.2; Rainfall, losses and potential reductions in run-off volumes for Bradford city centre

Average annual rainfall; Jacobs Well, Bradford		
Jacobs Well, Bradford, average rainfall (2008 - 2010)	775mm/year	Data supplied by CBMDC
Jacobs Well, Bradford, average annual rainfall factored for losses (net run-off = 'harvesting potential')	562mm/year	775/100x72.5

Volume of rain falling within 2kmsq city centre area, per year		
Volume of rain falling within 2kmsq city centre area per year	3,100,000m^3	2000x2000x0.775
Volume of rain falling within 2kmsq city centre area per year & factored for	2,248,000m^3	2000x2000x0.562

losses		

Building roof area and rainfall available for RWH, per year		
Area of buildings within 2kmsq	1,039,739m^2	Determined using ArcMap
Total volume of rain falling on buildings within 2kmsq area, per year	805,798m^3	1039739x0.775
Volume of rain falling on buildings within 2kmsq area & factored for losses (i.e. available for harvesting from buildings), per year	584,333m^3	1039739x0.562

% reduction in run-off through RWH from buildings, per year		
Jacobs Well annual rainfall factored for losses except filter loss (10%)	624mm	562/0.9
Volume of rain falling in 2kmsq city centre area factored for losses except filter loss	2,496,000m^3	2000x2000x0.624
% run-off reduction following RWH from buildings in 2kmsq city centre area	23%	584333/2496000x100
SPILLAGE FROM FULL RWH STORAGE TANKS NOT ACCOUNTED FOR.		

Appendix 6: Roof yield coefficients, rainfall events and wetting losses

Rainfall event duration and intensity will have a marked effect on run-off volumes, as will variations in roof type and material Short, less intense rainfall events will produce little run-off and so little rainfall to collect due to the initial wetting of roof surfaces and ponding within the roof surface structure. Conversely, as rainfall event duration and intensity increase, proportionally less rainfall will be 'lost' to roof wetting and ponding, and more will be available as run-off. Additionally, if roof surfaces are already wet following earlier rainfall, than run-off will occur quicker from subsequent rainfall events.

Such factors will therefore create an element of uncertainty with respect to roof yield coefficients and calculated volumes of harvested rainwater; whilst a dry, flat roof may well have a yield coefficient of 0.6 at the start of a rainfall event, this coefficient is likely to become less applicable as the roof becomes saturated and rainfall volumes increase; the more rain that falls, the greater the proportion of run-off. As noted by Wallingford (2011), for higher volume rainfall events, the wetting loss of roof surfaces becomes 'trivial'. It should be noted that in addition to wetting losses, losses also occur due to evaporation, more in higher temperatures, and wind.

In considering roof yield coefficients further and based on an assumption that the most frequent UK rainfall events per year have an average rainfall depth of 2mm (comprising 125 events of 170 events per annum), Wallingford (2011) observe that these shallow depth events equate to 35% of total annual rainfall[9]. The shallowness of these predominant events highlights the importance of wetting and evaporative losses relative to rainfall volumes, with Wallingford (2011) noting that initial losses potentially comprise a 'significant component' in run-off assessment.

Neither within the RainCycle tool nor within SUDS Solutions (2005) or an associated paper detailing the use of the RainCycle tool (Roebuck and Ashley, 2006[10]), is an explanation given for the determination of yield coefficients for flat roofs. Whilst some authors provide details of why yield coefficients vary, e.g. roof material entrapping more or less water, many do not.

Table A6.1 examples a range of flat roof yield coefficients identified in literature and via the internet. It can be seen that the range of yield coefficients varies widely, even within the same organisations.

[9]This value is based on an annual UK rainfall depth of 713mm/year using 100 year time series rainfall data. See Wallingford (2011) for further information.
[10]In this paper, a roof yield coefficient of 0.85 is given, although neither roof type nor pitch is given.

Source	Roof description	Yield coefficient
Honigstock (undated)	Conventional flat roof	0.95
Downey (2009)	Flat, gravel and tar	0.8 - 0.85
Environment Agency (2010)	Flat roof with gravel layer	0.8
Farreny *et al*. (2011)	Flat, rough roof	0.62
Worm & van Hattum (2006)	Flat cement roof	0.6 - 0.7
Environment Agency (2009)	Flat roof; smooth surface	0.55
SUDS Solutions (2005)	Flat roof with smooth surface	0.5 - 0.6
Environment Agency (2009)	Flat roof with gravel layer or thin turf (<150mm)	0.45
SUDS Solutions (2005)	Flat roof with gravel layer or thin turf (<150mm)	0.4 - 0.5

Table A6.1; Examples of yield coefficients for flat roofs

The reduced effect of initial wetting losses and therefore the less relevance of roof yield coefficient values as increased volumes of rain falls, and the variety of yield coefficients identified, illustrates the difficulty in producing definitive values for rainwater harvesting and related reductions in run-off volumes to drainage systems; each rainfall event and its antecedent conditions is unique, thus necessitating the use of assumptions and margins of error in calculations.