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Rainwater Harvesting: Trade-offs between Urban Pluvial Flood Risk Alleviation and Mains Water Savings

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Abstract: Stormwater run-off generally refers to pluvial (i.e. rainfall related) water that does not soak into the ground at the point at which it falls. The volume and timing thereof, specifically from roof tops is highly influential to urban flood control in addition its capture has the potential for non-potable uses within (e.g. for WC flushing and for washing machines) and outside the home (e.g. car washing and garden watering). The former runs a risk of flash floods where local and downstream stormwater (or combined sewer) systems become overburdened in times of extreme rainfall events. The later will influence potential future urban water supplies, which is particularly important at time(s) where mains water availability is scarce (e.g. times of drought or when the national demand for water in the UK increases beyond supply capabilities) population. Rainwater harvesting (RWH) systems can benefit flood risk and water supply however their ability to do either / both is dependent on the subtleties of filling and emptying (i.e. stored water volume or spare storage capacity) which are not fully understood, particularly in peak flow events. Through the use of five years worth of daily rainfall data for Birmingham (2007 - a record breaking year for UK flooding, to 2011) these subtleties are investigated through a sensitivity type analysis of tank size, occupancy rates and technology efficiency. The results show that RWH tanks sized according to BS8515 would not have been capable of capturing rainfall that fell in peak flow events. Moreover not all yearly non-potable demands would have been met. A simple intervention could re-engineer urban RWH systems; over-sizing RWH tanks by a factor of 3.0 (i.e. use the larger of 15% yearly non-potable demands or rainfall) would allow for non-potable demands to be met and roof-top run-off eliminated.

Keywords: Rainwater harvesting; Pluvial flood risk; Sustainable urban Drainage.

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1. Introduction

Urban Pluvial flooding in towns and Cities around the world are caused by high intensity and/or prolonged rainfall events which inundate surface water removal networks (i.e. stormwater and/or combined sewer systems) rendering them incapable of removing surface water sufficiently fast to avoid back up and ultimately flooding (Houston et al., 2011). In extreme rainfall events the ensuing flooding can cause costly devastation, exampled most dramatically in 2007 where the UK experienced the wettest May to July period for over 250 yrs resulting in 55,000 homes being flooded (EA, 2007, Cabinet Office, 2007). Pluvial events are most pronounced and likely in urban areas due to the predominance of impervious surfaces (tarmac / concrete roads, pavements and pathways and rooftops) which have inadvertently interrupted the natural infiltration process of the water cycle (UN, 2009, Rozos and Makropoulos, 2013). Despite engineers' best attempts to manage these natural systems over the last century, through engineered pipe network solutions, the frequency at which they are being tested beyond their original design parameters (e.g. 6DWF) is becoming ever more frequent. Moreover it is estimated that due to the onset of climate change and yet more increases in impermeable urban surface areas that in 2050 within the UK approximately 3.2 million people will likely be at risk of pluvial floods (EA, 2009). Part of the problem of pluvial flood risk is in its unpredictability, due to the unbounded broad range of street furniture that exists which facilitates run-off (EEA, 1999). In addition there are the inherent complexities of both mapping and management (Falconer et al, 2009). Part of the solution is to develop new tools and strategies through broad-based European studies (e.g. EU RainGain and EU FLIRE) and to upgrade and decouple all poor capacity sewerage and stormwater systems (Severn Trent Water, 2014). In addition, SuDS surface water management systems (Woods-Ballard et al, 2007) offers significant potential to and to limit the number of properties and people at risk of flooding through increasing natural attenuation - or simply through intermediate holding of rainwater until these large pluvial surges subside. Roof space accounts for a significant percentage of urban impermeable surfaces in densely populated areas within cities and therefore reducing the rooftop to river flows (Garrison and Hobbs, 2011) is a key factor to be considered.

At the same time an equal risk within the City water supply systems is developing. Increased urbanization has played, and will continue to play, a significant role here in terms of rapid increases in water flows (i.e. those coming into and those needing to be moved out of the city) to match increasing demands (Atkins, 2013). This requires a reconsideration of how we use and source available local water making use of what may have traditionally been considered softer options (Brandes et al, 2009). Rainwater harvesting (RWH) is one such method where non-potable (i.e. not drinkable) water is captured (typically from rooftops), stored (in a tank) and subsequently used without treatment – this is possible, due to the fact that not all of our urban end-uses require mains quality water (Thomas, 1998, Leggett et al., 2001, Fewkes, 2006, EA, 2010, UKRHA, 2011). For example, in the domestic sector, for an average dwelling, 37% of demands (for toilet flushing and clothes washing) are non-potable (see Section 2). In actuality, RWH offers the potential to both reduce pluvial flood risk and to partially meet future water demands in densely populated areas (Nolde, 2007), not least in the UK (Fewkes, 2012). However, the more favorable outcome for each, as in life, depends on whether the tank is viewed as half full or half empty; success in mitigating for pluvial flood risks depends on how empty the tank is and success at meeting demands depends on how full the tank is. Therefore a trade off must exist, and this will be greatly influenced by the dynamics of the tank filling through rainfall capture and emptying through demand draw-off (Ward et al, 2010, Hunt et al 2012). Both are prone to variability making performance prediction therein far from straight forward.

By using five years worth of rainfall data from Birmingham, the UK's second city (Figure 1), this paper asks the following key question in respect to this trade-off: '*to what extent and at what additional costs can domestic RWH minimize rooftop run-off whilst meeting non-potable demands?*' The underlying six-step methodology is outlined in Section 2 with results being presented in Section 3 then discussed in Section 4. Conclusions are subsequently drawn in Section 5.

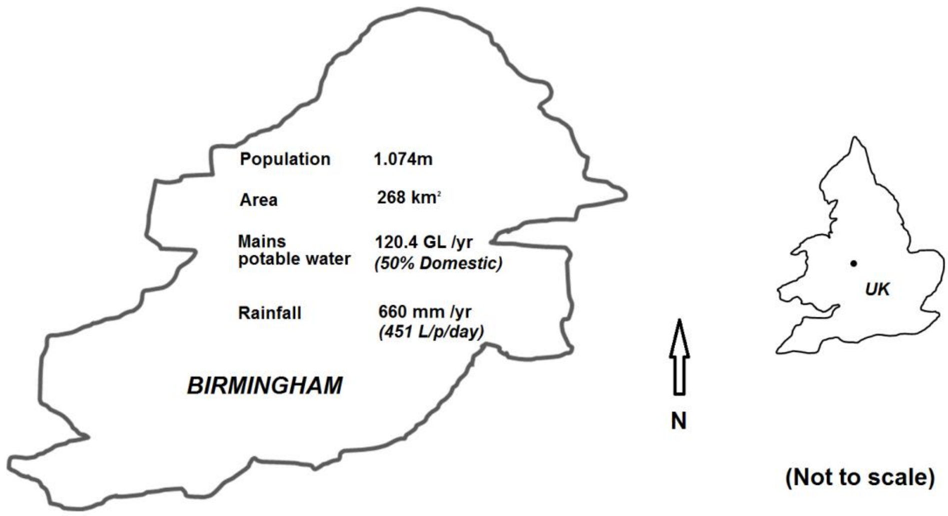

Figure 1: Birmingham, UK, showing key water data and geographical location.

2.0. Methodology:

The methodology consists of six key steps as listed below, a detailed description of each follows.

Step 1 – Calculate non-potable demands (Section 2.1)
Step 2 – Calculate potential non-potable rainwater supplies (section 2.2)
Step 3 – Size RWH tanks and asses yearly performance of system (Section 2.3)
Step 4 – Calculate yearly payback for investment (Section 2.4)
Step 5 – Conduct a sensitivity analysis (Section 2.5)
Step 6 – Discuss results and strategise on RWH interventions (Section 4)

2.1 Step 1 - Calculating non-potable demands.

Total daily water demands per person are assumed to be 147 litres. This is in broad agreement with the values reported by (Farmani et al, 2012, Hunt et al, 2012, Zadeh et al, 2013, Zadeh et al, 2014). The breakdown by end-use is given in Table 1 from where it can be seen that each water demand (I to vii) is calculated by multiplying a technology factor by a behaviour factor - adopted directly from the Code for Sustainable Homes (see DCLG, 2007, Hunt et al, 2012, 2013). It is well-reported that rainwater can be used for WC flushing and Washing machines (Legget et al, 2001) therefore these total non-potable demands for the specified daily demand are 53.8 litres / person / day (Table 1). The daily household non-potable demand is 129.2 litres, calculated by multiplying the total daily demand per person by the occupancy rate (assumed average occupancy rates of 2.4, Office of National Statistics, 2011). A recent study by EST suggested that the total demand per person may decrease as occupancy rates increase (EST, 2013), however, the subsequent relationship between water uses i) to vii) and respective influencing factors (Table 1) were not explored here. In actuality technological factors (T) would likely not change, although user behaviour factors (U) could. For further information on the influence to demand of making changes to T and U see, for example, Zadeh et al., 2014.

Table 1. Breakdown of household water demands (*Italics* shows non-potable uses)

Water use	**Technological factor (T)**	**User behavior factor (U)**	**Total water demand(s)** (litres / person / day)
i- Basin	-	-	1.7
ii- Bath	230 litres / bath	0.11 baths / day	25.3
iii – Shower	12 litres / minute	4.37 minutes /day	52.4
iv – Sink	-	-	10.4
v – Dishwasher	1 litre / place setting	3.6 place settings / day	3.6
vi - Washing Machine	*13 litres / kg*	*2.1 kg /day*	*27.3*
vii - WC	*6 litres / flush*	*4.42 flushes / day*	*26.5*
viii – Total demand *(non-potable = vi + vii)*			147.1 *(53.8)*
ix – Total household demand *(non-potable = occupancy x viii)*			352.8 *(129.2)*

This paper assumes a linear relationship between non-potable demands and occupancy with the proviso that it is appreciated that subtle changes can exist (EST, 20013, Bello-Dambatta et al, 2014) however they are not considered as variables here.

2.2. Step 2 - Calculating potential non-potable RWH supplies.

In this step potential rainwater supply volumes are calculated according to Equation 1.

$$Q_t = R_t.A.(Z_1.Z_2.Z_3) \tag{1}$$

Where:

Q_t = Flow into RWH tank in time t (Litres);
R_t = Average rainfall in time t (mm);
A = Plan surface area of the roof (m^2);
Z_1 = Coefficients for roof pitch (dimensionless);
Z_2 = Coefficients for material type (dimensionless);
Z_3 = Coefficients for filter (dimensionless);

Typically RWH suppliers will base estimates of rain water supplies using three approaches with increasing levels of data refinement.

Approach 1: Yearly rainfall data (single value);
Approach 2: Monthly rainfall data (averaged to give daily values for each month);
Approach 3: Actual daily rainfall data (applied directly for each day).

In this research the rainfall data (R_t) is taken from the Birmingham Wast Hills Observatory weather station (established 1982) which collects rainfall via an automated Tipping Bucket Rain Gauge (TBRG) and provides digital output data half-hourly data for actual rainfall (mm) and rate of rainfall (mm/hr).

In Approach 1, R_t is the total accumulated rainfall in a single time step (of 365 days) whereas in Approach 2 and 3 it is calculated on a daily basis using 365 separate time steps (i.e. from t_0 to t_{364}). The inefficiencies of Approach 1 and Approach 2 (where data is usually easy to obtain) for calculating Q_t when compared to Approach 3 (where data is sometimes hard to obtain) are discussed further in Section 4.3.

It is assumed that not all the rainwater that falls is collected. In this paper assessment losses are assumed to occur from a pitched (Z_1 = 0.9) tiled (Z_2 = 0.95) roof with in line filters (Z_3 = 0.95). In other words 81% of the rainfall volume falling on the roof is successfully collected for re-use (Woods-Ballard et al, 2007).

2.3. Sizing RWH tanks and assessing yearly performance

Step 3a – Sizing:

In the UK RWH tanks should be sized according to BS8515; i.e. the lower of 5% annual household demand (Section 2.1) and 5% annual rainwater supply (Section 2.2). This means that homes located in areas with low rainfall areas (i.e. South East, UK) and/or homes with low occupancy rates will adopt smaller tanks than those in high rainfall areas (i.e. North West, UK) and/or homes with high occupancy rates (Hunt et al, 2014).

Step 3b - Assessing yearly performance:

The performance assessment of tanks considers two specific aspects:

Aspect 1 – Resource security - Ability to meet non-potable demands through RWH (Section 3.2);
Aspect 2 – Flood risk: Ability to reduce 'Pluvial' flows through RWH (Section 3.3);

Both aspects rely on a water balance equation, adapted from McMahon et al. (2007).

$$V_t = V_{t-1} + Q_t - D_t \quad (2)$$

Subject to $0 \leq V_t \leq S$

Where:

V_t = Stored water in RWH tank at time t (*Litres*);
V_{t-1} = Stored water in RWH tank in time $t-1$, i.e. stored water volume from previous day (*Litres*);
Q_t = Flow into the RWH tank in time t *(Litres)*;
D_t = Non-Potable demand in time t (*Litres*);
S = Useable RWH tank volume (*Litres*).

A 'yield-before-spillage' approach is adopted (Mitchel, 2007 Roebuck, 2007, Hunt et al, 2011, 2012) and spillage (i.e. overflow) occurs once S is exceeded. The total yearly overflow O_{hh} per household (l/hh/yr) for the RWH tank is the sum of the daily spillages. No leakage or evaporation losses are assumed within the tank itself (it is essentially a sealed underground unit, Chu et al, 1997). In essence therefore this means when daily inflows are insufficient to meet daily non-potable demands water levels *'drawdown'* will occur within the RWH tank and where daily inflows are more than sufficient to meet daily non-potable demands a *'topping up'* will occur. If the RWH tank is empty or to be more precise, the extractable volume is zero [an RWH tank will never empty as a 'reserve' is maintained to ensure the pump remains submerged.] then no draw down can occur and the demands will be met through mains water. When the tank is filled any overflow passes into the mains storm water system or (in some cases) combined sewer systems adding to pluvial flood risk. Where sufficient 'empty' storage space (or *holding capacity*) occurs within the tank pluvial flood risk is reduced.

2.4. Step 4 - Calculating yearly 'payback' from investment

The payback considers.

Aspect 3 – Economics: Ability to save money through RWH (Section 3.4).

Payback periods for RWH system are typically worked out by assessing the total cost of an investment (I) divided by the yearly payback (E). In this paper the yearly payback comes from substitution of mains water (which is chargeable) with rainwater (which is free). This is defined here through three equations:

$$E_1 = E_{mw}.d_{hh} \quad (3)$$

$$E_2 = E_{mw}.D_{hh} \quad (4)$$

$$E_3 = (E_{mw}.Q_{hh}) + E_{sw} \quad (5)$$

Where:

E_1 = Yearly payback actually achieved per household per year (£/hh/yr)

E_2 = Yearly payback potential per household per year calculated based on the savings that could have been made if all the non-potable demands had been met through non-potable supplies (£/hh/yr)

E_3 = Yearly payback potential per household per year calculated based on the savings that could have been made if yearly overflow O_{hh} is completely eliminated, i.e. through total rooftop rainwater capture and use from a single dwelling (£/hh/yr)

E_{mw} = Cost (to the customer) of mains water (£/l)

E_{sw} = Property surface water charge (£/hh/yr)

d_{hh} = Non-potable water use per household per year (l/hh/yr)

D_{hh} = Non-potable water demand per household per year (l/hh/yr)

Q_{hh} = Flow into tank per household per year (l/hh/yr)

Within this paper it is assumed that E_{mw} is £0.0153/l and E_{sw} is £91.85/hh/yr based on a new 3 bedroom property, where 'new' refers to a property without a 1989/1990 rateable value. Values refer to charges for 2013/2014 from Severn Trent Water, which supplies Birmingham (STW, 2013).

2.5. Step 5 – Conducting sensitivity analyses.

A series of sensitivity analyses were conducted in order to ascertain their respective influence on Aspect 1 and Aspect 2. These considered changes to:

- Household non potable demands - through occupancy rates (3.2.1)
- RWH tank size (3.2.2)

3. Results

3.1. Base Case

The base case refers to a household of 2.4 occupants using 147l/person/day (Table 1) with a $50m^2$ roof and a 2358 litre tank sized according to BS8515.

Table 2. Yearly household water flows and economic savings
(2358 litre tank, $50m^2$ roof, 2.4 occupants, 147l/person/day demand)

Year	Q_{hh} (l/yr)	d_{hh} (l/yr)	D_{hh} - d_{hh} (l/yr)	O_{hh} (l/yr)	E_1 (£/hh/yr)	E_2 (£/hh/yr)	E_3 (£/hh/yr)
2011	35,218	30,795	16,363	4,423	47.1	72.2	145.7
2010	42,281	37,494	9,664	4,787	57.4	72.2	156.5
2009	33,093	31,087	16,071	2,006	47.6	72.2	142.5
2008	26,122	25,518	21,640	604	39.0	72.2	131.8
2007	17,890	17,890	29,268	0	27.4	72.2	119.2
Totals	154,604	142,784	93,006	11,820	218.5	360.8	695.8

Rainfall over a 5 year period (2007 to 2011) is considered - the minimum adequate requirement to ascertain real variations in low security rainwater catchment systems, such as RWH tanks (Heggen, 2000, Thomas, 2004).

3.2. Aspect 1: Resource security - ability to meet non potable demands through RWH

The total yearly non-potable household demand *(D_{hh})* is 47,158 litres/yr (i.e. 129.2 l/hh/day x 365 days) or 235,790 l for the 5 year period. From Table 2 it can be seen that 60% of this non-potable demand would have been met (Table 2). In all years non potable demands would not have been met requiring mains water to be used for non-potable end uses. The worst performing year was 2011 when only 38% of demands were met and the best performing year was 2007 when 65% of demands were met.

3.3. Aspect 2: Flood risk - ability to reduce 'Pluvial' flows through RWH

Over the five year period the overflow *(O_{hh})* was reduced by 92% through using available rooftop water *(Q_{hh})*. The least overflow was in 2011 when no spillage occurred and the highest overflow) was in 2008 when spillages of 4,787 l/yr occurred. One might consider then that 2008 would have been the worst year for flood risk based on Table 2. However by inspection of Figure 2, which shows: daily refined rainfall, RWH tank volume(s) and stormwater volume(s) over the 5 year period, a different story emerges. The summer of 2007 was in fact the wettest since records began; the met office reported that on average 414mm falling over the UK in 3 months (May to July) (EA, 2007).

This continued rainfall meant that even in the presence of an RWH system its ability to reduce pluvial flood risk was tested (Figure 2e). For example, in this period overflow was reduced by 73% in June (O_{hh} = 1519.4 litres) and 65% in July (O_{hh} = 2903.8). This is not insignificant and becomes even more striking when one considers that the rain fell over a 4 day period in June (i.e. O_{hh} = 467 litres on 15th; 148 litres on 18th; 168.7 litres on 22nd and 434.6 litres on 25th) and 8 days in July. This was dominated by an O_{hh} of 2000 litres on 20th July when 49mm of rain fell in one day. This event in particular would have made a major contribution to the risk of pluvial flash flooding and the RWH tank, designed according to BS8515, did little to ameliorate its impact. This was because the RWH tank even with repeated draw off remained close to its filling capacity for long time periods.

3.4. Aspect 3: Economics - ability to save money through RWH

In terms of economic savings (E_1) the RWH system would have saved a total of £218 over the five year period (Table 2) with the highest return (£47) and lowest return (£27) occurring in 2008 and 2011 respectively. These total savings could have been increased by a factor of 3.2 (through total rooftop rainwater capture E_3) and 3.75 (through meeting all non-potable demands – E_2).

3.2. Sensitivity analyses.

Throughout the sensitivity analysis all changes are compared to the base case (Section 3.1).

3.2.1. Sensitivity analysis 1 - Changing non-potable demands through occupancy rates:

By increasing the occupancy rate to 4 (Table 3) yearly non-potable demands (D_{hh}) increased by 66% (to a total of 78577 l/yr), requiring a 20% increase in tank size (based on BS8515). The volumes of water collected from the rooftop (Q_t) remained unchanged as the same base conditions (i.e. for rainfall and roof area) applied. Over the five year period this resulted in an 8% increase in non-potable water use (d_{hh}) and a 96% reduction (to 552 litres) in total overflow (O_{hh}). This overflow occurred in a single year (2008) meaning that in the other 4 years it had been prevented – this included the peak storm event on July 20th 2007. Unfortunately, available non potable supplies were insufficient (D_{hh} - d_{hh} = 238,931 l) to meet non potable demands due to the fact that demand outstripped supply by 54% (i.e. $Q_t << D_{hh}$).
Over the five year period the value of E_1 increased by £17 (8%) only, although the potential savings E_2 increased by £241 (8%). Q_{hh} and E_3 remain unchanged being directly related to each other.

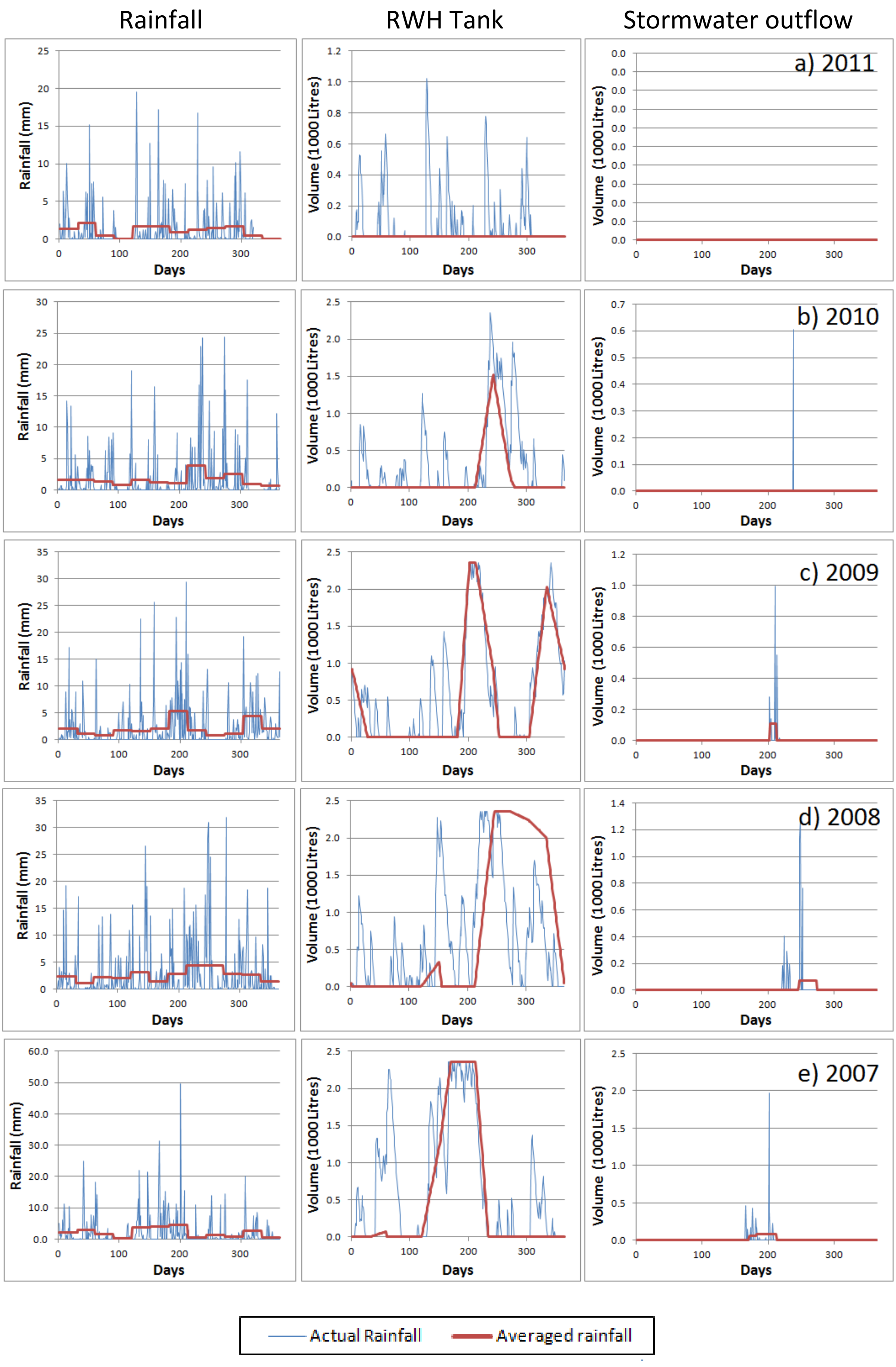

Figure 2. Fluvial flows due to captured rainfall from rooftops.

Table 3. Yearly household water flows and economic savings (2854 litre tank, 50m^2 roof, 4 occupants)

Year	Q_{hh} (l/yr)	d_{hh} (l/yr)	D_{hh} - d_{hh} (l/yr)	O_{hh} (l/yr)	E_1 (£/hh/yr)	E_2 (£/hh/yr)	E_3 (£/hh/yr)
2007	35,218	35,218	43,379	0	53.9	120.3	145.7
2008	42,281	41,729	36,868	552	63.8	120.3	156.5
2009	33,093	33,093	45,504	0	50.6	120.3	142.5
2010	26,122	26,122	52,475	0	40.0	120.3	131.8
2011	17,890	17,890	60,707	0	27.4	120.3	119.2
Totals	154,604	154,052	238,931	552	235.7	601.3	695.8

By decreasing the occupancy rate to 1 (Table 4) the non-potable demands decreased by 58%% (to a total of 19,649 l/yr), which required a 58% reduction in tank size (according to BS8515). Whilst plenty of rain fell on the roof space and yearly non-potable demands were easily met (i.e. Q_{hh} >> D_{hh}) this resulted in a 567% increase (compared to the base case) in total overflow to (67,008 l) over the five year period. More importantly this overflow occurred for sustained periods in all five years.

Over the five year period the value of E_1 decreased by £84 (39%), and potential savings E_2 decreased by £210 (58%). Q_{hh} and E_3 remain unchanged being directly related to each other.

Table 4. Yearly household water flows and economic savings (982 litre tank, 50m^2 roof, 1 occupant)

Year	Q_{hh} (l/yr)	d_{hh} (l/yr)	D_{hh} - d_{hh} (l/yr)	O_{hh} (l/yr)	E_1 (£/hh/yr)	E_2 (£/hh/yr)	E_3 (£/hh/yr)
2007	35,218	17,824	1,825	17,394	27.3	30.1	145.7
2008	42,281	19,419	230	22,862	29.7	30.1	156.5
2009	33,093	17,792	1,857	15,301	27.2	30.1	142.5
2010	26,122	17,309	2,340	8,813	26.5	30.1	131.8
2011	17,890	15,252	4,397	2,638	23.3	30.1	119.2
Totals	154,604	87,596	10,650	67,008	134.0	150.3	695.8

3.2.2. Sensitivity analysis 2 – Changing the size of RWH tanks:

When taking the base case and over-sizing the tank to 5000 Litres would have eliminated roof top run-off in June 2007 and reduced the run-off volume on June 20th 2007 to 1780 Litres. A further over-sizing to 6000 litres would have reduced run-off to 780.5 Litres. To have eliminated stormwater outflow *(O_{hh})* from rooftops in all years the RWH tank volume would have needed to be 6800 litres (2.9 times larger than that advocated by BS8515).

When considering whether it is worth the cost of over-sizing the tank in order to capture all peak fluvial incidents it is worth identifying system that domestic RWH system can cost anywhere between £2,500 and £6,000 depending on the size of the tank (Roebuck, 2007, EA, 2009, Fewkes, 2012). The tank (and associated extra labour costs involved with increased ground works) is reported to be the most expensive item and therefore the main component of any additional investment requirements (EA, 2011). The cost of other ancillary items (i.e. pipework, filters, pumps etc) could be assumed to be relatively unchanged. This is because pumping capacity, pipe lengths and diameters would not need to be altered.

Table 5 shows that by resizing the tank by a factor of 7 times (i.e. 1000 to 7000 litres) the total cost quadruples, hence an economy of scales exists. At the same time the resulting monetary payback (excluding any interest) also more than quadruples (from £134 to £696 - E_3 in Table 3) over the five year period.

Table 5. Cost of Rainwater Harvesting tanks and soil excavation and disposal.

Tank size (litres)	**Height (m)**	**Diameter (m)**	**i - Cost[a] (£)**	**ii - Soft soil Excavation[b] (£)**	**iii - Soft soil disposal[c] (£/m^3)**	**iv - Total (i + ii + iii)**
1000	1.2	1.0	359	40	105	504
2800	2.18	1.55	766.80	112	132	1011
3500	1.25	2.15	1,122.99	140	143	1405
5000	1.68	2.15	1,498.80	200	205	1904
7000	2.20	2.15	1,529.99	280	235	2045

Notes: [a] Tanks from www.rainwater-harvesting.biz; [b] Excavation £40/m^3; [c] Deposited at no more than 25m distance to a skip £15/m^3 - skip hire: 6m^3 (Midi) for £130, 3m^3 (mini) for £90, skips are assumed to be filled only to the maximum capacity specified (Hunt et al, 2014).

4.0 Discussion

4.1. To what extent can we meet demands and minimise flood risk?

When one solution (RWH) is used to maximise dual benefits each of which has opposing requirements, undoubtedly a trade-off will exist. The influencing factors for RWH to meet demands is that there is sufficient stored water and the influencing factor for minimising flood risk is that there is sufficient ‘spare’ empty storage capacity to capture rainfall. Demand influences directly the rate at which water is drawn off and is highly influenced by occupancy (modelled herein) but also the influence of micro components (Zadeh et al, 2014 and Butler et al., 1991) and user behaviour which can change daily and seasonally (Butler, 1991). The point is that lower daily demands (e.g. through low occupancy) are more likely to be met than higher demands (e.g. through high occupancy) and whilst this is accompanied by lower investment costs the payback is also much less. The direct advantage of having higher demands is that daily draw off keeps ‘spare’ empty storage capacity high, maximising the potential for alleviating pluvial flood risk, the opposite is true where demands are low. Over sizing tanks using a *‘15% rainfall’* rule in BS8515, rather than 5%, would offer greater potential to meet all non-potable demands, however this would come at a premium. Although this premium may be worth paying as it can significantly reduce stormwater rooftop run-off and lower pluvial flood risk. Moreover the premium would not exist if water providers waivered the stormwater charge for those who invest in these larger tanks. Conversely sizing tanks according to *‘5% demand’* rule would have significant limitations in certain circumstances where RWH had been adopted as a dual solution. For example, a very large house (and roof space) with low demands (e.g. single occupancy) would adopt a small tank (according to BS8515) and yet a large rooftop to river run-off will exist. Hence the 15% rainfall rule would work here also. One influencing factor is whether individual households will have sufficient ‘spare’ underground space either to the front or rear of the property. Fortunately, the tank height considered here (1 to 2m max) meant that costly groundworks (>2m) were avoided and it was the diameter only which increased. Although this may be prohibitive where limited outside space exists. The other problem could arise where a large tank is adopted and demand is low, meaning that the tank will for the most part remain very full even though sufficient empty spare storage capacity is a key requirement. In addition the last thing you would want is for water to be sitting in a tank for long periods stagnating. So perhaps what is required is a smarter system that maintains levels appropriate to the lower demand (through a float system) which allows for pluvial flows to be captured and diverted at times when peak events have sufficiently subsided. This would have the added benefit that the tank would be capable of meeting the needs of the household (through changing the float setting) should the occupancy number increase. Another option is to use RWH as part of an interconnected multiple-dwelling (or building) community system which allowed for multiple-node RW collection and redistribution. For RWH to be a truly impacting urban solution for mitigating pluvial flood risk and meeting demand within cities it would need to have widespread uptake and not just in the domestic sector as considered here.

4.2. Is it economically viable and feasible for cities in the UK?

In this research it has been shown that the largest economic savings possible could only be achieved if all domestic (rooftop) run-off were eliminated and all domestic demands were met. However one stumbling block is that in reality the savings shown here could only ever occur if provision were made by local water companies to waiver the property surface water charge (E_{sw}) where no rooftop run-off occurred. Is this feasible? Certainly it would require assurance to water companies that no run-off has occurred. One option could be a total disconnection of the guttering system from the mains however it is dubious as to whether this would ever be allowed to happen. A second option might be to ensure that all guttering is connected to the RWH tank and any overflow is subsequently metered (an additional ‘smart’ feature perhaps), in this way the user is directly charged for the amount of rooftop run-off that occurs. In this way it also provides the ideal incentive for domestic users to invest in RWH systems. The shortfall here is that those that can pay will.

A more feasible solution might be to use policy instruments to push rather than nudge those with bigger domestic roof spaces in higher flood risk areas to look at alternatives such as RWH. RWH is actively supported in many regions, including Australia, Canada, USA, Korea, Tawian (Schuetze, Santiago-Fandiño, 2013) but this carrot falls well short of the stick. For example, in regions such as Japan, RWH has long been compulsory for buildings over 30,000m^2 (Leggett et al., 2001) and more recently in the Flemish region of Flanders (Belgium) this applies to any roof-surface over 70m^2 (Bello-Dambatta et al 2014). Such policy instruments would do well in the UK to improve the feasibility and uptake of RWH systems. Although this needs careful attention as RWH is not a one-size fits all solution. Perhaps it is better to address site specific pluvial run-off issues, assessing roof size run-off against flood risk potential. In addition planning restrictions do already exist where additional wastewater access is required on very large developments and the UK government is making steps in the right direction has just launched a consultation on proposals to set an ‘expectation’ that’s SuDS will be provided in all new domestic developments of 10 houses or more (Pitcher, 2014). This makes the outcomes of this research highly relevant to current thinking. As with any investment the feasibility and economic viability has to be viewed in the longer-term and consider the wider implications, for example energy and carbon, (EA, 2010) through a full LCA and cost-benefit analysis (Ghimire et al., 2014).

4.3. Data refinement – how refined should we go?

The data presented in this paper have shown that rainfall patterns are far from average and shows that RWH performance prediction with coarse monthly data, although often used for preliminary assessments

(Thomas, 2002, Hunt et al, 2012) should be treated with caution. This is because subtleties of tanks filling and emptying during the year, particularly in ‘peak’ rainfall events need to be carefully studied. Not least because they have implications for ‘flash’ flood risk potential (due to pluvial flows) and the (non-potable) supply-demand balance. Using actual daily rainfall (as outlined in STEP 2) provides a hindsight approach to the dynamics of tanks filling and emptying and has the potential to be used as a pre-cursory foresight approach that more carefully assigns RWH tank sizes based on broader future requirements. As drawdown (i.e. when demands are required) and recharge (i.e. when rain falls) can occur independently of each other and at any point during the day therefore it might have been deemed appropriate to match half hourly data (which was obtained) with half hourly uses. However, this level of detailing was not considered and appears to be well beyond the scope of the majority of research currently being undertaken in this area.

5.0 Conclusions

This paper showed that Rainwater harvesting (RWH) systems can benefit pluvial flood risk and non-potable water supply within domestic properties. However it was shown also that their ability to do either / both was very much dependent on the subtleties of tanks filling and emptying (i.e. stored water volume or spare storage capacity). By using five years (2007 - 2011) worth of daily rainfall data for Birmingham, UK, which included peak flow events of 2007, a sensitivity type analysis of an individual domestic RWH system was explored from where it was shown that RWH tanks sized according to BS8515 would not have been capable of capturing all rooftop rainfall that fell in peak flow events and would not have been able to supply all of the yearly non-potable demands. A simple intervention was proposed which could re-engineer urban RWH systems; over-sizing RWH tanks by a factor of 3.0 (i.e. adopting a design parameter of the larger of 15% yearly non-potable demands or rainfall). This would allow for non-potable demands to be met and roof-top run-off to be eliminated - provided that sufficient empty capacity was maintained through controlled discharge once storm surges had subsided. Whilst this could quadruple the economics to the individual through investment in larger tanks there would be similar increases in economic returns, meaning that the benefits and payback period were unchanged. However, for this to work water providers would need to allow those who adopt RWH systems with oversized tanks to be granted reprise from the household stormwater charge. As there is never a one-size fits all solution for RWH, careful consideration of pluvial flood risk potential would be required on a year by year, case-by-case basis.

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Author Contributions

Dexter V.L. Hunt undertook the main body of the research within this paper. Contributions from Christopher D.F. Rogers helped shape the discussion sections of the paper and provided critical judgement on the research being undertaken.

Conflict of Interest

The authors declare no conflict of interest.

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