Towards the Quantification of Rainwater Tank Yield in South East Queensland by Considering the Spatial Variability of Tanks

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Summary

This paper reports a study aimed at quantifying the yield from rainwater tanks in South East Queensland (SEQ) by considering the spatial variability of tanks. The methodology involves Monte Carlo simulation of tank storage behaviour by considering the spatial variability of input variables, ie, tank sizes, inflows to the tank, household water demand and losses associated with the tank inflow. Probability distributions and probability based methods have been used to represent the spatial variability of input variables. The results have indicated that the error introduced to the average annual yield of a system with multiple internally plumbed rainwater tanks can be in the order of 14% when spatial variability is ignored. For single family new residential households (ie, detached dwellings) in SEQ, the rainwater tank yield found through stochastic simulation is 37 kL/h/y, if the tank is used for the same household end uses. Further work is in progress to include a large sample of tank sizes and roof areas as well as water uses of both new and existing single family residential houses in Gold Coast, Ipswich and Sunshine Coast.

Keywords
Rainwater tank yield, stochastic simulation, potable water savings, rainwater harvesting.

Introduction

Domestic rainwater tanks are promoted as an alternative source of water supply in Australian major cities. Understanding the amount of water supply (ie, yield) from rainwater tanks is essential for urban water supply planning, in particular to assess the long-term supply security. A common approach used by practitioners to quantify the yield from a system consisting of a large number of domestic rainwater tanks is, linear extrapolation of the supply obtained from a single tank based on average tank and water demand characteristics. This approach assumes that the yield of individual domestic rainwater tanks in a given area is the same for all the tanks and, that the tank characteristics and household water uses have linear relationships with the tank yield. However, several studies have shown that the amount of water supplied from rainwater tanks varies with such factors as prevailing climate, tank volume, area of the roof connected to the tank and household water use (Fewkes and Butler, 2000; Fewkes and Warm, 2000; Coombes and Barry, 2007; Mitchell, 2007; Ghisi, 2010; Basinger *et al.*, 2010; Khastagir and Jayasuriya, 2010; Palla *et al.*, 2011 and Neumann *et al.*, 2011). These studies have also shown that the tank and water use characteristics have non-linear relationships with the tank yield. Also, studies on household end use measurements have clearly shown that the volume of water use by individual end uses varies from house to house (Roberts, 2005; Willis *et al.*, 2009; Beal and Stewart, 2011).

The spatial variability of supply from domestic rainwater tanks in an urban area has also been reported in Beal *et al.* (2012) and Chong *et al.* (2011a and 2011b). Unlike the above-mentioned studies based on computer simulations, these studies have analysed water consumption data obtained from households with and without rainwater tanks. Both studies have examined rainwater tank supply in South East Queensland (SEQ), Australia, where installation of internally plumbed rainwater tanks for toilet, clothes washing and garden uses, is a mandatory requirement in all new houses (Queensland Water Commission, 2010). Beal *et al.* (2012) have used 2008 water consumption data, and have found that rainwater tank yield in the SEQ varies from 20 kilolitres/household/year (kL/h/y) to 95 kL/h/y with a mean of 50 kL/h/y. Chong *et al.* (2011a and 2011b) have used 2009 and 2010 consumption data, and have found that rainwater tank supply varies from 24.5 kL/h/y to 88.5 kL/h/y with a mean of 58.8 kL/h/y. These studies clearly show that supply from rainwater tanks can vary spatially. At present, further studies are in progress in the SEQ to quantify the spatial variability of tank sizes and tank inflows. Some outcomes of such studies are used in the analysis reported in this paper.

All these studies indicate that it is not realistic to assume the factors that can affect the supply from domestic rainwater tanks would remain uniform in a given urban area, which could be a suburb, a town or a city. As mentioned earlier, these factors include tank size, connected roof area, losses from the roof due to different roof material, prevailing climate, household occupancy rates, household end uses to which tank water is used and the water usage behaviour of individual household occupants. Therefore, it is likely that an approach that uses linear upscaling of the yield of a single tank with average characteristics to determine the yield of a system with multiple rainwater tanks, can introduce errors. The main reason for such errors is the non-linear dependency of the rainwater tank yield on the parameters that define household water use and the tank (Mitchell *et al.,* 2008; Neumann *et al.,* 2011; Maheepala *et al.,* 2011).

Yield of a system with multiple rainwater tanks has been examined in a number of studies (Mitchell *et al.,* 2008; Xu *et al.,* 2010; Neumann *et al.,* 2011; Maheepala *et al.,* 2011; Mashford *et al.,* 2011 and Coultas *et al.,* 2011). All these studies have considered the spatial variability of the above-mentioned factors. They have shown that the use of average values for rainwater tanks characteristics as well as for household water demand can result in an overestimation of the supply from a system with multiple tanks. The reported overestimations are in the order of 14% for Melbourne-based data (Mitchell *et al.,* 2008; Xu *et al.,* 2010; Maheepala *et al.,* 2011), 18% for Canberra-based data (Maheepala *et al.,* 2011) and 14% for Brisbane-based data (Coultas *et al.,* 2011).

This paper reports a study aimed at quantifying potable water savings of domestic rainwater tanks in SEQ, which is one of the fastest growing urban regions in Australia, covering about 22,420 km2. The analysis reported in the paper can be considered as an extension to Coultas *et al.* (2011), which reported preliminary results of a study undertaken to quantify the yield of rainwater tanks in SEQ, using assumed probability distributions for tank sizes, effective roof areas and household end water uses, based on literature sources. The reason for using assumed data in Coultas *et al.* (2011) was the lack of observed (or measured) data at the time of undertaking the study. Observed data relevant to SEQ have become available since then, and this paper reports an analysis undertaken to quantify the yield of rainwater tanks in SEQ, considering the spatial variability exhibited in the observed data of tank characteristics and household demands.

Methodology and Results

To quantify the yield of rainwater tanks in SEQ, we used Monte Carlo (or stochastic) simulation, which was a method for iteratively evaluating a deterministic model using sets of random numbers as inputs (Kroese *et al.,* 2011). Our method involved simulation of storage behaviour of a rainwater tank using sets of tank and household end use characteristics sampled either directly from probability distributions, or from a large number of plausible values generated using probability based methods. Rainwater tank characteristics included tank size, connected roof area and losses from the roof. Two types of losses were considered: initial and continuing loss of water from the roof. Tank characteristics were sampled from probability distributions. Water demands of household end uses were sampled from a set of plausible time series, which were generated using a probability-based method for predicting the household water use.

The rainwater tank model described in Mitchell *et al.* (2008) was used for the stochastic simulation of rainwater tanks. The Mitchell *et al.* (2008) rainwater tank model was a water balance model, capable of simulating the processes of rainfall, roof runoff, and tank storage behaviour. It consisted of two modules: rainfall-runoff module, which computed the amount of roof runoff into the tank, and storage module, which computed the amount of water stored in the tank. The model allowed each tank parameter be specified either as a continuous probability distribution with a minimum and a maximum value, or as an average value.

Table 1. End use frequency statistics of 61 SFR houses in Brisbane (data source: Beal and Stewart, 2012).

Statistic	Frequency (events per day)							
	Toilet Half Flush	Toilet Full Flush	Tap	Shower	Bath	Dishwasher	Clothes Washer	Irrigation
Mean	4.87	4.21	58.70	2.13	0.13	0.55	0.71	0.12
Std Dev	3.97	2.68	33.42	1.99	0.28	0.68	0.56	0.19
Skewness	1.67	1.29	1.13	5.11	2.12	1.94	2.93	1.94

Table 2. End use event mean volume statistics of 61 SFR houses in Brisbane (data source: Beal and Stewart, 2012).

Statistic	Mean Volume of End Use Event (litres/event)				
	Toilet Half Flush	Toilet Full Flush	Tap	Dishwasher	Clothes Washer
Mean	3.89	7.44	1.19	6.55	99.45
Std Dev	1.10	1.58	0.51	8.82	69.06
Skewness	-0.49	1.23	1.18	1.76	1.10

Table 3. Shower flow rate and duration statistics of 61 SFR houses in Brisbane (data source: Beal and Stewart, 2012).

Statistic	Shower Event Flow Rate (litres/minute)	Shower Event Duration (minutes)
Mean	7.82	5.72
Std Dev	3.18	2.22
Skewness	2.32	1.23

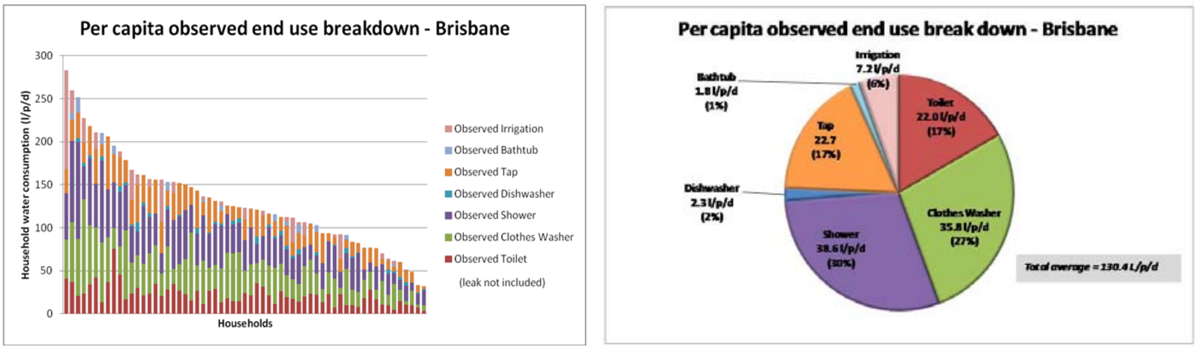

Figure 1. Observed per capita water consumption of 61 houses in Brisbane (data sourced from: Beal and Stewart, 2011).

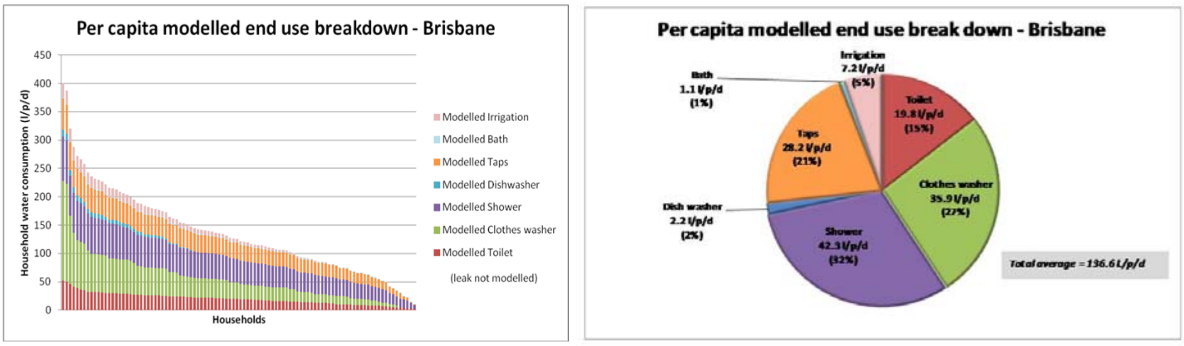

Figure 2. Modelled per capita water consumption of 100 houses in Brisbane.

The probabilistic demand model described in Duncan and Mitchell (2008) was modified and used to simulate the water demands of household end uses. The household end uses included in this model were: toilet use, tap use, showers, baths, dishwashers, clothes washers and garden irrigation. Modifications to the household demand simulation method included changing fixed volumes of water used for taps, clothes washer, dishwasher and baths to probability distributions, which allowed accounting for the spatial variability present in such end uses. The probabilistic demand model quantified the water demand of each end use through a two stage process. The first stage defined the probability of an end use starting in a given time step using diurnal data. The second stage quantified the volume of water use by that end use, during the given time step, using probability distributions of frequency of that end use (input variables are shown in Table 1) and volume per event (input variables are shown in Table 2 and Table 3). All end use demands were generated at one minute intervals, which were then aggregated to any higher order time step. The probabilistic demand model was calibrated using Brisbane's measured data sourced from Beal and Stewart (2011).

Table 4. Observed and modelled household end use demands for Brisbane.

	Household End Use Water Demand in Litres/Person/Day							
	Toilet	Clothes Washer	Shower	Dishwasher	Tap	Bathtub	Garden	Total
Observed Mean	21.9	35.8	38.6	2.3	22.7	1.9	7.2	130.4
Observed Standard Deviation	11.9	20.7	20.9	2.5	11.4	3.9	17.4	55.1
Modelled Mean	19.8	35.9	42.3	2.3	28.2	1.1	7.6	136.6
Modelled Standard Deviation	10.3	30.8	15.4	3.4	10.6	0.02	7.1	38.7

The measured data represented 61 single family residential (SFR) households, contained a mixture of efficient and non-efficient household appliances, and an estimated amount of water considered to be lost through leaks. Leaks were not considered in our analysis simply because the probabilistic demand model did not have an option to model leaks. The average household consumption during the measured period (ie, 14-28 June 2010) without considering leaks was 130.4 Litres/person/day (L/p/d) (Figure 1 and Table 4). The simulated or modelled value of household consumption was 136.6 L/p/d (Figure 2 and Table 4). Comparison of the observed end uses of 61 houses and the modelled end uses of 100 houses are shown in Figure 1, Figure 2 and Table 4. The calibrated demand model was used to generate 100 plausible demand time series over the simulation period (ie, January 1960 to December 2010), in order to feed into the Mote Carlo simulation to determine the tank yield.

The probability distributions for tank variables and household end uses were constructed from the observed data of 20 new SFR households. Details of the rainwater tank parameters used for the Monte Carlo simulation are given in Table 5. In line with Queensland's current water savings target (Queensland Development Code, 2008; Queensland Water Commission, 2010), toilet use, clothes washers and garden irrigation were supplied from the rainwater tank. The rainwater tank simulation assumed that the supply from the tank was switched to mains supply, when the tank was empty (ie, no trickle supply). Behaviour of the rainwater tank was simulated on a daily basis. Simulation was carried out over a period of 50 years, from 1960 to 2010. The simulation process involved computation of the daily supply from the tank over the simulation period, over a large number of iterations. For each iteration, a set of tank parameters was sampled from the probability distributions given in Table 5, and a time series of demand was sampled for each end use being supplied from the tank, from a sample of 100 plausible demand time series, generated from the above-mentioned calibrated demand model. An iteration could be viewed as daily simulation of tank behaviour of a detached dwelling with an internally plumbed rainwater tank over a 50 year period. Number of iterations was varied from 100 to 35,000, and for each case, the average annual yield was computed from the daily time series of tank supply. It was noticed that the average annual yield became almost a constant when the number of iterations was greater than 10,000 (Figure 3). Hence 10,000 iterations were considered as adequate to represent the spatial variability of tank supplies, for our study.

Table 5. Parameters values used for Mote Carlo simulation of rainwater tank behaviour of 50 years.

	Tank Size	Effective Roof Area	Initial Loss	Continuing Loss	Occupancy
Units	**KL**	**m^2**	**mm**	**%**	**No.**
Minimum	0.79	27.00	0	0	1
Mean	4.67	76.60	0.5	15	2.6
Maximum	5.61	135.00	1.75	30	6
Probability Distribution	Normal	Normal	Normal	Normal	
Standard Deviation	1.06	28.84	0.5	5	
Sample size	20	20	0[1]	0[1]	61

Note 1: data not available for SEQ. Used Melbourne-based data reported in Xu *et al*. (2010).

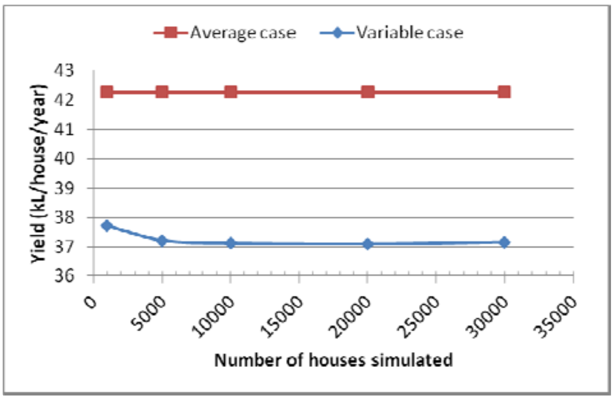

Figure 3. Expected rainwater tank yield for different runs of stochastic simulation.

The average rainwater tank yield for 10,000 tanks (or iterations) is shown in Figure 4. The average annual yield vary from 12.6 kL/h/y to 88.7 kL/h/y, with a mean value of 37.12 kL/h/y and a standard deviation of 9.97 kL/h/y. That is, the long-term, expected rainwater tank yield in the SEQ for SFR households is 37.12 kL/h/y, if the tank water is used for toilet flushing, garden watering and clothes washing (ie, the red horizontal line shown on Figure 4). To examine implications of the common practice for computing tank yield, a simulation was performed by using average values obtained from the 10,000 iterations, for tank parameters and demand time series. The tank yield for the average case was 42.28 kL/h/y (ie, the purple horizontal line shown on Figure 4), which was about a 14% overestimation compared to the yield obtained by considering the spatial variability of tank supply.

The tank yield computed through stochastic simulation was compared with the tank yield computed by the Queensland Water Commission (QWC). The QWC study involved the use of billing records of 1,841 single family residential (SFR) houses in Brisbane during the period from January 2011 to June 2011. This sample had 120 SFR houses with internally plumbed rainwater tanks (IPR) and 1,721 SFR houses without IPR. It was assumed that the houses with IPR supplied toilet, clothes washer and external irrigation from the rainwater tank. The sample with IPR was called ‘sample B’ and the other sample was called ‘sample C’. Both samples were considered to be consisting of efficient appliances for toilets, clothes washers and showers. The average household consumption of sample B and C were 381 litres/household/day (L/h/d) and 481 L/h/d, respectively. Based on a comparison of the average water consumption in sample B and C, the average yield obtained from a rainwater tank in Brisbane was estimated as 38.46 L/p/d (or 36.55 kL/h/y based on the average occupancy rate of 2.6 people/household, which is the same for the sample of 61 houses used in our study).

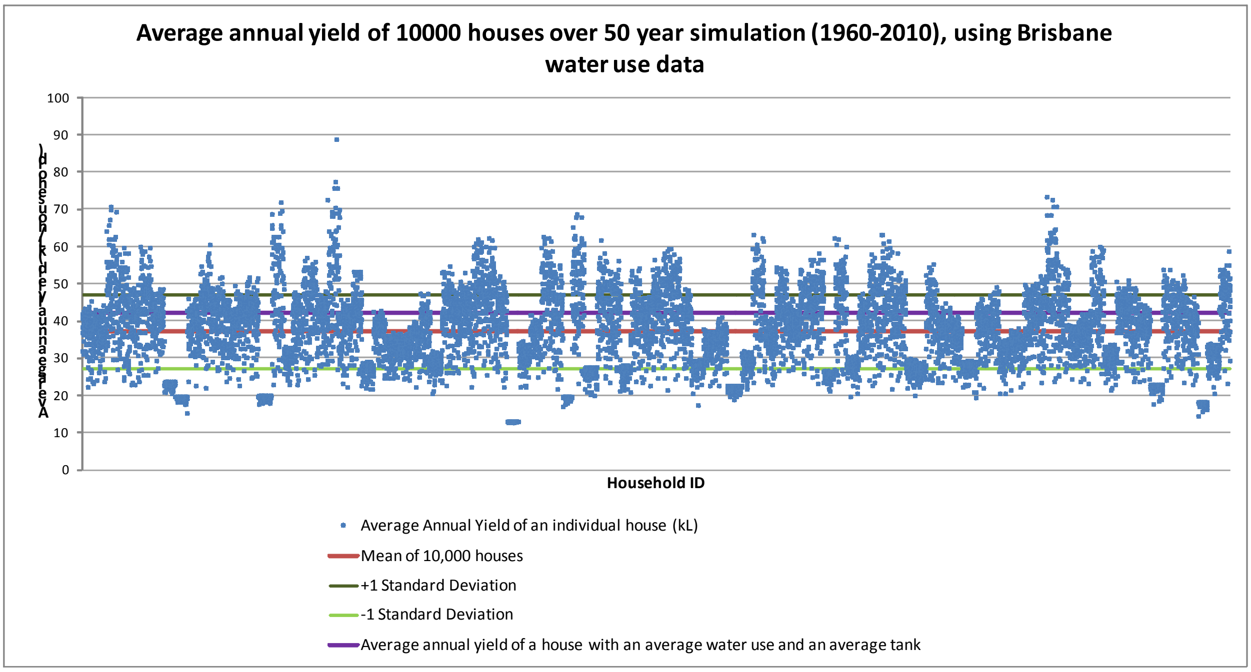

Figure 4. Mote Carlo simulation of 10,000 domestic rainwater tanks with each tank’s behaviour simulated on a daily basis over 50 years.

In summary, our study indicated 39.09 L/p/d (or 37.12 kL/h/y), as the rainwater tank yield in SEQ, which is of similar order of magnitude to the QWC’s study which indicated 38.46 L/p/d(or 36.55 kL/h/y) as the rainwater tank yield in SEQ. Our study considered the spatial variability of tank characteristics and household water use and used stochastic simulation to capture that variability, in order to quantify the tank yield, whereas the QWC study compared billing records of SFR houses with and without rainwater tanks in Brisbane. The fact that the tank yield obtained from our study is of similar order of magnitude to the tank yield estimated from the billing records (difference is 0.63 L/p/d), indicates that stochastic simulation has the ability to capture the spatial variability present in rainwater tank supplies across an urban area in a reliable manner.

Conclusions and Work in Progress

In this study, we have showed that potable water savings obtained with domestic rainwater tanks in SEQ can be quantified and upscaled to the regional scale satisfactorily and reliably, through the use of stochastic or Monte Carlo simulation technique. Upscaling of rainwater tank yield is essential to assess the security of water supply at the SEQ regional scale. The tank yield found through the stochastic simulation of supply and demand behaviour of rainwater tanks in the SEQ is 37 kL/h/y, which is of similar order of magnitude to the tank yield estimated from the billing records by the QWC. If the spatial variability present in tank water supply and household water consumption is ignored, the tank yield is 42 kL/h/y, which is about a 14% overestimation compared to the tank yield that takes into account the spatial variability of tank supply.

However, it should be noted that for the study reported in this paper, the spatial variability of rainwater tank characteristics were derived only from 20 new single family residential houses in SEQ and the spatial variability of household water use was derived from 61 new and existing single family residential houses in Brisbane, which might not be an adequate sample to represent the SEQ region. Hence the above-mentioned results should be used cautiously for the SEQ region. The study is in progress to include a large sample of tank sizes and roof areas as well as water uses of both new and existing single family residential houses in Gold Coast, Ipswich and Sunshine Coast.

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