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Modelling of a roof runoff harvesting system: The use of rainwater for toilet flushing

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Abstract The water balance of a four-people family rainwater harvesting system was calculated in a case study. The experimental water saving efficiency (WSE) was calculated as 87 %. A simple computer model was implemented to simulate the behaviour of the rainwater harvesting system. In general, the rainwater collector volumes predicted by the daily model had shown a good correlation with the experimental values. The difference between the experimental and the predicted values for the stored volume can be explained by the lack of maintenance of the system that can affect its performance. On the basis of a long-term simulation of 20-year rainfall data, the following parameters were calculated: rainfall, water demand, mains water, rainwater used, overflow and WSE. The collection of rainwater from roofs, its storage and subsequent use for toilet flushing can save 42 m^3 of potable water per year for the studied system. The model was also used to find the optimal size of the tank for the single-family household: a storage capacity of approximately 5 m^3 was found to be appropriate. The storage capacity and tank size were distinguished. The importance to take into account the dead volume of the tank for the sizing was indeed highlighted.

Keywords modelling; rainwater collection; simulation; system efficiency; water saving efficiency

INTRODUCTION

At present, the availability of fresh water resource is one of the major issues the human race is facing due to world population increase, urbanisation, land use transformation, and pollution. Hence, the harmful consequences, such as health problems or social conflicts, could occur.

Thanks to the EU Water Framework Directive implemented to protect the aquatic environment, certain requirements have been set out involving potential use of rainwater harvesting. Rainwater harvesting has been a common practice worldwide for thousands of years (Pinfold et al., 1993; Simmons et al., 2001). The process consists in collecting and storing rainwater for the future use, such as toilet flushing, washing machines, garden watering, cleaning purposes, fire fighting, etc. The idea is to use collected roof runoff as a substitute for valuable drinking water. However, every European country has adopted a different perspective regarding the use of rainwater due to individual interpretations of the word “domestic” used in the European Directive 98/83/CE (European Official Journal, 1998).

Thus, in France, only external use (garden watering, cleaning, etc.) is allowed, except in special cases (drought, no mains network). Nevertheless, the rainwater harvesting devices were already available in the market, which according to suppliers accounted for 10,000 systems in 2007, out of which 67 were used in large buildings. Despite reluctance from the sanitary authorities (C.S.H.P.F, 2006), the increasing demand from private customers leveraged a reconsideration of rainwater harvesting, and a new decree authorised and clarified rainwater use inside buildings in August 2008 (Decree of August 21th, 2008). Even though there were investigations about rainwater reuse

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development at a large scale, French law has still forbidden the use of rainwater for drinking and bathing or clothes washing.

Now a question arises: Is the use of rainwater for toilet flushing perennial and financially viable at the scale of an individual household? On one hand, the system efficiency varies over the years depending, in particular, on rainwater. On the other hand, the cost of installation is relative to its storage capacity, which must also be optimal to satisfy the desired level of performance. Thus, the modelling of systems becomes necessary to simulate water flows. Results obtained by simulations will permit to assess the efficiency of the systems over years and to optimize the tank size. For rainwater harvesting, a number of models have been proposed (Dixon et al., 1999; Herrmann et Schmida, 1999; Vaes et Berlamont, 2001; Fewkes, 2004; Liu et al., 2007). Most of these models are not accessible to neophytes, or they were not validated with experimental data. In contrast, the proposed model, in this paper, to simulate the rainwater harvesting system is simple to implement and only consists of equations developed with a spreadsheet. In addition, this model was verified using data collected from an operational system.

In the present study, a commercially available rainwater collection system, installed in the south-west of France, was monitored over a period of one year. The inflows and outflows were determined from this operational system. Then, the collected data were used to validate a rainwater collection sizing model. Finally, this model was used to produce a continuous long-term simulation of the hydraulic performance of the rainwater usage system and to determine the optimal size of the tank.

PRESENTATION OF THE CASE STUDY

Description of the rainwater harvesting system and instrumentation

For the study, a commercially available domestic rainwater collection system was installed in a rural area of south west of France (Figure 1). The pilot house occupied by a family of two parents and two children is located in a village situated in country. The climate is oceanic with warm summer. Every year, it falls about 760 mm of rain in the region.

Rainwater is first collected from the 204 m^2 surface area tiled roof. This water is then channelled via open zinc gutters and down pipes to a wire filter with a mesh before entering into an underground, 5 m^3 capacity PEHD storage tank (Sotralentz Habitat), through a calm inlet. Any overflow is led into a nearby canal. A pumping system using a submerged (approximately 0.10 m) intake with an inlet filter attached to a float, then pumps water inside the house, through a treatment process composed of a 25 µm filter and an active carbon filter. When insufficient water is available in the tank, a probe activates a valve to allow pumping from a backup drinking water tank. Rainwater collected is available for toilet flushing and can supply two 9-L flush WCs.

The device also includes a rain gauge with tipping bucket and a pressure transducer to measure water tank level. A triangular weir and a flow meter were used to measure the volume evacuated via the overflow. Water meters were installed to measure the total volume delivered to the toilet flushing system and another to record the quantity of mains water supplied. A central processing unit monitored these parameters every 5 minutes or 15 minutes for the water meters.

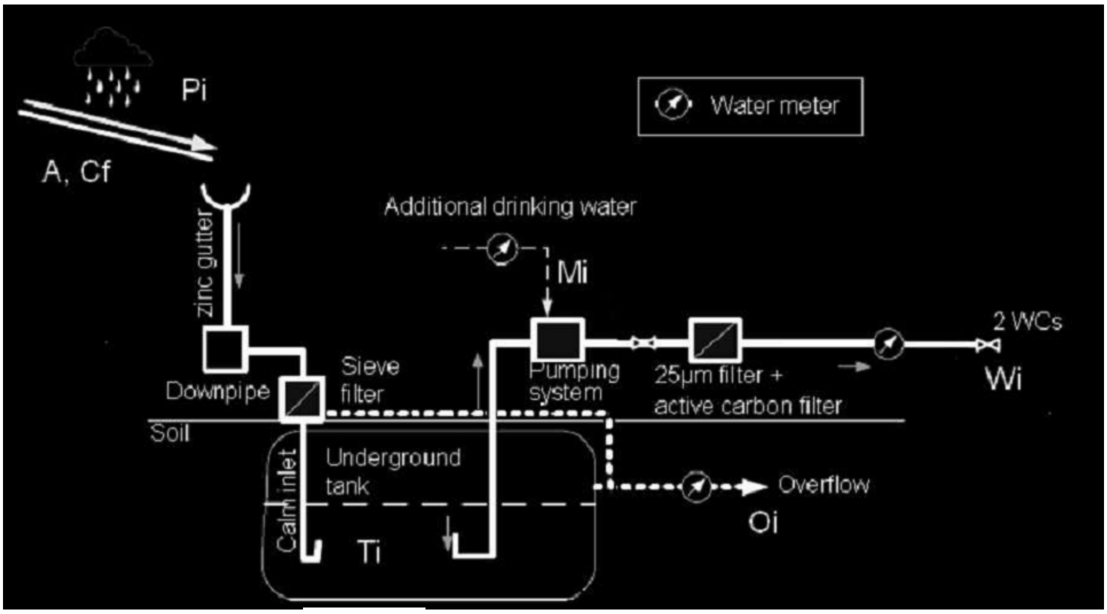

Figure 1. Rainwater harvesting system
P_i is the rainfall level (mm), A is the roof area (m^2), C_f is the roof runoff coefficient, T_i is the volume in storage (m^3), O_i is the rainwater volume overflowed (m^3), M_i is the mains water supply (m^3), W_i is the volume delivered to the toilet flushing system (m^3).

Experimental results

The quantitative monitoring of the rainwater harvesting system installed in a household in the south-west France was done from March 2009 to February 2010. This period corresponds to a rainfall of about 766 mm distributed among 174 days and 40 % of these rainy days presented precipitations inferior to 2 mm. The rainfall recorded at the test site is shown in Figure 2. The figure also shows the 30-year (1971-2000) averages of monthly rainfall data monitored at a station located approximately 40 km (Albi, Meteo France) away from the test site, and the average values for the 20-year period from 1990 to 2009.

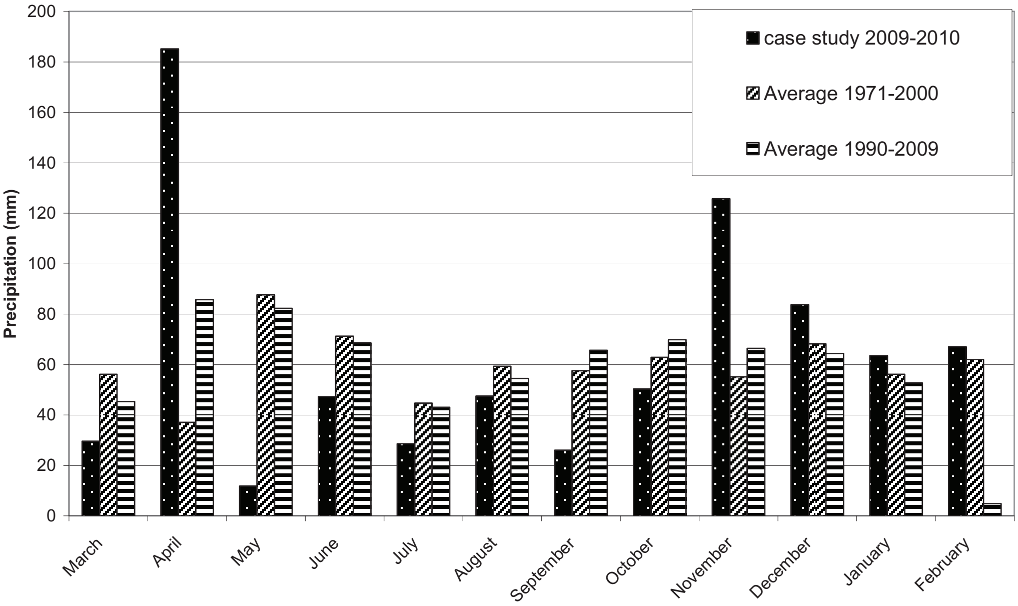

Figure 2. Monthly rainfall for the studied area

In this study, the daily WC flushing demand varies between 0 L and 309 L for the household with an annual average of 120 L, which corresponds to 30 L i.e. 3.3 flushes per day per inhabitant. This value is approximately 20 % of the average per person domestic water consumption (137 L per day) in France (C.I.Eau, 2010). The family, in this case study, was also a representative of a French household. In July, the WC usage in the test house was higher than expected due to a faulty ballcock, which resulted in the loss of almost 3 m^3 of water in one day.
The water saving efficiency (WSE) is a measure of how much mains water has been conserved in comparison to the overall demand of the WC and is also given by dividing the used rainwater volume by the WC demand volume, as given in Equation 1.

Equation 1. WSE (%)

$$WSE = \frac{W_t - M_t}{W_t} \times 100$$

Where W_t is the total volume delivered to the toilet flushing system during the studied period (m^3), M_t is the mains water supplied (m^3).

The results of the 12-month period are given in Table 1. Mains water supply was used for 53 days over the entire study period: 15 days in March-April, 5 days in July and 33 days from mid-August to the end of September. WSE ranges from 52 % in September to 100 %. A similar study in the UK was realised with a storage tank of 2.032 m^3 and a house occupancy varying between three and five people. A monthly WSE ranging from 4 % to 100 % was obtained (Fewkes, 1999). Our study showed that 48 m^3 of water was used for toilet flushing over the whole study period, of which 6 m^3 was supplied from the mains network. As a result, 42 m^3 of potable water was saved. The corresponding WSE of the system was 87 % for the toilet flushing.

Table 1. Water saving efficiency of the rainwater system for March 2009-February 2010

Month	Rainfall (mm)	WC demand (L)	Mains water (L)	Rainwater used (L)	Over-flow (L)	Water saving efficiency (%)
March	30	4 114	1 041	3 073	*	75
April	185	4 164	629	3 535	7 442	85
May	12	3 577	0	3 577	2 317	100
June	47	3 001	0	3 001	920	100
July	29	6 827	1 225	5 602	41	82
August	48	3 790	1 667	2 123	2 464	56
September	26	3 218	1 560	1 658	0	52
October	50	3 602	0	3 602	841	100
November	126	3 705	0	3 705	7 041	100
December	84	4 142	0	4 142	2 541	100
January	64	4 264	0	4 264	1 976	100
February	67	3 835	0	3 835	2 740	100
Minimum	12	3 001	0	1 658	0	52
Maximum	185	6 827	1 667	5 602	7 442	100
Totals	**766**	**48 239**	**6 122**	**42 117**	**28 321**	**87**

* Monitoring of the overflow not started

Rainfall loss occurred from the system due to absorption by the roofing material, wind effects around the roof and gutter overflowing. The roof runoff coefficient (C_f) and overall efficiency (OE) of the system were evaluated using relationships given in Equation 2.

Equation 2. Roof runoff coefficient (C_f) and overall efficiency (OE) of the rainwater system

$$Cf = \frac{Vc_t}{P_t.10^{-3} \times A} \qquad \text{with} \qquad Vc_t = W_t - M_t + O_t$$

$$OE = \frac{Vu_t}{P_t.10^{-3} \times A} \qquad \text{with} \qquad Vu_t = W_t - M_t$$

Where, P_t is the total rainfall level during the study period (mm), A is the roof area (m^2), Vc_t is the volume of rainwater counted (m^3), O_t is the rainwater volume overflowed (m^3), Vu_t is the volume of rainwater used (m^3), W_t is the total volume delivered to the toilet flushing system (m^3), M_t is the mains water supply (m^3).

From April 2009 to February 2010, the precipitation (P_t) multiplied by the roof area (A) resulted in 150 m^3 of roof runoff, while the total volume counted (Vc_t) was 76 m^3. The roof runoff coefficient (C_f) was thus evaluated to 0.51, which indicates a loss of approximately 50 % of the rainwater. This value is low for a tiled roof (Fewkes, 1999) and after verifications it was highlighted that the time step for overflow measuring was too long and it was checked on site that the overflow volume was under evaluated. A volume of rainwater used of 39 m^3 corresponds to an overall efficiency (OE) of the system of 0.26. At the same time, it was highlighted a rain inferior to 2 mm did not generate a runoff.

In the rainwater harvesting system studied, the wire filter at the entrance of the tank is automatically rinsed once a week. Frequency of cleaning is independent of the weather. Thus, when a rain occurs just after the cleaning, a partial clogging can occur that will remain till the next week, which can affect the overall efficiency of the system. Indeed some overflows were registered, even when the tank was not full. In addition, when the mains water supply was used, 1 150 L of stored runoff remained in the tank, which corresponds to 20 % of the 5 000 L. It is also important to dissociate the commercial tank volume and the effective volume available for the storage.

MODELLING THE SYSTEM PERFORMANCE

Description of the model

A computer model was developed in a spreadsheet to simulate the behaviour of a rainwater harvesting system. An initial loss (L) was considered. The information needed is the maximum volume of storage available (T_{max}), the roof area and the runoff coefficient (C). The input data are precipitation (P_i) and water demand (W_i) based upon time interval of the day. Equations developed in the spreadsheet were used to simulate collection (R_i), storage (T_i), use of mains water (M_i) and over-flow (O_i) (Figure 3).

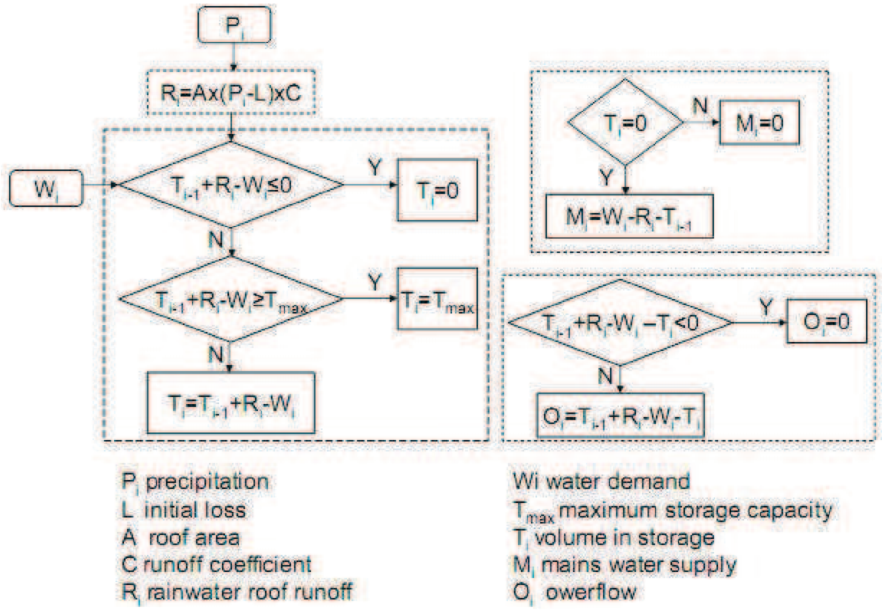

Figure 3. Flowchart for rainwater tank storage model

Validation of the model with experimental data

The selected roof area was 204 m^2, which corresponds to the area of the studied household. The volume available for the storage is 3.848 m^3 because of the dead volume as explained before. The volume stored in tank was initialised with the experimental value. An initial loss of 2 mm was considered. Considering this loss, the runoff coefficient was evaluated to 0.71 when only precipitation superior to 2 mm were considered. The rainfall and WC usage data, collected during the 12-month monitoring period, were used as input into the model as daily time series.

The simulation results were plotted against the corresponding values predicted for the stored volume (Figure 4). For stored volume, the regression $y=0.81x+0.44$ with R^2 of 0.72 was observed. The overflow events and their volumes obtained through the simulation and on site are shown in Figure 5. A linear trendline $y=1.26x+0.00$ with a correlation coefficient R^2 of 0.68 was observed.

Some simulated stored volumes were lower than the experimental values. The too small experimental value of C can explain that.

Some overflow events measured on site are not included in the simulated results because of the clogging of the wire at the entrance of the tank. The most evident example of such events occurred on 1st August 2009 and is indicated by an arrow in Figures 4 and 5. As a result, the experimental stored volume was less than the simulated one.

In order to verify the above proposed explanation, experimental data were corrected: the volume overflowed on 1st August 2009 because of the clogging of the wire was erased and was considered to have been stored in the tank. New tank volumes calculated from the simulation were compared to the corrected experimental data (Figure 6). The regression obtained for the volume in storage was greatly improved with these corrections: $y=1.03x-0.22$ with R^2 of 0.91. For the overflow volumes, the regression of simulated values against corrected experimental data was enhanced to $y=1.40x+0.00$ with R^2 of 0.70.

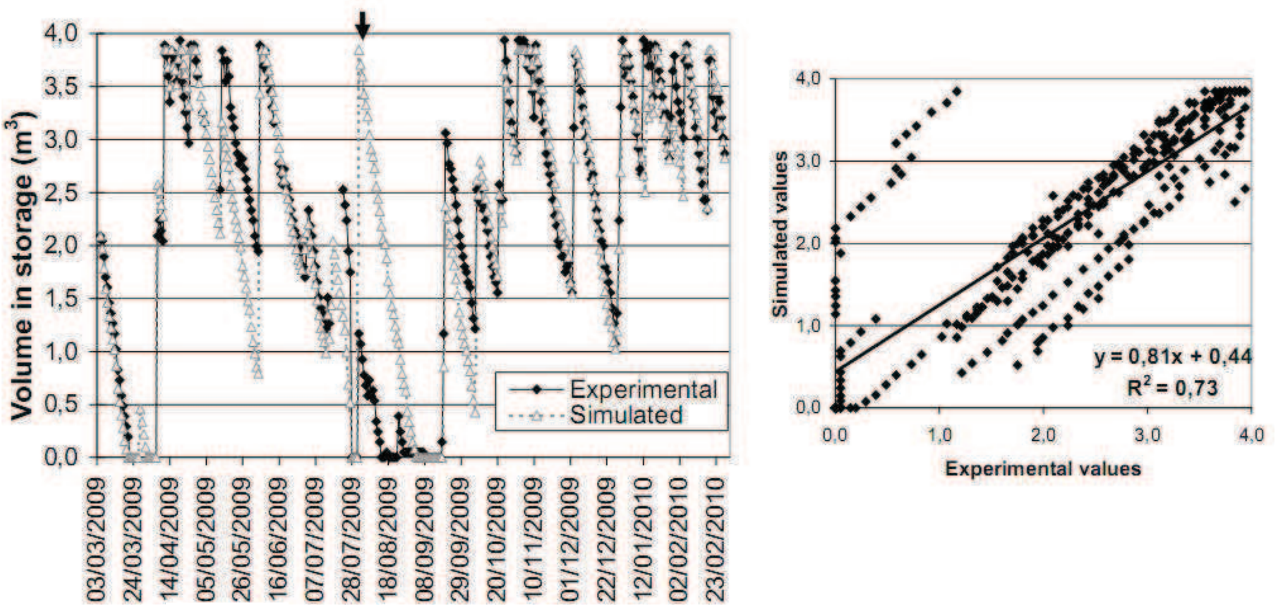

Figure 4. Volume stored in the tank – Experimental and simulated values
The arrow highlights an overflow event that occurred when the tank was not full because of the clogging of the wire at the entrance of the tank.

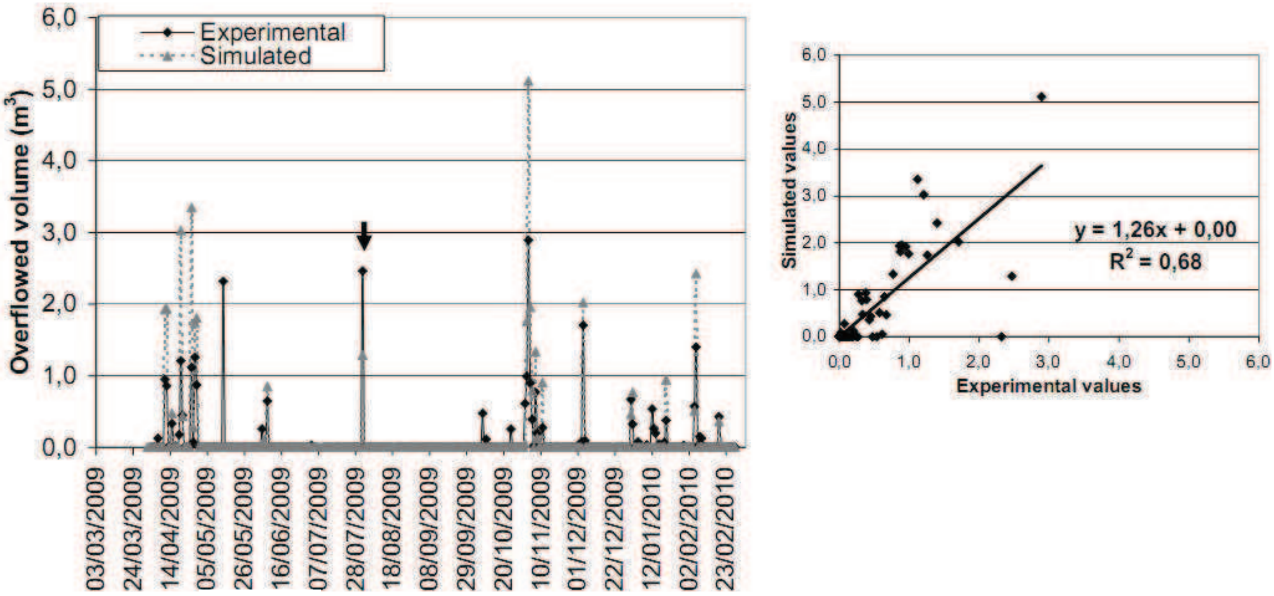

Figure 5. Volume overflowed – Experimental and simulated values
The arrow highlights an overflow event that occurred when the tank was not full because of the clogging of the wire at the entrance of the tank.

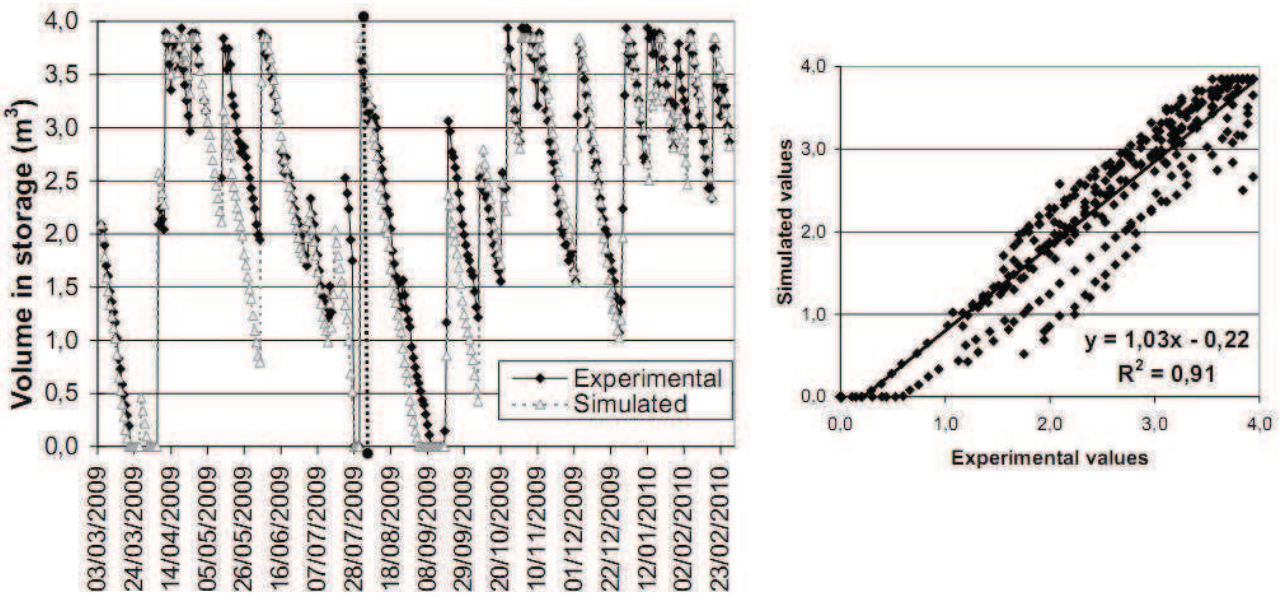

Figure 6. Volume stored in the tank – Corrected experimental and simulated values
Correction realised on the experimental data is shown by a vertical dotted line.

To evaluate the sensitivity of the model to this parameter, two other values of C were tested for the simulation. Results are presented in Table 2. C is not crucial for the simulation of the stored volume in this case. But considering the overflowed volume, the increase of C particularly affects the slope of the regression of simulated values against experimental values. Nevertheless results are coherent with the experimental observation that the overflowed volume was under evaluated because of the inappropriate time step of 5 minutes. This under evaluation resulted in a too low runoff coefficient evaluation. According to simulations, the WSE of the system is 88 - 90 %, which is near the experimental value of 87 %.

Table 2. Sensitivity of the model to the runoff coefficient

C	Volume stored in the tank (m^3) Simulated values = f(experimental values)			Overflowed volume (m^3) Simulated values = f(experimental values)			Simulated rainwater used (L)	Simulated mains water (L)	Simulated WSE (%)
	Slope	Offset	R^2	Slope	Offset	R^2			
0,7	1,03	-0,22	0,91	1,40	0,00	0,70	42,1	5,7	88
0,8	1,02	-0,13	0,90	1,66	0,01	0,71	42,5	5,2	89
0,9	1,02	-0,04	0,89	1,94	0,02	0,70	43,0	4,8	90

LONG-TERM SIMULATION

Hypothesis

The model was used to simulate the system performance over twenty years. The same values were used for the roof area, the roof runoff coefficient and the available storage volume. Historical daily rainfall data measured in Albi (Meteo France, 40 km away from the study site) for the period 1990-2009 (Figure 2). According to another study (Fewkes et Butler, 2000), the use of daily data was appropriate. They indeed recommend using a daily data model for a storage fraction i.e. the storage capacity of the tank divided by the rainwater captured in a year, superior to 0.01. In this study, the storage fraction for the system varies from 0.018 to 0.033 depending upon the year. The family behaviour regarding the toilet flushing was considered to remain the same over the period. As a result, the water demand series obtained during the one year experiment was reproduced twenty times. The abnormal consumption due to the malfunctioning of the ball was replaced by the mean value of 120 L. The operation of the system was simulated for twenty years.

Results

On the basis of a long-term simulation of 20-year rainfall data, the following parameters were calculated for each year: rainfall, WC demand, mains water, rainwater used, over-flow and WSE (Table 3). The annual WSE ranges from 85 to 100 %. A 20-year period simulation showed that 829 m^3 of potable water can be saved for a single-family household that corresponds to an average of 42 m^3 per year. Now the average domestic water consumption is 137 L per day per person in France (CIEau, 2010) which corresponds to 50 m^3 per year per person. As a result rainwater use for toilet flushing permits to save around 21 % of domestic water consumption.

Table 3. Water saving efficiency of the rainwater system – 20 years simulation

Year	Rainfall (mm)	Rainfall – initial loss (mm)	WC demand (L)	Mains water (L)	Rainwater used (L)	Over-flow (L)	Water saving efficiency (%)
1990	737	534	43 838	3 646	40 192	32 109	92
1991	695	501	43 838	197	43 641	30 026	100
1992	1055	818	43 958	788	43 170	76 076	98
1993	819	588	43 838	6 143	37 695	45 617	86
1994	810	584	43 838	1 565	42 273	44 220	96
1995	980	767	43 838	0	43 838	65 629	100
1996	918	678	43 958	0	43 958	55 716	100
1997	641	434	43 838	2 505	41 333	19 861	94
1998	606	389	43 838	0	43 838	14 722	100
1999	886	651	43 838	1 718	42 120	49 866	96
2000	787	554	43 958	0	43 958	37 234	100
2001	586	361	43 838	6 491	37 347	18 911	85
2002	764	542	43 838	3 652	40 186	33 839	92
2003	591	401	43 838	6 656	37 182	20 593	85
2004	678	472	43 958	0	43 958	25 955	100
2005	598	420	43 838	4 541	39 297	20 984	90
2006	557	399	43 838	1 677	42 161	18 660	96
2007	630	421	43 838	3 593	40 245	19 173	92
2008	828	600	43 958	2 850	41 108	44 377	94
2009	763	586	43 838	2 644	41 194	42 377	94
Minimum	557	361	43 838	0	37 182	14 722	85
Maximum	1 055	818	43 958	6 656	43 958	76 076	100
Totals	14 928	10 698	877 360	48 667	828 693	715 944	95

SIZING THE TANK

The theoretical WSE was calculated for different volumes of storage using the model. First time, the one-year experimental WC demand series was used. Second time, the impact of the unusual water consumption due to the malfunctioning of a ball was evaluated by replacing the abnormal value by the mean value. The WSE increased with the size of the tank, as increasing the capacity increased the amount of water available for the use, to finally reach an asymptote (Figure 7). The optimal size is assumed to correspond to that tank size where further increase in size produced only a small increase in reliability. We considered the optimum was reached when the increase in WSE becomes inferior to one percent for a storage rise of 0.5 m^3. With this criteria and according to the simulation, the maximum theoretical WSE of 97% can be achieved with a storage volume of 6,5^3 and 5 m^3 if no leak is considered. The sizing was validated by the 20-year simulation results, which conduct to an optimal storage volume of around 5 m^3.

In fact the storage volume of 5 m^3 used in our case study was firstly selected because it is most widely used for a single-family household in France. Now our results confirm this sizing was quite optimal to satisfy the WC demand of the family. But as discussed previously, 20 % of the tank volume was dead volume and only 3.85 m^3 was actually available for the storage.

It is also important to complete the possible mains water saving using rainwater by vigilance against leaks. To be optimal, the dimensioning of a tank for rainwater harvesting must take into consideration the volume remaining in the tank when the system transfers to mains water supply.

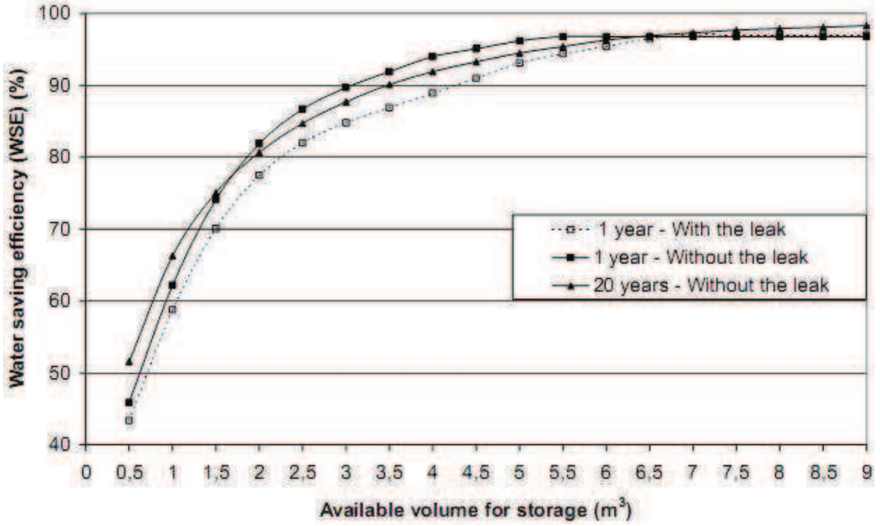

Figure 7. Optimization of rainwater tank size for a 4-people household with a 204 m^2 tiled roof area

CONCLUSIONS

A rainwater collection system of a 4-people household with a 5 m^3 tank was monitored over a twelve-month period. An average daily consumption of 30 L per person was established. Results indicate that 87 % of the WC flush was saved over a year. It was highlighted that 20 % of the tank were in fact not available for the storage. A simple model was developed in a spreadsheet to simulate water balance of the studied system. The calculated volumes were compared to the experimental data. The model produces acceptable results to predict the system performance. The noticed difference between the experimental and the predicted values highlights the importance of the maintenance. The clogging of the filter at the entrance of the tank can indeed affect the overall efficiency of the collection system. Experimental daily flushing demand and twenty years of historical daily rainfall data were used as input to the system simulation model. The results for the system efficiency clearly show that rainwater collection systems can significantly reduce the potable water consumption. Thus, an average saving of 42 m^3 of water was determined. Finally, the model was used to find the optimal size of the tank. A volume available for the storage of 5 m^3 was found to be appropriate for the single-family household. Nevertheless, it is important to distinguish the volume available for the storage from the commercial volume of the tank, which must be higher. The dead volume cannot indeed be neglected when the mains water supply is used and must be taken into account for the sizing.

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