Assessment of a Water Harvesting System for a Smart Building Considering Climate Change

M. Abdellatif, A. Al-Shamma'a, S. Tunnington, R. Al khaddar, and W. Atherton

***Abstract*—With climate change now a reality rather than speculated possibility, the future change of rainfall patterns will affect the demand for potable water. Forthcoming regulatory changes will mean that over 90% of UK homes will have their water usage metered, making consumers more and more aware of how expensive the commodity of "common or garden" water has become. In this paper, the design of different rainwater harvesting (RWH) systems is evaluated for three residential properties of different roof areas. The design considered climate change effect and change in future rainfall for three periods 2020s, 2050s and 2080s under the high (AIFI) and low (B1) SRES scenarios in the NW of England. The RWH systems were shown to fulfill between 25% and 85% of WC, washing machine and outdoor use demand making the systems more valuable as a sustainable solution.**

***Index Terms*—Climate change, rainwater harvesting, rainfall, sustainability.**

I. Introduction

Surcharging of stormwater drains is a problem that is exacerbated by intense rainfall and increasing development. Existing stormwater sewers become overloaded and surcharged, causing localised flooding incidents. If the stormwater discharges to a combined sewer then surcharging causes foul water to flood, which could have health implications as well as the potential to cause damage to property [1]. RWH can reduce flood risk in the UK (especially summer storms), save energy/carbon emissions (at least that associated with the displaced water) and save householders money.

RWH is now explicitly mentioned in UK key government documents such as the Building Research Establishment's Environmental Assessment Method [2] and the Code for Sustainable Homes [3]. 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 [4], the government's water strategy document and water company Strategic Direction Statements [5], identify that RWH has a part to play in urban water management strategies. Furthermore, the Draft Flood and Water Management Bill [6] 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. 55% of treated water is used in households and the UK Government, under their Sustainable Building Strategy, suggests that a 25% reduction in potable water use in new buildings is necessary. This 25% reduction can be partly met by efficient appliances, but the remainder will need to be met by other means. Rainwater harvesting is seen as the most likely option [1].

A number of factors have so far contributed to the lack of progress in RWH. Ambiguity in the financial viability of RWH systems is a key reason; lack of experience and the absence of well-run demonstration sites are others [7]. Nevertheless, there has been a rise in the number of RWH systems being implemented in residential properties, new commercial buildings and in schools.

There are some studies that considered the RWH with mathematical modelling for purpose of design/performance assessment e.g. [7]-[10]. However, none of these considered the issue of climate change along with the water harvesting tank size.

The focus of this paper is mainly on RWH systems under climate change. So, long-term scenarios are therefore required to gain further knowledge of system behavior in order to develop robust and sustainable management for the buildings. Assessment for climate change is normally carried out by comparing future rainfall with the baseline period (1961-1990) as recommended by Intergovernmental Panel on climate change (IPCC), so on average a 30 years' time scale. This paper considers three future periods, the 2020s (2010-2039), the 2050s (2040-2069) and the 2080s (2070-2099).

Fig. 1. Location of the studied sites (Cumbria, Lancashire & Cheshire).

II. Sites characteristics

This study selected three residential properties at Cumbria, Lancashire &Cheshire counties, represented by TW, WN and WR respectively in the North West of England (NW). The sites represent various climatic regions (the north, middle, and

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the south), as shown in Fig. 1. The exposure of the NW region to westerly maritime air masses and the presence of extensive areas of high ground mean that the region is considered as one of the wettest places in the UK. The average annual rainfall in the highest parts of Cumbria is over 3200mm, in contrast to Manchester where the average annual rainfall is only 860mm [11]. Table I show characteristics of the sample properties considered in each site.

TABLE I: DESIGN PARAMETERS AND VALUES FOR THE STUDIED SITES

Parameter	Property 1	Property 2	Property 3
Roof area (m^2)	60	100	150
No. of occupants	3	4	6
No. rooms	2	3	4
Analysis period (years)	30	30	30

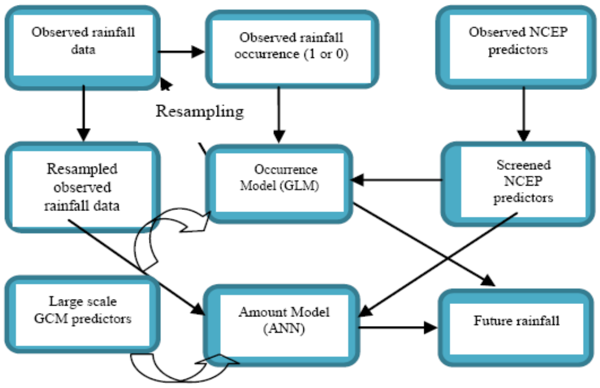

Fig. 2. A flow chart illustrating the downscaling procedure with hybrid GLM-ANN.

III. METHODOLOGY

A. Future Rainfall

Time series of rainfall are generally required as input to impacts models when assessing potential impacts arising as a consequence of global climate change. In order to produce plausible scenarios of change, it is of considerable importance that realistic series of rainfall, which reflect the large-scale changes in the atmosphere, are employed.

Future rainfall has been projected at the three locations in a previous study see [12] using a combination of a Generalized Linear Model (GLM) and an Artificial Neural Network (ANN) (hereinafter known as the hybrid GLM-ANN model, Fig. 2). Unlike other downscaling techniques, the developed model uses a two-stage process to model rainfall; an occurrence process which uses the GLM with a logistic regression model and an amount process which uses an ANN network model trained with a Levenberg-Marquardt approach. The developed model was used to simulate future rainfall using climatic variables produced from HadCM3 GCM for emissions scenarios high (A1FI) and low (B1) scenarios to understand the relationship between climate change and hydrology in the selected sites, see [12] for calibration/verification of this model. The following is the description of the occurrence model (GLM),

$$p_i(y_i) = \frac{1}{\left(1 + e^{-(x_i \beta_i)}\right)} \quad (1)$$

where,

y_i = response which represents the ith elements of the response vector Y.

β_i = $(k+1)$ column vector of unknown parameters to be estimated including the intercept.

x_i = $(k+1)$ raw vector of explanatory variables (climate predictors) accounting for the ith observation ($i = 1 \ldots N$).

k = Number of predictors.

A multi-layer feed forward artificial neural network (MLF-ANN) model was used to build a non-linear relationship between the observed rainfall amount series and the same selected set of climatic variables (predictors) used for the rainfall occurrence model [12].

B. Rainwater Harvesting Tank Sizing

Based on the British Standard BS 8515, the rainwater tank must be big enough to hold 5% of the annual rainwater yield, or 5% of the annual non-potable water demand, whichever is the lesser and can be estimated as follows:

1) Water yield

Rainfall varies widely across the UK. Even sites quite close to each other can have quite different rainfall figures. The following equation gives the annual yield for water harvesting tank which is function of the annual rainfall depth.

$$YR = (A.e.h.\eta.0.05)UF \quad (2)$$

where:

YR = annual rainwater yield (5% of) to give tank size (litres)

A = collecting area (m^2)

e = yield coefficient – 0.75 for tiled pitch roof

h = annual depth of rainfall (mm)

η = hydraulic filter efficiency- 90% minimum

UF = assumed utilization factor-0.75

The Baseline and future annual rainfall depths have been applied for water harvesting model yields for the three periods and the three sites under the high and low scenarios.

2) Water usage (demand)

Demand is dependent on the efficiency of appliances specified and purposes the rainwater will be used for. Demand is also dependent on the number of people and of days in the year the building is occupied and can be estimated as follows,

$$DN = Pd.n.365.0.05 \quad (3)$$

where:

DN = annual non-potable rainwater demand (5% of) to give tank size (litres)

Pd = daily non-potable requirements per person (litre)

Domestic daily WC demand is 33% of daily water use per person which is 150.

Domestic daily Outdoor demand is 3% of daily water use per person (150).

Domestic daily washing machine demand is 12% of daily water use per person (150).

n = number of occupants

Tank saving efficiency can also be calculated using the equation:

$$YR/DN \quad (4)$$

IV. Results and Discussion

In order to verify whether the downscale rainfall model has the ability to capture the observed feature of each site an example of the verification has been presented below for both occurrence and amount (more details see [12]).

Monthly average wet days are indications of how often it rains in a month; it can be used as indirect measure of rainfall frequency. The visual plots in Fig. 3 show the monthly average wet days as well as dry days for the observed and simulated rainfall for the three sites for calibration and validation periods. All plots show that the occurrence model is well simulated by the GLM for all sites and periods which demonstrates that GLM is a good choice for downscaling future rainfall occurrence. This would entail the assumption that model parameters are assumed time invariant and would not change in the future.

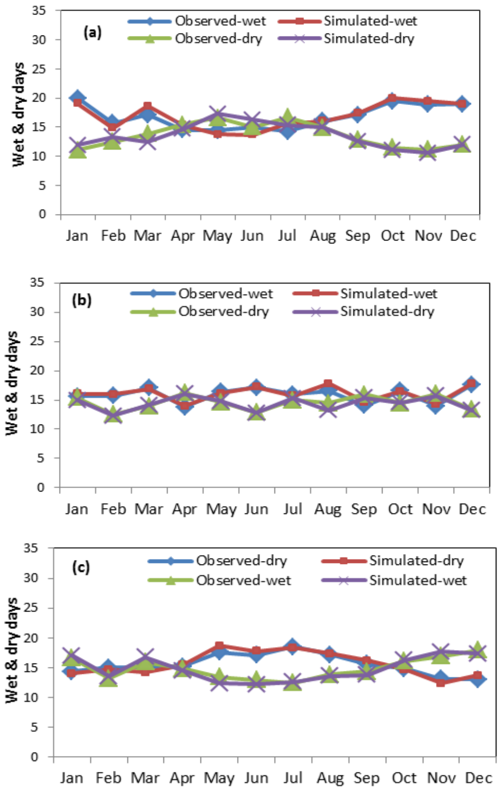

Fig. 3. Average numbers of wet and dry days for observed and simulated occurrence model for the (a) Cumbria (b) Lancashire and (C) Cheshire.

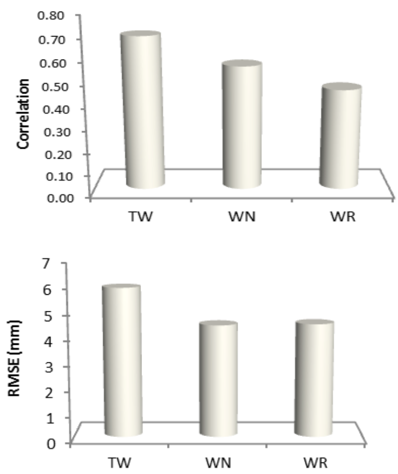

Fig. 4. **Correlation (R)** root mean square error (RMSE) of rainfall amount model.

The efficiency and ability of the rainfall model to predict rainfall amount that best matched the observed rainfall are expressed here in terms of their correlation coefficient (R) and root mean square error (RMSE) and are presented in Fig. 4 for the overall period 1961-2001. The higher values of R and lower values of RMSE obtained by models built using the hybrid GLM-ANN approach indicate that this modelling approach has reasonable accuracy in reproducing the rainfall amount.

Trend study for observed rainfall data is widely used as a base reference or a caveat of climate change studies e.g. [13].

It can also provide a quick visual check for the presence of unreasonable values (outliers). However, the usefulness of trend study is always being questioned. Possible trends in the data are investigated to offer an historical context before further climate change assessments in this work.

Fig. 5 shows the series plots and their trend lines for the average monthly rainfall for each station. Annual monthly rainfall series has no significance trend for all stations, based on the Wald test [14]. So generally, the plots indicate that climate change did not take place during the observed period of data (1961-2001) for these locations, due to inclusion of the control period 1961-1990 in the trend study where the climate is considered normal as reported by the IPCC.

Another analysis for the observed rainfall is the Inter-stations relationship. The daily rainfall box plots are different across the sites for the entire statistics, especially the 3rd percentile; median and maximum (see Fig. 6). In these figures, the effects of threshold on rainfall distributions are also investigated for the three sites. Selecting threshold is important because it is related to the definition of the occurrence of a rainfall event, the limitations inherent to the measurement of rainfall and the recording equipment.

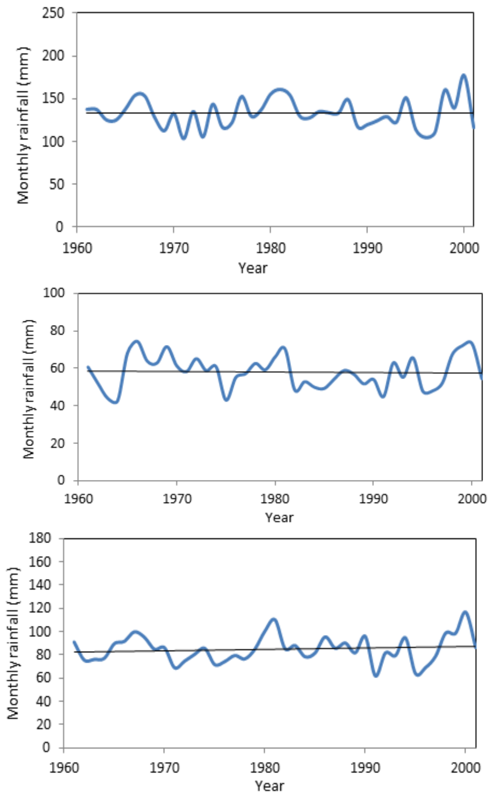

Fig. 5. The average monthly rainfall series with linear trend lines annual at Cumbria, Lancashire & Cheshire (top to bottom).

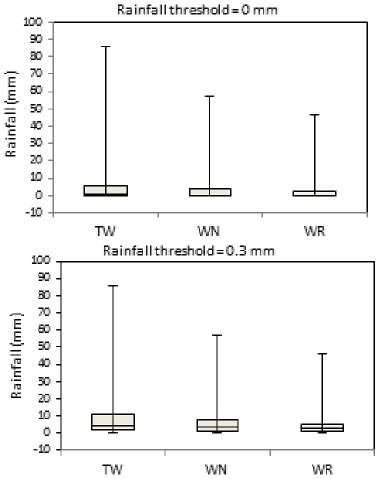

Fig. 6. The daily rainfall box plots across Cumbria (TW), Lancashire (WN) &Cheshire (WR) for annual time series for 1961-2001.

Projection of future rainfall has been assessed. In Fig. 7 the small vertical error bars displayed at each point show the maximum and minimum of the annual average rainfall amount values of 30 years for 2020s, 2050s and 2080s. The annual rainfall, the maximum and minimum average rainfall can slightly increase or decrease for the three future periods at all sites.

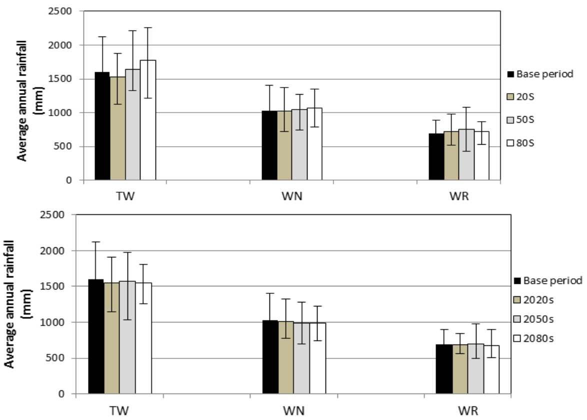

Fig. 7. Average annual rainfalls at the three sites in the future for A1FI (upper) and B1 (lower). The error bar indicates the minimum and maximum rainfall.

The impact of the projected future rainfall on RWH has been assessed. Results in Fig. 8 reveals that future annual yield for RWH at the three properties in Cumbria are projected to experience significant increase for the tested high scenario (A1FI), especially in 2080s where the yield could reach up to 11% as a maximum. However, in the Lancashire (WN) and Cheshire (WR) results have shown a very slight rise, which is attributed to the location of Cumbria being in the wettest region in North-western England compared to others. The increase in annual yield significantly affects the amount of water supply saving with the same ratio for WC, outdoor and washing machines, with a larger amount for properties 2 and 3 due to larger roof area. The corresponding potable water saving at all sites will go up ranging between 27%-85% with the largest amount associated with the 2080s compared with 26%-77% of the base period. For the low scenario, the picture is somehow different where (Fig. 9) it is anticipated some decline in the annual yield and saving of RWH. The yield reduction could reach up to 3% at the three studied sites and for different property sizes as they suffer from a reduction in the rainfall; however there is still significant annual future saving between 25%-75% compared with 27%-77% of the base period.

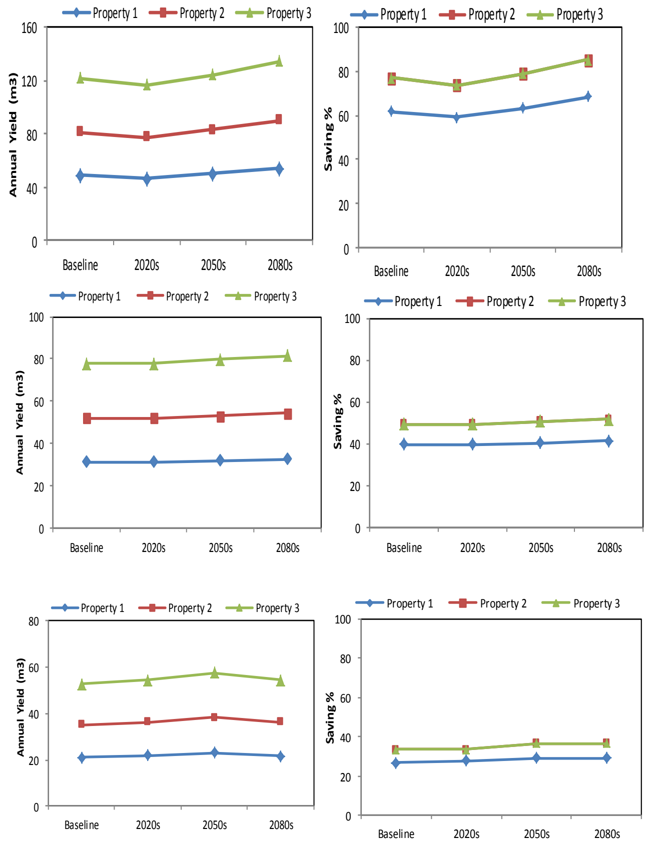

Fig. 8. Annual water yield and saving for water harvesting tank for the three future periods compared with baseline period under the high (A1FI) scenario for Cumbria (upper), Lancashire (middle) and Cheshire (lower).

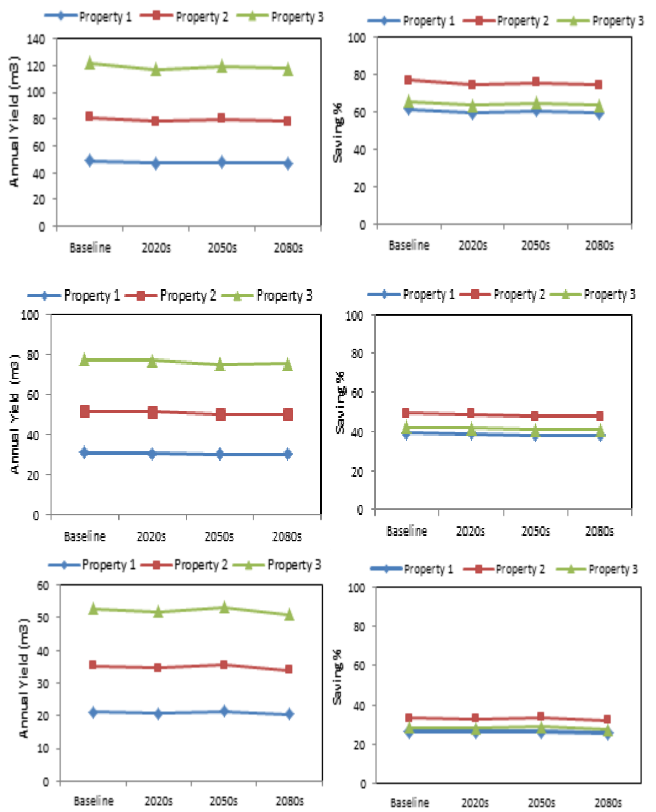

Fig. 9. Annual water yield and saving a for WHR tank for the three future periods compared with baseline period under the low (B1) scenario for Cumbria (upper), Lancashire (middle) and Cheshire (lower)

Impact on the RWH tank size is also investigated and results have been given in Table II, Table III and Table IV for Cumbria, Lancashire and Cheshire. From the Tables, it is clear that the tank design is expected to change gradually in the far future under A1FI scenario however; under the low scenario consistent drops are evident except in 2050s for Cheshire with very marginal contributions of 1%. This could be due to the warm climate in this region which contributes to high evaporation and thus much rainfall. The increase in A1FI would range between 2%-11% with a large contribution from Cumbria.

TABLE II: PROPOSED FUTURE RWH TANK SIZE (LITRES) IN CUMBRIA (BOLD INDICATES AN INCREASE IN TANK SIZE)

Time period	Property 1		Property 2		Property 3	
	A1FI	B1	A1FI	B1	A1FI	B1
Base period	2433.0	2433.4	4055.1	4055.7	6082.6	6083.5
2020s	2327.3	2348.1	3878.8	3913.6	5818.2	5870.3
2050s	**2490.7**	2391.4	**4151.2**	3985.7	**6226.8**	5978.5
2080s	**2694.1**	2353.1	**4490.2**	3921.9	**6735.4**	5882.9

TABLE III: PROPOSED FUTURE RWH TANK SIZE (LITRES) IN LANCASHIRE (BOLD INDICATES AN INCREASE IN TANK SIZE)

Time period	Property 1		Property 2		Property 3	
	A1FI	B1	A1FI	B1	A1FI	B1
Base period	1554.4	1554.4	2590.6	2590.6	3885.91	3885.9
2020s	**1554.6**	1539.6	**2591.0**	2566.0	**3886.53**	3849.1
2050s	**1593.0**	1506.1	**2655.0**	2510.1	**3982.56**	3765.2
2080s	**1593.0**	1507.3	**2655.0**	2512.1	**3982.56**	3768.2

TABLE IV: PROPOSED FUTURE RWH TANK SIZE (LITRES) IN CHESHIRE (BOLD INDICATES AN INCREASE IN TANK SIZE)

Time period	Property 1		Property 2		Property 3	
	A1FI	B1	A1FI	B1	A1FI	B1
Base period	1054.5	1054.5	1757.5	1757.5	2636.3	2636.3
2020s	**1089.3**	1036.6	**1815.6**	1727.7	**2723.3**	2591.5
2050s	**1148.6**	**1063.0**	**1914.3**	**1771.6**	**2871.5**	**2657.5**
2080s	**1148.6**	1019.8	**1914.3**	1699.6	**2871.5**	2549.4

V. CONCLUSION

Using rainwater in buildings reduces demand for potable water and reduces storm water problems in overloaded sewers, both are urgent requirements as a sustainable technology to create smart building.

The design of RWH systems for three properties at three selected sites in of North West of England has been evaluated using a simple approach (based on British Standard BS 8515). The three systems for the properties use the same parameter values and future rainfall for the sites with change only in roof area and occupants. The effect of projected future rainfall shows that design and saving efficiency of the system are affected with the climate change especially under the high scenario of the IPCC. This would necessitate the engineer to consider the climate change when designing the RWH system.

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M. Abdellatif, "A hybrid generalised linear and Levenberg-Marquardt ANN approach for downscaling future rainfall," *Hydrology Research Journal*, vol.44, no. 6, pp. 1084-1101, 2013.

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She is currently the Manager of Rain Catcher Products and Services. Mrs. Tunnington is a member of Liverpool Chamber of Commerce, Chester Network, Construction & amp; Building Materials- Professionals Group, Ecogrid, Green and SuDS.

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Dr. Atherton has been nominated for teaching awards on a number of occasions and is currently a Programme Leader in the School of the Built Environment.