The verification of a behavioural model for simulating the hydraulic performance of rainwater harvesting systems

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Abstract
This paper describes the field testing of a commercially available rainwater harvesting or collection system and the verification of a model which simulates system performance. A rainwater harvesting system was installed successively into three properties and monitored for periods of twelve, six and eight months. The model verified is a behavioural model which simulates the operation of the rainwater collector’s storage tank with respect to time by routing simulated mass flows through an algorithm which describes the operation of the store. The input data in time series form is used to simulate the mass flow through the model based upon a time interval of either, a minute, hour, day or month. The model uses a daily time interval to predict system performance for different combinations of roof area, demand, storage volume and rainfall level. Rainfall losses during collection are quantified and incorporated into the model. Finally a series of curves are presented based upon the verified model which enable the performance of rainwater harvesting systems to be predicted in the UK.

Introduction
This study describes the field testing of a rainwater harvesting system and the verification of a model which simulates the systems performance. The objectives of the field tests were fourfold. Firstly, monitor and record the rainfall, wind speed and wind direction at each test site. Secondly, monitor and record the inflows and outflows from the rainwater collector at each test site to determine the volume of mains water conserved during predefined time periods, e.g. per week, per month or per annum. Thirdly, use the data collected to verify and refine a model which simulates the operation and hydraulic performance of a rainwater collection system. Finally, the sensitivity of the model to the time interval of the input data time series and the method of modelling the rainfall losses is investigated.

The rainwater harvesting system and instrumentation
A rainwater harvesting system with a storage tank of 2032 litres was installed successively into three UK properties and its performance monitored at each location for periods of twelve, eight and six months. The collected rainwater was used only for WC flushing in each of the test properties.

Each of the test sites was located within the Nottingham area. The properties at test sites 1 and 2 were two storey houses while at test site 3 the property was a bungalow. All of the properties had pitched roofs covered with profiled, granular faced concrete tiles. Rainwater was collected from the whole roof area at each site. The projected roof plan areas were 85 m² (site 1), 57 m² (site 2) and 56 m² (site 3). All of the properties were fitted with 9 litre dual flush WC’s.

The system monitored is available commercially and uses a pump and accumulator to distribute water to the WC (Figure 1). Rainwater is collected from the house roof by gravity via a 100mm diameter downpipe into a polythene tank. A coarse filter fitted into the downpipe ensures debris such as leaves do not collect in the tank. An overflow is fitted to the storage tank which discharges into the household’s surface water drain. Water is supplied under pressure from the accumulator. When insufficient rainwater is available, a float switch fitted near the bottom of the tank activates a magnetic valve which allows approximately 250 litres of mains water to flow into the collector via a funnel.

A schematic diagram of the instrumentation system is included in figure 1. The water flow rate from the collector to the WC was measured using a positive displacement flow meter. The data logger recorded the total flow at intervals of 1 minute at site 1 and 1 hour at sites 2 and 3. The inflow of mains make-up water was monitored using the same method. The


volume of rainwater inflow from the roof was determined by measuring the level of water in
the collection tank at intervals of 1 minute at site 1 and 1 hour at sites 2 and 3 using a pressure
transducer. Water overflowing from the system was collected in a 250 litre spill tank.
Discharge into the drain was via a 25mm pipe fitted with a positive displacement flow meter.
The data collected was used to determine the percentage of WC flushing water conserved
each month.
At each test site a weather station was installed to monitor rainfall, wind speed and direction.
The weather station was used to quantify run-off losses due to wind effects and absorption by
the roofs at each test site. A detailed description of the instrumentation and the justifications
for the techniques adopted is reported elsewhere (Fewkes, 2004).

Results and discussion

The variables measured during the study are identified in figure 2. The performance of the
rainwater collector is described by its water saving efficiency ($E_T$). Water saving efficiency is
a measure of how much mains water has been conserved in comparison to the overall demand
of the WC and is given by equation (1).

\[
E_T = \frac{\sum_{t=1}^{n} Y_t}{\sum_{t=1}^{n} D_t} \times 100
\]

Where:
- $t = \text{duration of time interval, for example, minute, hour, day or month}$
- $T = t_1 + t_2 + \ldots + t_n = \text{total time period under consideration}$

The results for test sites 1, 2 and 3 are given in tables 1, 2 and 3 respectively. The
performance of the system in terms of its water saving efficiency is given for each of the
months the system was monitored. The selection of a monthly monitoring period was
arbitrary. The water saving efficiency at site 1 ranged from 4% for June to 100% for
September and February. At site 2 the minimum water saving efficiency occurred in
February with a value of 37%, maximums of 100% occurred during January, March and
April. A maximum saving of 100% was achieved at site 3 during October with the minimum
efficiency of 59% being recorded during March. The WC demand was fairly constant at each
site. The average WC usage at site 1 was 6.5 flushes per day per person, the corresponding
values for sites 2 and 3 were 2.7 and 3.8 flushes per day per person. Domestic water usage in
the UK has been researched by various workers, for example, Thackray et al (1978) and
Butler (1993). Butler’s survey estimated the average WC usage in a household was 3.7
flushes per day per person which is in good agreement with Thackray’s figure of 3.3 flushes
per day per person. WC usage at test site 1 was higher than expected. The high usage rate may
in part be attributable to the downstairs WC which usually required at least two flushes to
clear the WC pan.
Rainfall loss during collection occurs due to absorption by the roofing material and wind
effects around the roof. The rainfall loss was modeled using an initial depression storage loss
($E$) with a run off coefficient ($C_f$) (Pratt and Parkar, 1987).
The model is of the general form:

\[
Q_n = \sum_{i=1}^{n} Q_i = (\sum_{i=1}^{n} R_i A C_f) - E
\]

where:
- $T_i = t_1 + t_2 + \ldots + t_n = \text{time period for rainfall event, i.}$
Key
C – Pressure transducer
P – Positive displacement flow meter
R – Tipping bucket rain gauge
V – Vane anemometer
W – Wind direction indicator

Rainwater Tank

Mains water

Key
Rt = Rainfall (m) during time interval, t
Qt = Rainfall runoff (m³) during time interval, t
Mt = Mains make up (m³) during time interval, t
Ot = Overflow (m³) during time interval, t
Vt = Volume in store (m³) during time interval, t
Yt = Yield from store (m³) during time interval, t
Dt = Demand (m³) during time interval, t
S = Store capacity (m³)
A = Roof Area (m²)

Figure 1 Rainwater harvesting system and instrumentation

Figure 2 System Variables

MONTHLY TOTALS

<table>
<thead>
<tr>
<th>Month</th>
<th>Final Vol. (Vt) (Litres)</th>
<th>Overflow Vol. (Ot) (Litres)</th>
<th>WC Make-up Vol. (Mt) (Litres)</th>
<th>Store Yield (Yt) (Litres)</th>
<th>Rainwater Runoff (Qt) (Litres)</th>
<th>Rainfall (Rt) (mm)</th>
<th>Water Saving Efficiency (Et) (%)</th>
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Table 1 Monthly performance indicators including water saving efficiencies (Site 1)

MONTHLY TOTALS

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<tr>
<th>Month</th>
<th>Final Vol. (Vt) (Litres)</th>
<th>Overflow Vol. (Ot) (Litres)</th>
<th>WC Make-up Vol. (Mt) (Litres)</th>
<th>Store Yield (Yt) (Litres)</th>
<th>Rainwater Runoff (Qt) (Litres)</th>
<th>Rainfall (Rt) (mm)</th>
<th>Water Saving Efficiency (Et) (%)</th>
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<td>597</td>
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<td>3535</td>
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Table 2 Monthly performance indicators including water saving efficiencies (Site 2)
MONTHLY TOTALS

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<th>Final Vol. (V₁) (L)</th>
<th>Overflow Vol. (O₁) (L)</th>
<th>WC Demand (D₁) (Litres)</th>
<th>Make-up Vol. (M₁) (Litres)</th>
<th>Store Yield (Y₁) (Litres)</th>
<th>Rainwater Runoff (Q₁) (L)</th>
<th>Rainfall (R₁) (mm)</th>
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<td>20499</td>
<td>20580.6</td>
<td>430.8</td>
<td>81.76</td>
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Table 3 Monthly performance indicators including water saving efficiencies (Site 3)

Therefore

\[ Q_{T_i} = (R_{T_i} A C_f) - E \] (3)

Where \( Q_{T_i} \) is rainwater run off during rainfall event i (litres), \( T_i \) is duration of rainfall event i (minutes), \( E \) is depression storage loss (litres), \( C_f \) is run off coefficient, \( R_{T_i} \) is rainfall during rainfall event i (mm) and \( A \) is the projected plan roof area (m²). Other variables are as previously defined. It is worth noting that \( E \) can also be expressed in mm of rainfall by dividing the depression loss by the collection area.

Linear regression analysis was used to produce the rainfall loss parameters for each test site which are summarised in table 4. The values of \( E \) are 0.21, 0.12 and 0.21 for sites 1, 2 and 3 respectively. At site 1 the value of \( C_f \) is 1.04 which is high compared with values of 0.95 and 0.93 for sites 2 and 3 respectively. The high value is probably attributable to an area of vertical walling adjacent to a single storey construction covered with a mono pitched roof which abutted the front elevation of the property. The walling which was part of the main two storey construction was orientated south and intercepted rainfall which then drained onto the mono-pitched roof. If 6m² or 50% of this vertical walling is assumed to contribute to the overall collection area the \( C_f \) value reduces to 0.97. However for consistency between sites rainfall collection is calculated using the roof plan area and the values of \( C_f \) and \( E \) initially determined. Pratt and Parkar (1987) obtained a run off coefficient of 0.987 and a depression storage loss of 0.32 mm for a roof subcatchment of five bungalows. The run off coefficients and depression storage losses for this study are comparable with Pratt and Parkar’s values. An alternative approach is to use an overall run off coefficient which is estimated using the relationship:

\[ C_{f_o} = \frac{Q_T}{R_T A} \] (4)

Where \( Q_T \), \( R_T \) and \( A \) are as previously defined. The value of \( Q_T \) was equated to the total volume of roof rainwater run off and \( R_T \) to the total rainfall during the trial period at each respective site. The overall run off coefficients \((C_{f,o})\) for sites 1, 2 and 3 were 0.93, 0.93 and 0.86 respectively.
The correlation between rainwater run off and both wind speed and direction was investigated. Data collected from both the weather station and the collection system were analysed. The correlation between rainwater run off, wind speed and direction is very weak with values of the coefficient of determination ($r^2$) ranging between 0.041 – 0.243. At each test site the wind speed and direction did not influence significantly the amount of rainwater collected.

**Modelling system performance**

The data collected in this study was used to assess the desirable characteristics of a rainwater collection sizing model. The rainwater collection sizing model consists of two parts:

i. Provision of rainwater supply and WC demand patterns or time series

ii. Simulation of system operation.

The rainfall and WC usage data collected during the monitoring periods was used as input into the system simulation model. The algorithm for the model used a yield after spillage (YAS) operating rule (Jenkins et al, 1978):

$$Y_t = \min (D_t, V_{t-1})$$

$$V_t = \min (V_{t-1} + Q_t, S) - Y_t$$

The variables are as previously defined. The sensitivity of the rainwater collection sizing model to the time interval of the rainfall and WC time series, and the magnitude of the run off coefficient, was investigated.

**Verification of the rainwater collection model system model**

The correlations between the monthly modelled values of $E_T$, $V_T$, $O_T$, and $M_T$ and the corresponding measured values at each site were determined. For example, the predicted values of $E_T$ at site 1 were plotted against the respective measured values. A straight line was fitted to the data points using linear regression. The intercept of the straight line was set to zero before determining the gradient (m) of the line and the coefficient of determination ($r^2$). The values of m and $r^2$ for $E_T$, $V_T$, $O_T$ and $M_T$ at sites 1, 2 and 3 are given in tables 5, 6, and 7 respectively.

The values of m and $r^2$ for $E_T$ range between 0.98-1 and 0.83 - 0.98 respectively. The largest range of m and $r^2$ values are between 0.95 - 1.14 and 0.86 - 0.98 respectively and are associated with $M_T$. The lowest value of $r^2$ is linked to site 2 and the modelled value of $M_T$ (Tables 5 - 7). The results of this analysis indicate a YAS model based on an hourly time interval accurately simulates the performance of the field tested 2000 litre rainwater collection system.

**Time interval sensitivity**

The sensitivity of rainwater collectors to the time interval of the input time series has been investigated by other researchers. For example, Heggen (1993) demonstrated daily time series result in more accurate simulation of system performance than either weekly or monthly time series. More recently, Coombes and Barry (2007) used a sub hourly time interval to simulate the performance of rainwater harvesting systems located in various parts of Australia.

In this study the accuracy of models using daily time intervals compared to hourly time intervals was investigated. The sensitivity of the model to the time interval (t) of the input WC time series was investigated using a daily time interval YAS operating algorithm. The rain loss variables $E$ and $C_f$ were set to the same values as used in the hourly model. The correlations between the monthly modelled values of the performance indicators ($E_T$, $V_T$, $O_T$, and $M_T$) and the corresponding measured values at sites 1, 2 and 3 are given in tables 5, 6 and 7 respectively.
The values of $m$ and $r^2$ at site 1 range between 0.89 - 1.01 and 0.98 - 0.93 respectively (Table 5). The lowest values of $m$ and $r^2$ are associated with the final volumes. At site 2, $m$ varies between 0.94 - 1.05, whilst the limits of $r^2$ are 0.95 - 0.99. Again the lowest values are associated with $V_T$ (Table 6). The ranges of $m$ and $r^2$ at site 3 are 0.96 - 1.19 and 0.82 - 0.96 respectively. The high value of $m$ is related to $M_T$ and the low value of $r^2$ to $E_T$ (Table 7). These results indicate a YAS model with a time interval of a day produces results comparable to the hourly based model and accurately simulates the performance of the field tested 2000 litre rainwater system.

**Rainfall loss sensitivity**

The sensitivity of both the hourly and daily time interval models to rainfall losses was investigated by setting the depression storage loss to zero. The values of the runoff coefficients were set to 0.93 (site 1), 0.93 (site 2) and 0.87 (site 3). The correlations between the monthly predicted values of the performance indicators and the corresponding measured values are given in tables 5, 6 and 7. The values of $m$ and $r^2$ for the daily model, range between 0.85 - 1.17 and 0.81 - 1.0 respectively. The ranges of $m$ and $r^2$ for the hourly model are 0.88 - 1.23 and 0.83 - 1.0 respectively. Generally the correlation analysis indicates the values of $E_T$ and $V_T$ are more accurately modelled than $M_T$ and $O_T$. The use of an overall runoff coefficient appears justified in either the hourly or daily time interval models.

**WC demand sensitivity**

The daily WC demand time series used as input data in the respective models for each site were replaced with an appropriate average daily WC demand. The average demands used were 175.51 litres/day (site 1), 97.2 litres/day (site 2) and 102.64 litres/day (site 3) in conjunction with overall rainfall coefficients of 0.93, 0.93 and 0.87 for sites 1, 2 and 3 respectively.

The correlations between the modelled performance indicators and the measured values are given in tables 5, 6 and 7 for sites 1, 2 and 3 respectively. The values of $m$ are between 0.77 - 1.18, whilst the range of $r^2$ is 0.7 - 0.99. Compared to the other models the incorporation of average constant demand patterns and overall rainfall coefficients results in the least accurate modelling of the performance indicators. However the correlation analysis does indicate the

<table>
<thead>
<tr>
<th>Year</th>
<th>Time Interval</th>
<th>Data Set</th>
<th>Percentage Conserved</th>
<th>Final Volumes</th>
<th>Over Flow</th>
<th>Make up</th>
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<td>Daily</td>
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<td>0.91</td>
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**Table 5 Correlations between monitored and modelled values of performance indicators at site 1**

<table>
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<tr>
<th>Year</th>
<th>Time Interval</th>
<th>Data Set</th>
<th>Percentage Conserved</th>
<th>Final Volumes</th>
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<td>Hourly</td>
<td>$y = 0.93x$</td>
<td>0.99</td>
<td>0.98</td>
<td>0.99</td>
<td>0.98</td>
</tr>
<tr>
<td>1998</td>
<td>Daily</td>
<td>$y = 0.95x - 0.12$</td>
<td>0.97</td>
<td>0.95</td>
<td>0.94</td>
<td>0.95</td>
</tr>
<tr>
<td>1998</td>
<td>Daily</td>
<td>$y = 0.93x$</td>
<td>0.97</td>
<td>0.98</td>
<td>0.94</td>
<td>0.96</td>
</tr>
<tr>
<td>1998</td>
<td>Daily</td>
<td>$y = 0.93 &amp; Av Flush$</td>
<td>1.05</td>
<td>0.93</td>
<td>0.99</td>
<td>0.98</td>
</tr>
</tbody>
</table>

**Table 6 Correlations between monitored and modelled values of performance indicators at site 2**
Table 7  Correlations between monitored and modelled values of performance indicators at site 3

overall integrity of this model type has been retained and could be used for the sizing of rainwater collection systems.

Design Curves
The behavioural model was used to assess the performance of a rainwater collection system in terms of its water saving efficiency. Average daily flushing demand data and fifteen years of historical daily rainfall data for eleven different UK locations were used as input time series to the system simulation model. A set of rainwater collector system performance curves for each of the geographic locations was developed. From the location specific curves a set of average curves were determined which have been shown to be sufficiently accurate for estimating rainwater collector system performance in the UK, these are illustrated in figure 3 (Fewkes and Warm, 2000). The water saving efficiency for a particular combination of roof area, rainfall, and demand are determined from figure 3 using the demand fraction (AR/D) and the storage period (S/d). The demand fraction is a dimensionless ratio and the storage period is expressed in days where d is the average daily demand, all other variables areas previously defined. The curves are powerful design tool from which the storage capacity required to achieve a desired performance level can be easily determined.

![Figure 3 Average water saving efficiency versus storage period (AR/D = 0.3 - 100)](image-url)
Discussion
The performance of a rainwater collection system has been monitored in three UK properties for periods ranging from six to twelve months. The flows of both rainwater and mains make-up water into and out of the collector were measured and logged. A weather station adjacent to the test site was used to monitor rainfall, wind speed and wind direction.
Sensitivity analysis was used to identify the essential characteristics of a rainwater collection sizing model. A rainwater collection sizing model using daily data can be used to accurately predict system performance. The use of hourly data is not necessary. The daily rainwater collection sizing model with a YAS operating rule can be used as a basis against which other model can be evaluated. The form of the WC demand time series does not have to be defined for accurate modelling, average usage data is satisfactory. However, this observation may not be universally applicable to all rainwater collection systems. Demand patterns which exhibit significant daily variance will possibly require more precise modelling.
The results of this study indicate the incorporation of rainfall losses into a rainwater collection sizing model is necessary if the collector’s performance is to be accurately assessed. The rainfall loss parameters for the collection areas were modelled using, an initial depression storage with constant proportional loss model. A simplified model using only a constant proportional loss or run off coefficient was demonstrated to produce acceptable results.
The amount of rainwater collected was not found to be significantly affected by wind speed and direction. Finally a set of design curves for the UK are presented. These are based on the analysis of historical daily rainfall from eleven different geographical sites in the UK and average flushing demand data.

References


