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

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

Abstract— **With climate change now a reality rather than speculated possibility, the future change of rainfall pattern will affect the demand for potable water. Forth coming 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 systems (RWH) 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 NW of England. The RWH systems were shown to fulfill between 25% and 85% of WC, washing machine and outdoor use demand making the system more valuable as a sustainable solution.**

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

M. Abdellatif is with Liverpool John Moores University (e-mail: m.e.abdellatif@ljmu.ac.uk).

A. Al-Shamma'a is with Liverpool John Moores University (e-mail: a.al-Shamma'a@ljmu.ac.uk@ljmu.ac.uk).

S. Tunnington is with Raincatcher products and services Ltd (e-mail: sue@raincatcher.co.uk).

R. Al khaddar is with Liverpool John Moores University (e-mail: r.m.alkhaddar@ljmu.ac.uk).

W. Atherton is with Liverpool John Moores University (e-mail: w.atherton@ljmu.ac.uk).

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 would have health implications as well as the potential to cause damage to property [1]. RWH can reduce flood risk in UK (especially summer storms), save energy/carbon emission (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 is another [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 considered the RWH with mathematical modelling for purpose of design/performance assessment eg. [7]; [8]; [9] and [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 baseline period (1961-1990) as recommended by Intergovernmental Panel on climate change (IPCC), so on average of 30 years time scale. This paper consider three future periods, the 2020s (2010-2039), the 2050s (2040-2069) and the 2080s (2070-2099).

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 the south), as shown in Figure 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 the Cumbria is over 3200mm, in contrast to Manchester where the average annual rainfall is only 860mm [11]. Table 1 show characteristics of the sample properties considered in each site.

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

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

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 Generalized Linear Model (GLM) and Artificial Neural Network ANN (hereinafter known as the hybrid GLM-ANN model, Figure 2). Unlike other downscaling techniques, the developed model uses 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 Levenberg-Marquardt approach. The developed model was used to simulate future rainfall using climatic variable produced from HadCM3 GCM for emissions scenarios high (A1FI) and low (B1) scenarios to understand 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),

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

Where,

y_i = response which represent 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…N).

k = Number of predictors.

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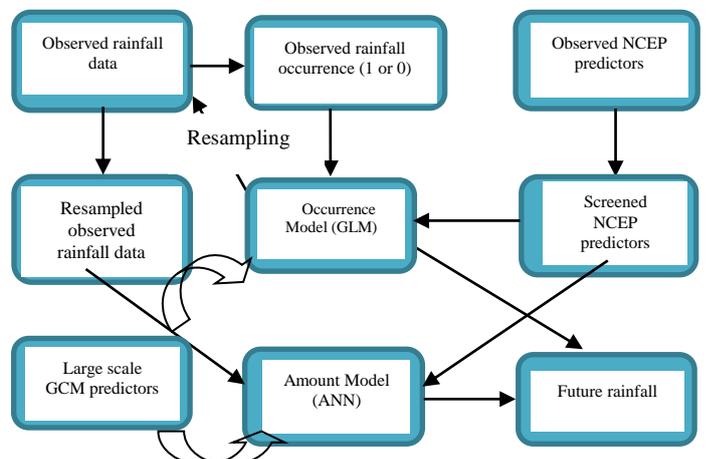

Fig. 2 A flow chart illustrating the downscaling procedure with Hybrid GLM-ANN

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:

- *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.

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

Where:
YR = annual rainwater yield (5% of) to give tank size (liters)
A = collecting area (m2)
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.

- *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,

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

Where:
DN = annual non-potable rainwater demand (5% of) to give tank size (liters)
Pd = daily non-potable requirements per person (liter)

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:
$$YR/DN \qquad (4)$$

IV. RESULTS&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 Figure 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 future.
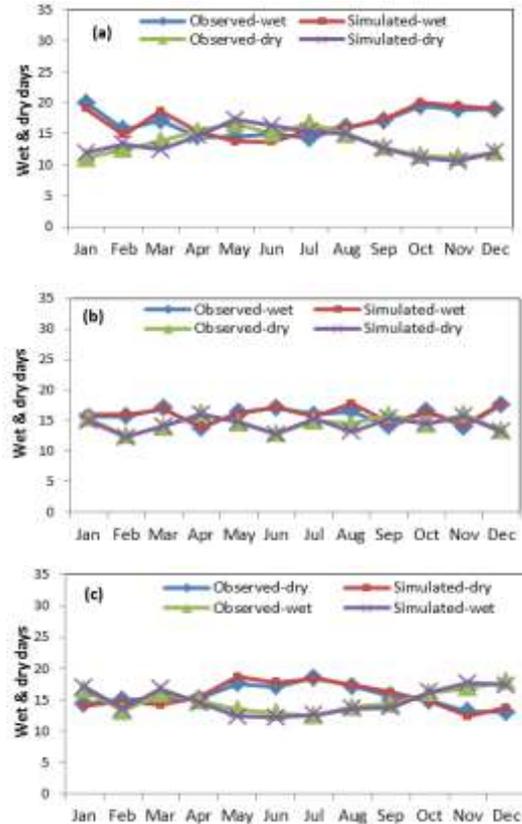

Fig 3 Average numbers of wet and dry days for observed and simulated occurrence model for the (a) Cambria (b) Lancashire and (C) Cheshire

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 presented in and Figure 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 reproduce the rainfall amount.
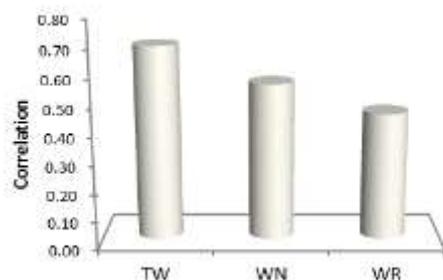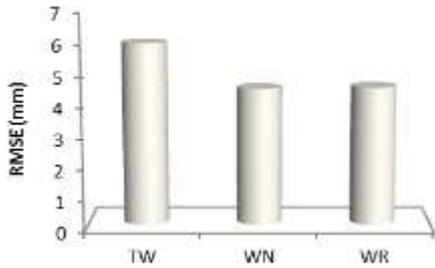
Fig 4 **Correlation (R)** Root Mean Square Error (RMSE) of rainfall amount model

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

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.

Figure 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 data (1961-2001) for these locations, due to inclusion of the control period 1961-1990 in the trend study where the climate consider 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 Figure 6). In these Figures, the effects of threshold on rainfall distributions are also investigated for 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.
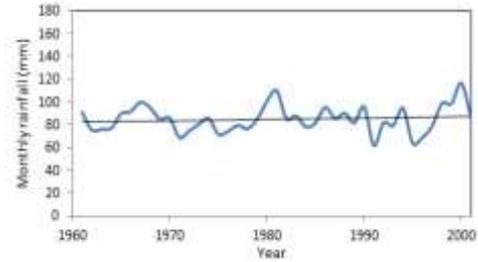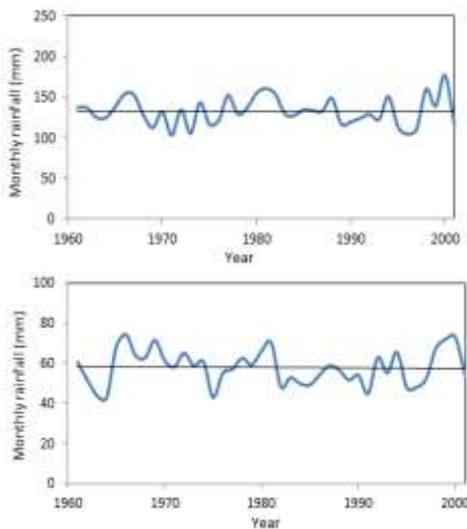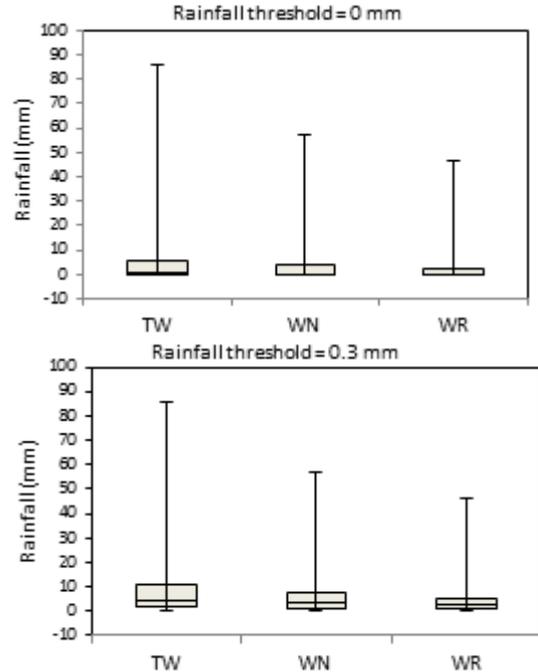

Fig. 6 The daily rainfall box plots across Cumbria (TW), Lancashire (WN) &Cheshire (WR) for annual time series for 1961-2001

Projection of future rainfall has been assessed. In Figure 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.
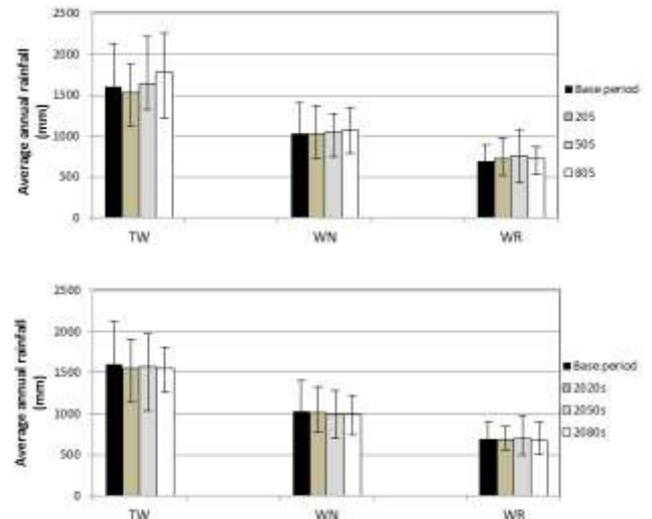

Fig 7 Average annual rainfalls at the three sites in the future for A1FI (upper) and B1 (lower). The error bar indicates the minimum and maximum rainfall

Impact of the projected future rainfall on RWH has been assessed. Results in Figure 8 reveals that future annual yield for RWH at the three properties in Cumbria are projected to experience significant increase for 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 showed 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 machine, with larger amount for property 2and 3 due to larger roof area. The corresponding potable water saving at all sites will go up ranging between 27%-85% with largest amount associated with the 2080s compared with 26%-77% of the base period. For the low scenario the picture is somehow different where (Figure 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 properties sizes as they are 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.
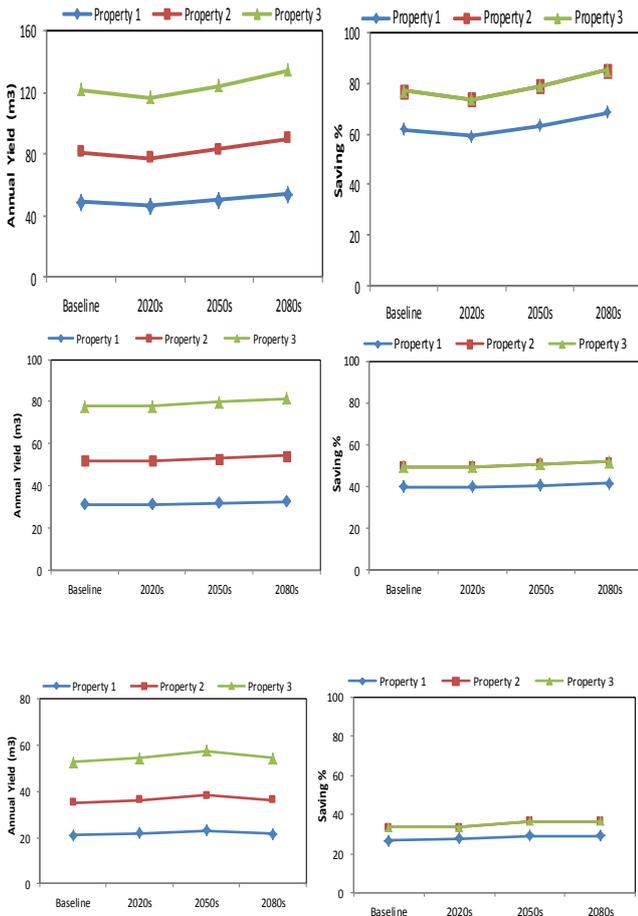

Fig 8 Annual water yield and saving for water harvesting tank for the three future periods compared with baseline period under the high (A1FI) scenario for Cambria (upper), Lancashire (middle) and Cheshire (lower)

Impact on the RWH tank size is also investigated and results have been given in Table 2, 3 &4 for Cambria, Lancashire and Cheshire. From the Tables, it is clear that the tank design is expected to change gradually in far future under A1FI

scenario however the low scenario one experience consistent drops except in 2050s for Cheshire with very marginal contributions of 1%. This could be due to the warm climate in this region which contribute to high evaporation and intern much rainfall. The increase in A1FI would range between 2%-11% with large contribution from Cambria.
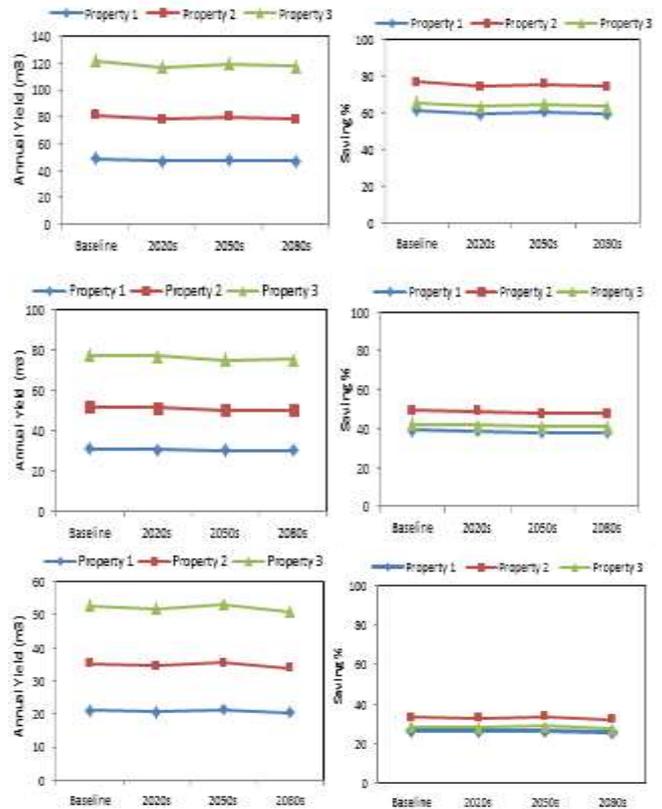

Fig 9 Annual water yield and saving a for WHR tank for the three future periods compared with baseline period under the low (B1) scenario for Cambria (upper), Lancashire (middle) and Cheshire (lower)

TABLE 2: PROPOSED FUTURE RWH TANK SIZE (LITERS) IN CAMBRIA (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 3: PROPOSED FUTURE RWH TANK SIZE (LITERS) 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 4: PROPOSED FUTURE RWH TANK SIZE (LITERS) 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 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 show 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 to the engineer to consider the climate change when design the RWH system.

VI. Acknowledgment

References

[1] C. Hassell. (June 2014) Rainwater Harvesting in the UK- A solution to increasing water shortages. [Online] available: www.ech2o.co.uk/downloads/delhiabstract.pdf

[2] BREEAM. (June 2014) BREEAM: BRE Environmental Assessment Method. [Online] available: http://www.breeam.org/.

[3] DBERR. (August 2007) Draft Strategy for Sustainable Construction: A consultation paper. Department for Business, Enterprise and Regulatory Reform. . [Online] available: http://www.berr.gov.uk/files/file40641.pdf.

[4] DEFRA. (February 2008) Future Water: The Government's water strategy for England. DEFRA. [Online] available: http://www.defra.gov.uk/environment/water/strategy/pdf/future-water.pdf.

[5] OFWAT. (January 2008) Strategic direction statements. OFWAT. [Online] available: http://www.ofwat.gov.uk/aptrix/ofwat/publish.nsf/Content/navigation-pr09 sds.

[6] DEFRA. (May 2009) Draft Flood and Water Management Bill. DEFRA [Online] available: http://www.defra.gov.uk/corporate/consult/flood-water-bill/index.htm.

[7] S.Ward, F. A. Memon, and D. Butler. Rainwater harvesting: model-based design evaluation. *Water Science & Technology*, vol. 6, no.1, 85-96. (2010).

[8] R. M. Roebuck & R.M. Ashley. Predicting the hydraulic and life-cycle cost performance of rainwater harvesting systems using a computer based modelling tool. In: Delectic, A. & Fletcher, T. (eds) Proceedings of the 7th International Conference on Urban Drainage and *4th International Conference on Water Sensitive Urban Design, Melbourne*, Australia, 2–7 April, 2006, Vol. 2, pp. 2.699–2.706.

[9] Y. Kim & M. Han. A Rainfall-Storage-Runoff (RSR) model for the design of a rainwater tank effective for flow control in urban drainage pipes. *Proc. of the 2nd IWA International Rainwater Harvesting Workshop*. Beijing, China, 11 September 2006. IWA [Online] available: http://www.iwahq.org. May 2007.

[10] A. Fewkes & P.Warm a method of modelling the performance of rainwater collection systems in the UK. Build. *Serv. Eng. Res. Technol*. Vol.2, pp.257–265. (2000).

[11]Met office. (December 2010).North West England & Isle of Man: climate [Online] Available at: http://www.metoffice.gov.uk/climate/uk/nw.

[12]M. Abdellatif, W. Atherton, R. Alkhaddar. Hybrid generalized linear and Lavender–Marquardt artificial neural network approach for downscaling future rainfall in North Western England, *Hydrology Research J*. Vol.44, no.6, pp1084–1101. (2013)

[13] G. Jenkins, M. Perry, G. Prior. *The Climate of the United Kingdom and recent Trends, Met Office Hadley Centre*, Revised edition, ISBN 978-1-906360-05-4. (2009).

[14] A.J. Dobson. *An Introduction to Generalized Linear Models*. London, Chapman & Hall / CRC. (2002)