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The influence of household rainwater harvesting system design on water supply and stormwater management efficiency

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Abstract: Rainwater harvesting is increasingly being recognised as a sustainable option for both urban water and stormwater management. This study explores the potential impact of household rainwater harvesting on water supply augmentation and stormwater management in a typical three-bedroom house in Newcastle-upon Tyne, NE England. The continuous simulation of historical rainfall events at 15-minutes resolution over a 30-year period (1984-2013) is carried out to evaluate the system's water saving and stormwater control efficiencies. Current and future rainfall projections are also incorporated in the analysis. The British Code of practice (BS 8515) is adopted to design the rainwater harvesting system. Results indicate that a rainwater harvesting system which is primarily designed for water supply augmentation with the size of 2.4 m^3 contributes 64% of non-potable water demand (toilet flushing) and an 86% reduction of stormwater runoff volume into the sewer system. A larger system (6.5 m^3) which is sized for both water supply augmentation and flood management provides 70% non-potable water supply and 96% reduction of stormwater runoff volume, indicating that a system which is designed for water supply only may be sufficient to achieve dual benefits. The relationship between storage and system efficiencies are explored for commercially available tanks for historical and future rainfall events. The influence of storage volume on flood peak attenuation is also explored for the historical flood events.

Keywords: Rainwater harvesting; Water supply; Stormwater management, Continuous simulation

1. INTRODUCTION

Growing urban populations and changes in rainfall patterns lead to ever-increasing pressure on potable water resources and urban flood risk in many countries including the UK. In recent years, Rainwater Harvesting (RWH) is increasingly being recognised as a potential decentralised option for both water supply augmentation and stormwater management. Earlier UK RWH studies typically focused on the potential impact of RWH on water supply augmentation only (Fewkes & Warm, 2000; Fewkes & Butler, 2000). Recent studies are beginning to explore their associated stormwater management benefits (Melville-Shreeve et al., 2017). However, it is still unclear is what benefits can be obtained from a simple, single volume tank, what efficiencies are achievable with respect to standard design methods and what is the relationship between water supply augmentation and stormwater management.

This paper presents a preliminary modelling exercise to systematically evaluate both water supply and source control benefits of a household RWH system in a typical three-bed room house in Newcastle-upon-Tyne, NE England. In the paper, the study site is described, together with-it rainfall regime and water demand. Evaluation is carried out using three indices to compare the performance of systems designed using British Standard Code of Practice for RWH design (BSI, 2013) under current and future climatic scenarios.

2. METHODOLOGY

2.1 Study site

This study focuses on a household rainwater harvesting system in a typical three-bedroom house in Newcastle-upon Tyne, NE England with a roof area of 80 m^2 (A) and an occupancy of 4 (Figure 1). Newcastle is vulnerable to surface flooding as over 90% of the city centre surface is impermeable. Recent widespread, localised flooding incidents have had a significant impact on society and the economy which indicates the need for more sustainable stormwater management solutions the city. Rainfall data sets over a 30-year period (1984-2013) at 15 minutes resolution at the Jesmond Dene rainfall gauging station were obtained from the Environment Agency and utilised in the study. UK Climate Projection 2009 (UKCP09) rainfall data sets at the daily interval were also generated and incorporated to evaluate the relative impact of future rainfall patterns (2050 - high emission scenario). The water consumption for toilet flushing is assumed as 50 l/person/day and evenly distributed throughout the day.

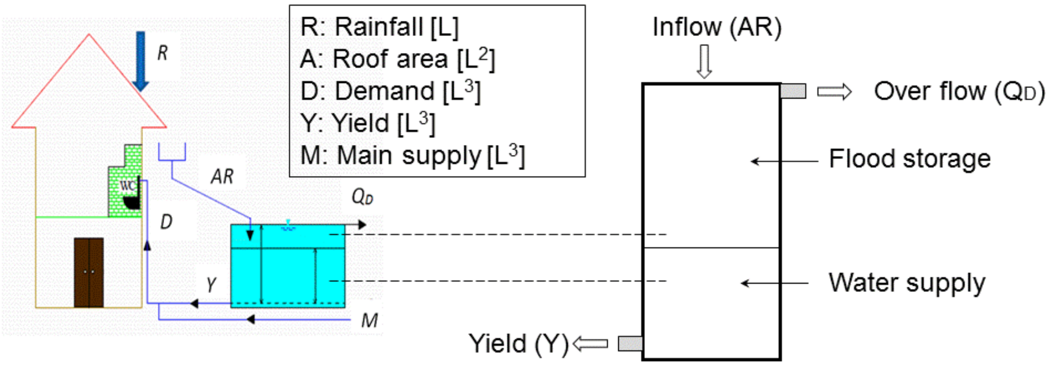

Figure 1. Schematic of the household rainwater harvesting system

2.2 System's performance evaluation

The performance of the rainwater harvesting system was modelled using a yield-after –storage (YAS) reservoir operating regime. Three non-dimensional indices are considered to evaluate system performance. The first index measuring water-saving efficiency, E_T, as defined by Dixon *et al*. (1999), is the ratio between the volume of rainwater supplied and the non-potable water demand (e.g. toilet flushing) during the simulation period is defined as:

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

where Y_t [L^3] represents the rainwater supply (yield) at each time step t, D_t [L^3] is the water demand at each time step, and T is the total number of time steps.

The second index, rainwater overflow ratio, O_T, is defined as the volume of rainwater stored in the system divided by the inflow to the rainwater harvesting system during the specified time interval as modified from Campisano & Modica (2012):

$$O_T = \frac{\sum_{t=1}^{T} AR_t - Q_{D_t}}{\sum_{t=1}^{T} AR_t} \qquad (2)$$

where $Q_{D\ t}$ [L^3] represents the rainwater exceeding the system capacity at each time step t, A is the roof area, R_t [L] is the rainfall amount at each time step, and T is the entire period under consideration.

The third index RPO represents the reduction in peak discharge because of rainwater storage over the simulation period as modified from Melville-Shreeve et al. (2017):

$$RPO = \frac{Q_P - Q_{RWH}}{Q_P} \quad (3)$$

where RPO, Q_P [L^3/T] and Q_{RWH} [L^3/T] represent the 'Reduction in Peak Overflow', peak discharge and peak discharge with rainwater harvesting system over the simulation period respectively.

3. RESULTS AND DISCUSSION

Household RWH system performance evaluation

The modelled water-saving efficiency (E_T) and the rainwater overflow ratio (O_T) of RWH systems over a 30-year (1984 - 2013) period for a range commercially available RWH system sizes (1.5 – 15 m^3) is shown in Figure 2 (E_T (1984 - 2013 & O_T (1984 – 2013). In addition, 100 equiprobable 30-year, daily rainfall time series were also used in the simulation to evaluate the potential impact of future rainfall patterns under a high emissions scenario. The mean of these results is shown in Figure 2 (E_T UKCP09 2050 & O_T UKCP09 2050).

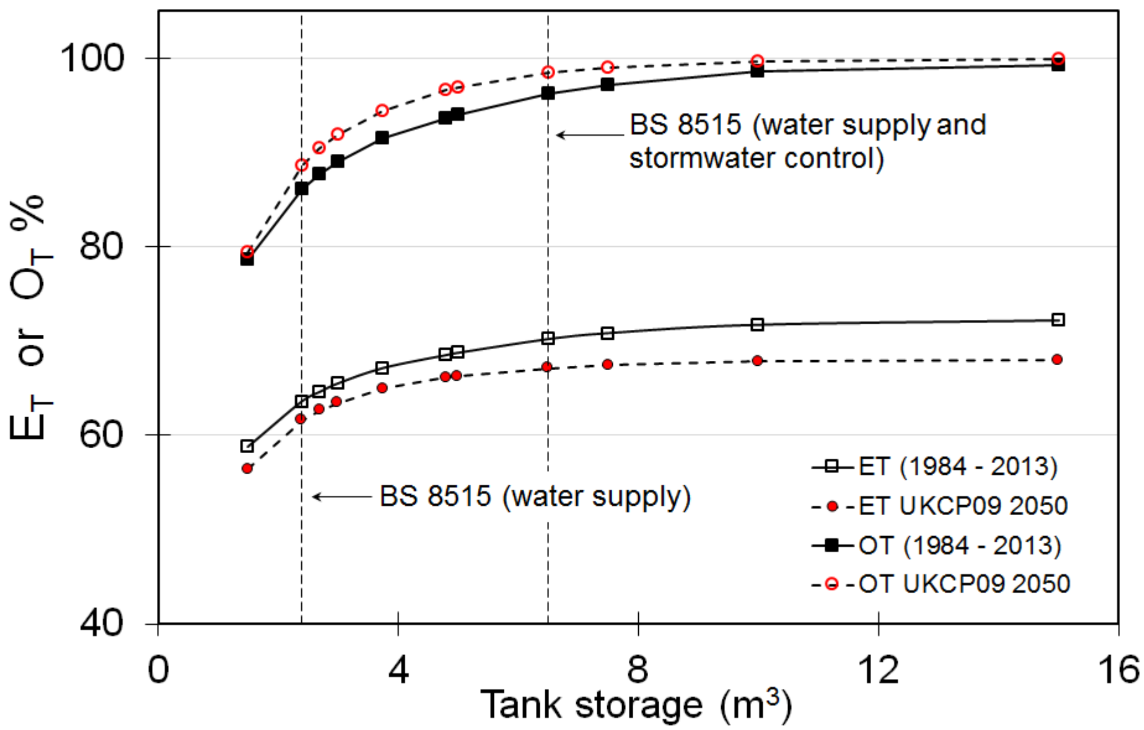

Figure 2. Water-saving and stormwater control efficiencies of the RWH systems

As shown in Figure 2, both E_T and O_T increase with tank size to a certain point whilst further increases in storage doesn't improve the efficiencies greater extent since inflow is fixed. The (BSI, 2013) is adopted to dimension the RWH tank. As shown in Figure 2, the system which is designed for water supply augmentation only has a volume of 2.4 m^3 contributes 64% of the non-potable water demand (WC) and a 86% reduction in stormwater runoff into the sewer system. A larger system (6.5 m^3), which is dimensioned for both water supply augmentation and stormwater management provides 70% of non-potable water supply and 96% stormwater control. Changes in future rainfall patterns with more dry spells lower the RWH system's water-saving efficiency (up to 6%) and increases the stormwater control efficiency (up to 3%). A 25% larger size tank (3 m^3) is required to meet the same (64%) non-potable water demand in 2050.

Table 1 summarises the impact of the RWH system on flood peak attenuation for the 20 largest roof runoff events over a 30-year period with 2.4 m^3 and 6.5 m^3 tank sizes. Estimated Minimum (Min), first quartile (Q1), Median, third quartile (Q3) and Maximum RPO of these 20 runoff events are shown in Table 1.

Table 1. RPO for the 20 largest historical events

	2400 l	6500 l
Min	0%	9%
Q_1	32%	100%
Median	77%	100%
Q_3	100%	100%
Max	100%	100%

The 2.4 m^3 tank exhibits relatively larger variations in RPO than 6.5m^3 tank as expected. As indicted these are substantial reductions in the peak of major storms even for the smaller tank. However, both tanks would have been unable to cope with most extreme historical rainfall event (circa. 100-year event) which occurred on 28th June 2012 when 50 mm rain fell in around 2 hours of which 22.6 mm fell in 15 minutes. For Newcastle, this is equivalent to the expected rainfall for the whole month of June. The smaller and larger tank provides 0% and 9% RPO for the 2012 event respectively. This is because the volume of the 2012 rainfall event is so high and the smaller tank has reached its full storage capacity.

CONCLUSIONS

This study explores potential benefits of RWH system on water supply augmentation and stormwater control in a three-bed rooms house in Newcastle-upon Tyne, NE England. The simulation results indicate that around 2/3 of WC demand could be supplemented by the domestic rainwater system. Simulation results also indicate that future rainfall patterns (2050 – high emission scenario) would require a 25% increase in the tank storage to meet the current water supply capacity. Furthermore, continuous simulation over the 30-year period (1984-2013) shows that the RWH system could provide over 75% flood peak attenuation and over 85% reduction in stormwater runoff volume.

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