Rainwater harvesting: model-based design evaluation

S. Ward, F. A. Memon and D. Butler

ABSTRACT

The rate of uptake of rainwater harvesting (RWH) in the UK has been slow to date, but is expected to gain momentum in the near future. The designs of two different new-build rainwater harvesting systems, based on simple methods, are evaluated using three different design methods, including a continuous simulation modelling approach. The RWH systems are shown to fulfill 36% and 46% of WC demand. Financial analyses reveal that RWH systems within large commercial buildings maybe more financially viable than smaller domestic systems. It is identified that design methods based on simple approaches generate tank sizes substantially larger than the continuous simulation. Comparison of the actual tank sizes and those calculated using continuous simulation established that the tanks installed are oversized for their associated demand level and catchment size. Oversizing tanks can lead to excessive system capital costs, which currently hinders the uptake of systems. Furthermore, it is demonstrated that the catchment area size is often overlooked when designing UK-based RWH systems. With respect to these findings, a recommendation for a transition from the use of simple tools to continuous simulation models is made.

Key words | rainwater harvesting, sustainability, tank sizing, water conservation, water demand management

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INTRODUCTION AND BACKGROUND

The uptake of rainwater harvesting (RWH) in the UK has been slow to date. However, this is set to change, particularly in the south-east of England, which has the lowest annual rainfall in the UK and has a low water resource per capita. RWH is now explicitly mentioned in key government documents such as the Building Research Establishment's Environmental Assessment Method (BREEAM 2007*a*) and the Code for Sustainable Homes (DBERR 2007). A rating against the latter became mandatory for all new dwellings in May 2008, although developments only need to meet the minimum standard. Additionally, *Future Water* (DEFRA 2008), the government's water strategy document and water company Strategic Direction Statements (OFWAT 2008), identify that RWH has a part to play in urban water management strategies. Furthermore, the Draft Flood and Water Management Bill (DEFRA 2009) promotes the use of sustainable drainage, defining such structures as '*any feature or aspect of a design that is designed to receive or facilitating the receipt of rainwater*'.

A number of factors have so far contributed to the lack of progress. Ambiguity in the financial viability of RWH systems is a key reason; lack of experience and the absence of well-run demonstration sites is another. Although some technical guidance is available (CIRIA 2001), the costing information provided is sketchy and there is limited advice on the appropriate system sizing methods to use. The outcome is that stakeholders such as local authorities and developers, are still reluctant to implement RWH systems in new developments (or indeed, to retrofit them). Nevertheless, there has been a rise in the number of RWH systems being implemented in new commercial buildings and in schools.

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UK-based RWH system suppliers and other water industry-based stakeholders often use 'rule-of-thumb' or simple mass balance approaches to system design. However, results provided by these tools lack the accuracy and detail to properly size RHW systems and can result in the calculation of unrealistic payback periods or overly optimistic whole life cost scenarios. (Roebuck & Ashley 2006).

A number of detailed models, capable of simulating RWH system design and/or performance have been developed and published and these are summarised in Table 1. Zoppou (2001) and Elliott & Trowsdale (2007) have produced detailed reviews of a range of modelling tools and also assess other urban stormwater drainage practices. Several of these models are either freely available or available to purchase. However, rarely do UK-based non-academic stakeholders utilise such tools, due to an apparent lack of awareness of the availability and capabilities of these tools.

Complex continuous simulation modeling tools do exist within the UK. For example, the Urban Water Optioneering Tool (UWOT) (Liu *et al.* 2007), permits quantitative and qualitative assessment of a range of alternative water management options. These include water efficient appliances, RWH, grey water reuse, SUDs and other decentralised technologies, across a range of spatial and temporal scales. The tool has been developed in Simulink and uses data inputs from an Excel-based user-interface to execute analyses via a DLL file. Technology selection is facilitated by the use of a multi-objective genetic algorithm. UWOT has been utilised to assess technologies in terms of a range of sustainability indicators (environmental, economic, social and technical), as well as to evaluate the inclusion of such technologies within the Elvetham Heath development in the UK (Makropoulos *et al.* 2008). At present work is being undertaken to improve access to and application of UWOT outside the academic arena.

Within the Australian water industry, two main modelling tools are currently utilised to assess RWH systems and other stormwater management practices–PURRS and MUSIC. The Probabilistic Urban Rainwater and wastewater Reuse Simulator (PURRS) is a behavioural model developed to evaluate the detailed design of source control strategies such as RWH tanks and OSD

Table 1 | Existing models for analysing RWH systems

Model	Developer	RWH only?	Functionality
DRHM	Dixon *et al.* (1999)	No	Mass balance with stochastic elements for demand profiling, simulates quantity, quality and costs
Rewaput	Vaes & Berlamont (2001)	Yes	Reservoir model, rainfall intensity-duration-frequency relationships and triangular distribution
RWIN (KOSIM)	Herrmann & Schmida (1999) and ITWH (2007)	No	Hydrological-based high resolution (5 min) rainfall-runoff model
PURRS	Coombes & Kuczera (2001)	No	Probabilistic behavioural, continuous simulation, evaluates sources control strategies
RCSM	Fewkes (2004)	Yes	Behavioural, continuous simulation, detailed analysis of time interval variation and yield-before/after-spill
MUSIC	CRCCH (2005)	No	Continuous simulation, modelling water quality and quantity in catchments (0.01 to 100 km^2)
Aquacycle	Mitchell (2005)	No	Continuous water balance simulation using a yield – before-spill algorithm
RSR	Kim & Han (2006)	Yes	RWH tank sizing for stormwater retention to reduce flooding, using Seoul as a case study
RainCycle©	Roebuck & Ashley (2006)	Yes	Excel-based mass balance continuous simulation using a yield-after-spill algorithm and whole life costing approach
UWOT	Liu *et al.* (2007)	No	Object-based behavioural, continuous simulation using Simulink

(on-site detention) facilities (Coombes & Kuczera 2001). In terms of RWH, the model simulates system performance and assesses storage tank sizes. Rainfall is simulated by a pluvio rainfall generator, when data is available, or by generating synthetic data using DRIP (Disaggregated Rectangular Intensity Pulse) when real data is unavailable (Coombes & Kuczera 2003). PURRS has been utilised to analyse the affect of RWH on stormwater peak discharge levels (Coombes & Kuczera 2001); the performance of RWH tanks for supplementing domestic water supply (Coombes & Kuczera 2003); in the calculation of mains water savings in comparison with other commonly used modeling tools (Lucas *et al.* 2006) and in comparing centralised water distribution systems with RWH in the context of climate change (Coombes & Barry 2007). It has also featured significantly in work undertaken at the Figtree Place water sensitive development in Newcastle, Australia (Coombes *et al.* 1999; Coombes *et al.* 2002).

The Model for Urban Stormwater Improvement Conceptualisation (MUSIC) was developed as an aid to decision making, to evaluate system design and planning strategies for stormwater management. The model provides the ability to simulate both the quantity and quality of runoff from catchments at a range of spatial and temporal scales; 0.01–100 km^2 at 6 min intervals up to 24 hours. MUSIC also models the effects of a range of treatment facilities on the quantity and quality of runoff downstream (CRCCH 2005). However, MUSIC is not a detailed design tool, as it does not contain algorithms for detailing the sizing of structural stormwater quantity/quality structures–it is billed as a 'conceptual design tool'.

Elliott & Trowsdale (2007) highlight the need for the development of both simple and sophisticated models, along with greater application and *testing* of existing models, in order to address gaps in research and knowledge. With respect to this, this paper investigates the design of two new RWH systems; one within an office building and the second being a series of communal systems within a housing development. The aim is to use system design data to evaluate three system design methods, in terms of estimated percentage of demand met and potential financial savings. The impact of the use of different rainfall data resolutions and the effect of analysing a group of communal systems as a whole or as parts will also be evaluated. The methods used within the analyses are applied using a computer-based modelling tool, RainCycle, which represents the state-of-the-art in UK-based system design. The tool is freely accessible via the internet and is utilised for the analyses rather than a more complex or purchasable tool, as it is potentially more readily available to those undertaking RWH system designs in the UK (suppliers, architects, developers etc).

METHOD

Models

Three methods are used within the design evaluation, two of which are based on the approach developed by Fewkes (1999), which built on an original concept devised by Jenkins *et al.* (1978). The core of this approach is a water mass balance in the form:

$$V_t = V_{t-1} + Q_t - D_t \qquad \text{Subject to } 0 \le V_t \le S \tag{1}$$

where:

V_t (Rain) Water in storage at end of time interval, t
Q_t Inflow during time interval, t
D_t Demand during time interval, t
S Storage capacity

From this the 'yield-after-spill' and 'yield-before-spill' (YBS) operating rules were developed (Fewkes & Butler 2000), which take the form (for YAS and YBS respectively):

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

$$Y_t = \min\begin{cases} Dt \\ V_{t-1} + Q_t \end{cases} \qquad V_t = \min\begin{cases} V_{t-1} + Q_t - Y_t \\ S \end{cases} \tag{2}$$

where:

Y_t Yield from store during time interval

The YAS and YBS rules determine the position of supply, demand and overflow in the calculation of storage volume. Fewkes & Butler (2000) undertook extensive analysis of the YAS and YBS algorithms which led to the derivation of capacity-demand and catchment-rainfall ratios (called the demand fraction and storage fraction, respectively. From this research it was concluded that the YAS operating rule (with an hourly or daily rainfall time series) provided the most accurate, conservative results.

Fewkes (1999) and Fewkes & Warm (2000) extended this work and developed a set of generic performance (water saving efficiency, E_T) curves for RWH in the UK. They also established a mathematical relationship for establishing a suitable tank size; an input ratio for the desired RWH system is calculated using:

$$AR/D \tag{3}$$

where:

A	Catchment area (m^2)
R	Average annual rainfall (mm)
D	Average annual demand (m^3)

This is used to locate a desired performance level (E_T) and the number of days storage (X) from the design curves. The tank size can then be calculated using:

$$S = XD_d \tag{4}$$

where:

X	Number of days storage
D_d	Average daily demand (l)

Within the present study, Method 1 is based on the YAS approach in the form of a continuous simulation which can utilise daily rainfall and demand time series, representing the state-of-the-art in UK-based RWH system design. Method 2 is a simplified version of the AR/D approach, which simply takes a user-defined number of days storage (rather than being selected using the AR/D ratio) and multiplies it by an average daily demand. Current best practice recommends that a dry-weather (i.e. a period without rainfall) supply volume equal to six days of demand should be used for the UK, as it is unusual to exceed six days without rainfall (CIRIA 2001). For example, if daily demand is $1\,m^3$, the tank should be $6\,m^3$. This approach was used when applying Method 2.

The final method, Method 3, is based on a different approach recommended by the Environment Agency (EA) (2008). This is a simple 'rule-of-thumb' method, which sizes the tank based on a user-defined percentage of average annual rainfall or demand (whichever is the lower). The equation for this approach takes the form:

$$S = PAC_fFR \tag{5}$$

where:

P	User-defined percentage (current best practise recommends 5%, i.e. 0.05)
C_f	Runoff coefficient
F	System filter efficiency

(R would be replaced by D if the annual demand was the lower of the two).

However, the application of this approach is recommended for smaller RWH systems only, such as domestic systems, as larger systems require a more rigorous analysis due to the complexity of demand patterns (EA 2008).

Analyses were undertaken using an Excel/VBA-based modelling tool, RainCycle (Roebuck & Ashley 2006). This tool implements the above three methods. Within Method 1, the tool optimises a predicted tank size based on inputs such as rainfall and demand level, to provide a balance between the estimated percentage of demand met and potential financial savings in relation to capital cost. Method 1 also includes the facility to calculate the whole life cost, payback period and cost-benefit of a RWH system (with mains top-up) in comparison with an equivalent mains water supply. The outlined methods and tool were utilised within the current study, rather than more academically orientated methods and tools, as they are currently easily accessible (free via the internet) to those who would be involved in RWH system designs (suppliers, architects and so on). In addition, synthetic or long-term rainfall time series were not used, as these would not necessarily be readily available to stakeholders.

Approach

The three previously described methods were used to calculate tank sizes for two case study developments. This was done in order to compare calculated tank sizes

Figure 1 | South-facing facade of the Innovation Centre Phase 2 building (Site 1).

with the actual tank sizes designed and installed by RWH system suppliers.

As previously mentioned, the modelling tool also permits whole life cost and cost-benefit analyses. As the RWH systems used within this study are within new developments no operating costs have yet been accrued. Furthermore, expected maintenance regimes and their associated costs were not available at the time of analysis. For these reasons no whole life cost analyses could be performed. Nevertheless, capital cost information was available; being £15,500 per system (storage tank plus associated piping, pumping and controls, *not* including installation costs) and this was used within Method 1 analyses to yield a payback period for both sites.

In addition, a cost-benefit analysis is given (using capital costs only), by comparing the *financial* savings of using a RWH system (plus mains-water top-up) with only using the mains water supply (this is a default function of the modelling tool). Savings (£) per year figures indicate the potential financial savings made by using rainwater via the RWH system, compared to the cost of supplying water via the mains water supply. Water supply and sewerage charges are held within the modelling tool, which are used to calculate annual mains costs based on the input demand data. Savings are then calculated using these figures in comparison to the volume of RWH utilised to supplement mains water. For whole life costs, a net present value (NPV) discounting approach is used, which is applied across the length of the simulation. As the financial analysis within this paper does not include whole life costs (maintenance, decommissioning etc), the algorithms used to implement these steps are not covered in detail within this paper (see Roebuck (2007) for details). Within the Method 1 continuous simulations, an analysis period of 25 years was used, as this duration is often quoted as being the minimum expected lifespan of RWH system tanks and components (Pushard 2004; WPL 2007).

Site Characteristics

Site 1 - Innovation Centre Phase 2 (ICP2) Building

The ICP2 on the University of Exeter's Streatham campus is an office building (Figure 1), which achieved the BREEAM 'Excellent' rating. The single RWH system within the building is used to supplement mains water and supplies WCs via a large underground storage tank and two header tanks. Additional site characteristics are summarised in Table 2. The building has recently been completed and is now partially occupied. A programme of RWH system monitoring is in place, which includes metering water usage, water quality sampling and a user perception survey.

Table 2 | Characteristics of Site 1 and Site 2

	Units	Site 1	Site 2
Type of development		Office building	Housing development
Size (approx occupancy)		300	415
Type of system		Single site	Communal
Use of RWH system		WCs (toilets)	WCs (toilets)
Standard average annual rainfall (30-year) near site	mm	807 (Exeter)	881 (Bude)
Total (roof) catchment area	m^2	1500	3893 (22.5/property)
Roof catchment characteristics		Flat, smooth	Pitched, tiled
Total storage tank volume	m^3	25	255.5
Average daily demand	m^3	5.19 (working day)*	19.92*
		0.36 (holiday)*	
Total yearly demand	m^3	1353†	7270*

*Calculated within RainCycle.
†Calculated by RWH system supplier.

Site 2 - Broadclose

The Broadclose housing development is located near Bude in Cornwall, south-west England, and is a new-build project involving The Guinness Trust, North Cornwall District Council, the Westcountry Housing Association and Midas Homes Ltd. The need for water efficiency measures was considered right from beginning of the design and planning phases and the homes currently achieve the EcoHomes ‘very good’ rating; EcoHomes is the domestic dwelling equivalent of the BREEAM (BREEAM 2007*b*).

Broadclose contains 173 homes divided across 13 ‘home zones’ (HZ), each of which has a communal RWH system, collecting runoff from south facing roofs, which is used for WC flushing. Additional site characteristics are summarised in Table 2. The mix of housing types within a particular HZ varies, but can include 1-bed flats, 2/3/4-bed houses and 2/3-bed bungalows, as illustrated in Figure 2. Consequently, the main storage tank for each HZ is a different size; runoff collected and demand experienced will vary depending on total roof catchment area and HZ occupancy.

Eight properties in different HZs are being metered as part of a monitoring programme to assess water conservation and financial performance and user perception surveys will be conducted across the entire development.

RESULTS AND DISCUSSION

Design evaluation: Site 1

The RWH system was supplied by Stormsaver, a UK-based supplier. An Excel tool based on the AR/D approach (Method 2) was used by the supplier to design the system. The tool uses parameters including local *annual* rainfall (based on a Met Office 40 year figure), roof area, estimated *annual* demand, number of days required storage, filter and runoff coefficients and system efficiency. The parameter values used in the RWH system supplier design are summarised in Table 3. Although the system manual quotes the pre-tank filter as being able to achieve 95% efficiency, the figure used in the design was 90%, so this has been used in the simulations.

Analysis

The RWH system supplier recommended a storage tank size of 25 m^3 and estimated an annual water saving of 816 m^3 (an estimated 60% of demand met), representing annual financial savings of £1,469 (compared to the mains water supply). The three methods were applied using the same parameter values (Table 3), including the annual demand figure of 1,350 m^3, so that this would not influence the tank sizing comparison. Method 1 simulation results suggested

Figure 2 | Houses and bungalows at Broadclose (Site 2).

that the maximum achievable estimated demand met would be 46% (619 m^3). Thus the supplier's estimate of 60% was potentially over-exaggerated. To achieve this, a 9 m^3 tank would be optimum, which would yield a financial saving of £1,459 per year. Although achieving a slightly lower percentage demand met, a 9 m^3 tank would cost approximately £9,000, leading to reduced capital costs and thus a lower payback period. CIRIA (2001) highlight that tanks are often oversized mainly due to over optimistic assumptions by system designers regarding rainwater catchment and collection efficiency (as identified above). This increases cost, does not allow occasional overflow of the tank and can inhibit rainwater system uptake. Methods 2 and 3 indicated storage tank sizes of 25 and 31 m^3 respectively. As previously mentioned Method 3 should not generally be applied to larger systems; the result is included to show how it compares to the other methods.

Rainfall resolution

In order to investigate the impact of different temporal resolutions of rainfall data, it was decided to use a single 30-year *annual* standard average rainfall figure (the supplier used a 40-year annual non-standard average), as well as a 30-year *monthly* standard average rainfall profile, disaggregated into average *daily* Figs. (month by month) within Method 1. RainCycle divides the monthly figure by the number of days within a month, thus producing *average* daily figures. In this respect, the daily data is not comparable to the variability that would be provided by using a daily long term rainfall time series (which was not available for these sites). Thus Method 1 uses *daily* values averaged from a monthly profile for the length of the simulation, which in this study was set as 25 years. The use of a 30-year average is in line with Environment Agency standard procedure. A 'standard average' *monthly* profile is representative of the variability of a particular month and is calculated using rainfall data for each month over a 30-year period. The use of an EA standard average for an area allows internal consistency across different analyses, as the same well-known and accessible baseline is being utilised.

Table 3 | RWH system supplier 1 design parameters and values for Site 1

Parameter	Units	Value used by RWH system supplier
Local rainfall (annual)	mm	764
Roof area	m^2	1500
Building occupancy		300
Estimated annual demand	m^3	1350
Days required storage		6.8
Demand days		250
Filter coefficient		0.9
Runoff coefficient		0.6
Analysis period	years	25

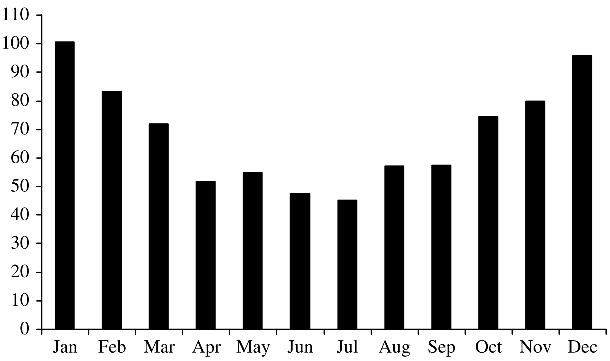

Figure 3 | 30-year standard average monthly rainfall data for Teignmouth (Met Office, 2007).

The EA 30-year standard average (1961–1990) annual rainfall for Exeter was identified as being 807 mm (DCC 2005), however monthly 30-year averages for Exeter were not available. In order to use monthly data, 30-year standard average monthly figures for Teignmouth (26 km from Exeter) were obtained from the Met Office (Figure 3). Teignmouth has a 30-year standard average annual rainfall of 820 mm and experiences the same rain shadow effect from Dartmoor as Exeter (DCC 2005). Utilising this data is a pragmatic approach, as it is readily available to any individual, such as RWH system suppliers. Therefore the authors did not have a data advantage over those who would normally perform system designs. A synthetically generated daily long term time series could have been used, but again this would not be accessible to all.

Simulations were run using Method 1 and the annual 30-year standard averages for Exeter (Simulation 2) and Teignmouth (Simulation 3) and also the *monthly* 30-year standard average profile for Teignmouth (Simulation 4). Results of these simulations and a comparison with the first are summarised in Table 4. Using a 30-year standard average monthly rainfall profile rather than a non-standard annual average increased the percentage of demand met by 3%. As can be seen in Table 4, the potential increase in rainwater utilised also decreased the annual system cost, thereby increasing the total long-term (25 year) savings. Additionally, using the monthly profile disaggregated to daily values, rather than a single annual figure, lead to a recommended tank size increase from 9 to 10 m^3.

Design Evaluation: Site 2

Analysis

The communal RWH systems within Site 2 were designed and supplied by a second RWH system supplier, again using an adaptation of Method 2. All of the parameters used in the supplier analysis were not available and thus some, such as demand, were calculated by the authors. These are summarised in Table 5.

Construction of Site 2 was completed in August 2008, but occupancy figures were not available at the time of the analyses. It was therefore decided to use the average household occupancy rate of 2.4 (DCLG 2006), leading to a total occupancy of 415. A WC volume of 6 l was used (as 6 l flush WCs are now fitted to new homes as standard), along with an average flush rate per day per occupant of 8 (the recommended value within RainCycle). This led to the estimated annual demand figure of 7,270 m^3. Other demand scenarios could have been examined, such as a combination of single or full flushes, but this was beyond the scope of the present study as such scenarios were not investigated by the supplier. A monthly 30-year standard average (1961–1990)

Table 4 | Method 1 results using different rainfall data for Site 1

	Units	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Difference (1 and 4)
Demand met	%	46	48	49	49	+3
Payback period	Years	7	7	7	7	–
RWH system cost	£/year	3,087	2,970	2,935	2,935	−152
Mains supply cost	£/year	4,547	4,547	4,547	4,547	–
Savings	£/year	1,459	1,576	1,611	1,611	+152
Total savings	£/25 yrs	36,482	39,408	40,292	40,285	+3803
Recommended tank size	m^3	9	9	9	10	+1

Table 5 | RWH system supplier 2 design parameters and author calculated values for Site 2

Parameter	Units	Value used by RWH system supplier
Total local rainfall (annual)	mm	881
Roof area	m^2	3893
Occupancy		415
Estimated annual demand	m^3	7270
Days required storage		6.8
Demand days		365
Filter coefficient		0.9
Runoff coefficient		0.85
Run duration	years	25

rainfall profile was obtained for Bude (Met Office 2007), which has an annual total of 881 mm. As runoff is only collected from south facing roofs, the average per property roof size (45 m^2, derived from site plans) was halved and then multiplied by the number of properties (173) to yield an approximate total catchment area.

An initial simulation was carried out using the values for the development as a whole (rather than by HZ). Method 1 results revealed that 36% of the WC demand would be met using RWH, yielding an average annual saving of £756 (compared to the mains water supply) or £4.37 per property, with a payback period of 23 years. No yield or financial data was provided by the supplier for this site, so no comparison could be made. Furthermore, Method 1 indicated the available storage (255.5 m^3) was not fully utilised, being empty on a large number of days and recommending a total storage capacity for the development of 12 m^3. Method 2 and Method 3 calculated tank sizes were 120 and 131 m^3, respectively.

Catchment area

A limiting factor in meeting demand appeared to be the size of the roof catchment area utilised. Using both north and south facing roof faces within Method 1 indicated that 72% of demand could be met with a revised tank size of 34 m^3. This could yield average annual savings of £9,571, or £55 per property, with a payback period of 11 years. Method 2 and Method 3 yielded tank sizes of 120 and 262 m^3, respectively, for the increased catchment area, which are in line with the actual total capacity. The figure for Method 2 does not change, as the method only uses the number of days storage; it does not account for changes in catchment area size.

Method 1 indicated the overall tank volume to be substantially over-sized. Nevertheless, a potential benefit

Table 6 | Comparison of results for each HZs in Site 2 using each method

HZ # Units	% Demand Met	PaybackPeriod	Savings £/year	Catchment area m^2	Actual tank size m^3	Method 1 tank size m^3	Method 2 tank size m^3	Method 3 tank size m^3
1	36.4	19	195	360	27	2	10.9	12.1
2	36.4	14	451	472.5	22.5	3	14.4	15.9
3	35	N/A	−9	270	22.5	2	8.4	9.1
4	35.8	16	349	427.5	27	3	13.2	14.4
5	36.1	15	399	450	22.5	3	13.8	15.2
6	35	N/A	−161	202.5	15	2	6.3	6.8
7	35	22	93	315	17.5	2	9.8	10.6
8	36.4	N/A	−213	180	15	2	5.5	6.1
9	35.8	N/A	−9	270	17.5	2	8.4	9.1
10	36.4	N/A	−213	180	15	2	5.5	6.1
11	36.4	N/A	−213	180	12	2	5.5	6.1
12	35.8	N/A	−263	157.5	15	2	4.9	5.3
12b	35.8	16	349	427.5	27	3	13.2	14.4
Total			755	3892.5	255.5	30	119.8	131.2

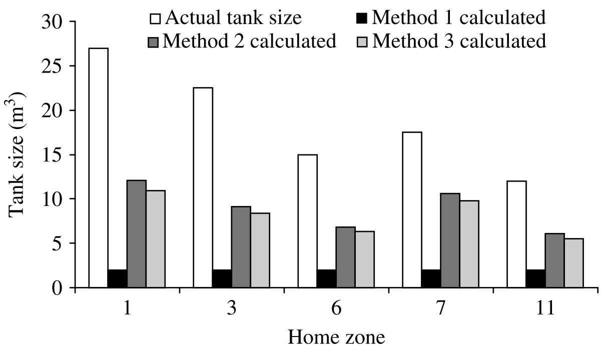

Figure 4 | Differences in HZ tank sizes derived using different methods, for Site 2.

of over-sizing storage tanks is the availability of extra storage capacity to reduce runoff during periods of heavy rainfall (depending on the detailed design of the system and the level of demand permitting an adequate airspace to be available prior to a rainfall event). This could prove beneficial in relation to climate change; projections indicate an increase in winter (already some of the wettest months) precipitation of between 5 and 15% (SWCCIP 2003). This would complement other SUDS techniques in use at Broadclose, such as swales and surface ponds.

To further explore the level of savings and to investigate the sizing of individual HZ storage tanks, the methods were applied separately to each HZ. These simulations used individual tank sizes and calculated the occupancy and catchment area based on the number of properties within each HZ. Table 6 summarises the tank sizing comparison results for each method for each HZ, along with the associated financial savings.

The total volume previously calculated for the whole development using Method 1 was $12\,m^3$, yet the aggregate of the 13 individual HZs tank size analysis is $30\,m^3$. Furthermore, there is a substantial difference between the actual implemented tank sizes and those calculated using the three methods. Tank sizes calculated using Method 1 are between 200% and 600% smaller than those calculated using Methods 2 and 3. It should be noted that had the number of days storage used within Method 2 been increased, tank sizes calculated would have also been higher (perhaps closer to the actual tank sizes installed). A comparison of actual tank sizes and those calculated using the various methods is illustrated in Figure 4 (for a selection of HZs, representative of tank sizes present in the development).

It was also identified that although the same annual financial savings were achieved, the distribution of the savings was highly variable across the HZs; some sustaining annual savings of £451 and others *losses* of £263 (compared to the mains-only water supply).

CONCLUSIONS AND RECOMMENDATIONS

The design of two RWH systems in two distinct new-build developments have been evaluated using three design methods integrated within a modelling tool. The tool represents the state-of-the-art in current UK-based RWH system design. The main findings were:

(1) WC demand levels of between 36% (for a group of communal domestic systems) and 46% (for a commercial system) could be met using RWH;
(2) Design methods based on a simplified AR/D approach and the EA approach generated tank sizes substantially larger than the YAS-based continuous simulation. Tanks within the case studies presented are considered to be oversized for the specified demand levels and catchment sizes, which is due to the type of design method enlisted by the RWH system suppliers;
(3) Despite overestimating tank sizes, the annual financial savings calculated by the RWH system supplier method (AR/D) were similar to those using the continuous simulation. However, payback periods would be significantly longer due to higher capital costs of larger tanks and thus the continuous simulation provides a better assessment of tank size in terms of cost-benefit analysis for a particular demand met level;
(4) Modelling several communal RWH systems as a whole rather than as separate systems can have implications for tank sizing results;
(5) Levels of demand met were limited by the catchment area size, which also had implications for financial savings. This indicates not enough consideration is given to the catchment size when designing a RWH system;

(6) The use of non-standard average rainfall data resulted in an underestimation of the demand met and the associated savings from implementing a RWH system;
(7) Financial savings made were greater for a large commercial building than for a series of communal systems within a housing development.

Based on these conclusions the following recommendations are made:

(1) A transition from the use of simple RWH system design methods based on single calculations to more sophisticated continuous simulation tools is necessary in the UK. This could be facilitated by increasing stakeholder awareness of the availability and capabilities of such tools;
(2) Stakeholders considering implementing RWH within a development need to be aware of the importance of sizing the roof collection area supplying a RWH system (as well as the building demand), in addition to appropriately sizing the storage tank;
(3) Stakeholders responsible for designing RWH systems should be made aware of the importance of using and promoting the use of EA standard average rainfall data, in order to promote consistency in analysis, whether using simple or complex design methods;
(4) Emphasis needs to be placed on the use of higher resolution rainfall data. Ideally daily data should be used but at least a monthly profile (disaggregated to daily, where daily data is not available), rather than a single annual figure, which seems to be current standard practice.

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