



Quantifying potable water savings of rainwater tanks in South East Queensland by considering the spatial variability of tank supplies

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Abstract

Installation of domestic rainwater tanks is promoted as an alternative source of water supply in many Australian cities. Understanding the amount of water supply (i.e. yield) from rainwater tanks is essential for urban water supply planning, in particular to assess the long-term water supply security. This paper reports a study aimed at quantifying the yield from rainwater tanks in South East Queensland (SEQ), Australia by considering the spatial variability of tank supplies. The methodology involves Monte Carlo simulation of tank behaviour by considering the spatial variability of input variables, i.e. tank sizes, inflows to the tank, household water demand and losses associated with the tank inflow. Probability distributions have been used to represent the spatial variability of input variables except for the household water demand. The household water demand has been disaggregated into end uses. Water demand of the each end use has been simulated probabilistically to generate a plausible set of demand time series for each end use. These plausible demand time series have been used as an input variable to the rainwater tank simulation. Our method is different to the commonly used approach, which 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. The results have indicated that the error introduced to the average annual yield of a system with multiple rainwater tanks, by ignoring the spatial variability, can be of the order of 14%, if the tank is used for toilet flushing, clothes washing and garden watering. For single family residential households (i.e. detached dwellings) in SEQ, the rainwater tank yield found through stochastic simulation is 37 kilolitres/household/year, if the tank is used for toilet flushing, clothes washing and garden watering. This is of similar magnitude to the tank yield estimated from the billing data of the single family residential houses in the SEQ region. 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

Installation of domestic rainwater tanks is promoted as an alternative source of water supply in Australian major cities. Understanding the amount of water supply (i.e. 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 the 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 & Butler, 2000; Fewkes & Warm, 2000; Coombes & 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/hh/year) to 95 kl/hh/year with a mean of 50 kl/hh/year. Chong et al. (2011a and 2011b) have used 2009 and 2010 consumption data, and have found that rainwater tank supply in the SEQ varies from 24.5 kl/hh/year to 88.5 kl/hh/year with a mean of 58.8 kl/hh/year. 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.

The above mentioned 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, Australia. SEQ is one of the fastest growing urban regions in Australia, covering about 22,420 km². It contains the major cities of Brisbane and the Gold Coast. 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 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) is 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 at the SEQ scale, 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.

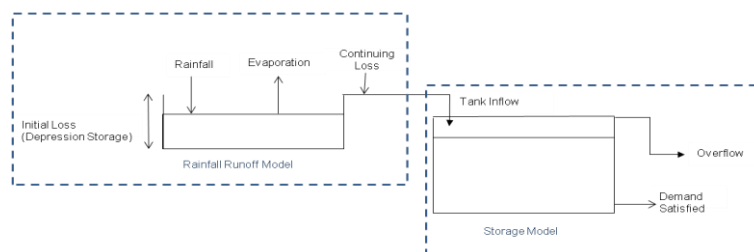


Figure 1 Schematic representation of the rainwater tank model (source: Neumann 2011, adapted from Mitchell et al., 2008)

The rainwater tank model described in Mitchell et al. (2008) was used for the stochastic simulation of rainwater tanks (see **Figure 1**). 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 (see **Figure 1**). 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.

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 1 End use frequency statistics of 61 houses in Brisbane (data source: Beal and Stewart, 2011)

Statistic	Frequency (events per day)							
	Half flush	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 houses in Brisbane (data source: Beal and Stewart, 2011)

Statistic	Mean volume of end use event (litres/event)				
	Half flush	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 & duration statistics of 61 houses in Brisbane (data source: Beal and Stewart, 2011)

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

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 (i.e. 14-28 June 2010) without considering leaks was 130.4 litres/person/day (Figure 1 and Table 4). The simulated or modelled value of household consumption was 136.6 litres/person/day (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 (i.e. January 1960 to December 2010), in order to feed into the Monte Carlo simulation to determine the tank yield.

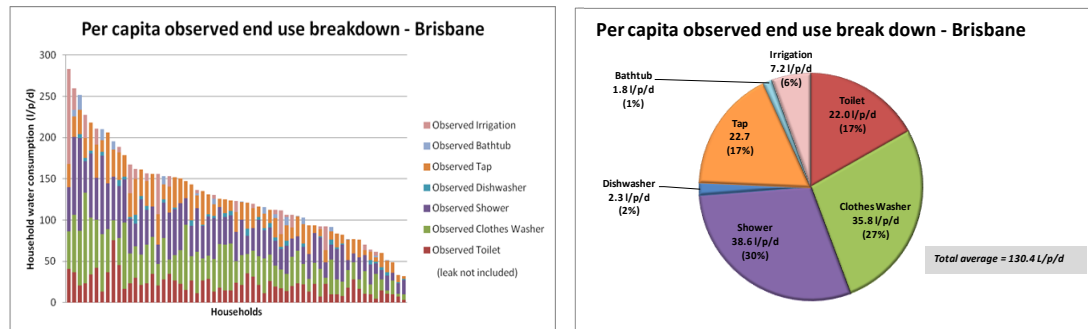


Figure 1 Observed water consumption of 61 houses in Brisbane

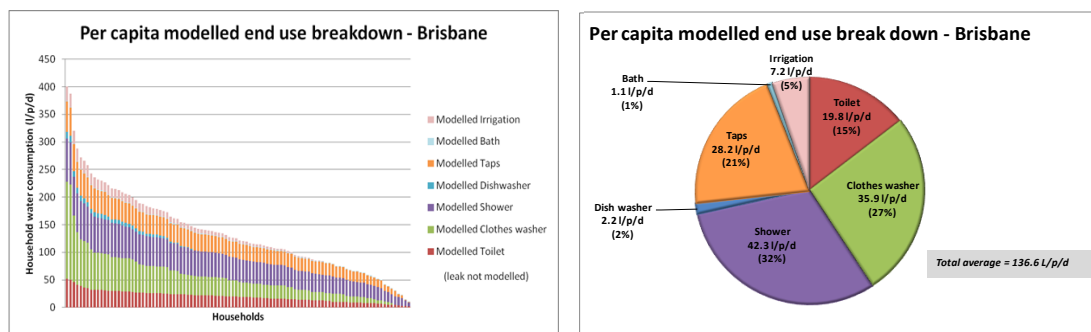


Figure 2 Modelled water consumption of 100 houses in Brisbane without considering leaks

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	21.96	35.76	38.63	2.33	22.72	1.78	7.21	130.4
Observed Standard Deviation	11.96	20.7	20.92	2.54	11.41	3.85	17.39	55.1
Modelled Mean	19.82	35.86	42.27	2.25	28.20	1.10	7.15	136.6
Modelled Standard Deviation	10.30	30.79	15.42	3.40	10.64	0.02	7.11	38.7



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**

Table 5 Parameters values used for Monte Carlo simulation of rainwater tank behaviour for 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	Truncated Normal	Truncated Normal	Truncated Normal	Truncated 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)

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 (i.e. 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 (see **Figure 3**). Hence 10,000 iterations were considered as adequate to represent the spatial variability of tank supplies, for our study.

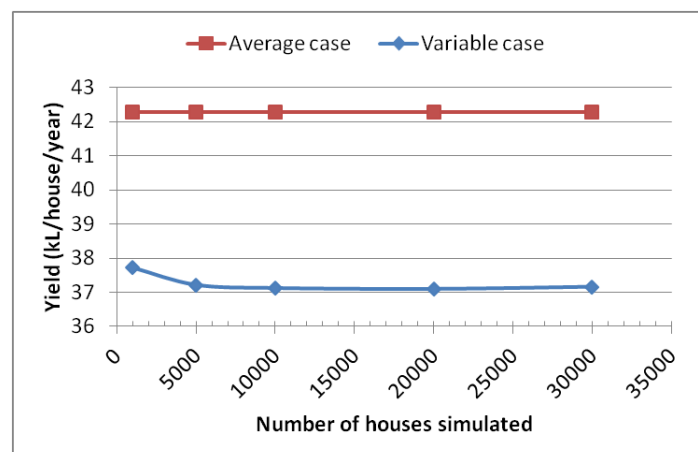


Figure 3 Expected rainwater tank yield for different runs of stochastic simulation



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/hh/year to 88.7 kl/hh/year, with a mean value of 37.12 kl/hh/year and a standard deviation of 9.97 kl/hh/year. That is, the long-term, expected rainwater tank yield in the SEQ for SFR households is 37.12 kl/hh/year, if the tank water is used for toilet flushing, garden watering and clothes washing (i.e. 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/hh/year (i.e. the purple horizontal line shown on **Figure 4**), which was about 14% overestimation compared to the yield obtained by considering the spatial variability of tank supply.

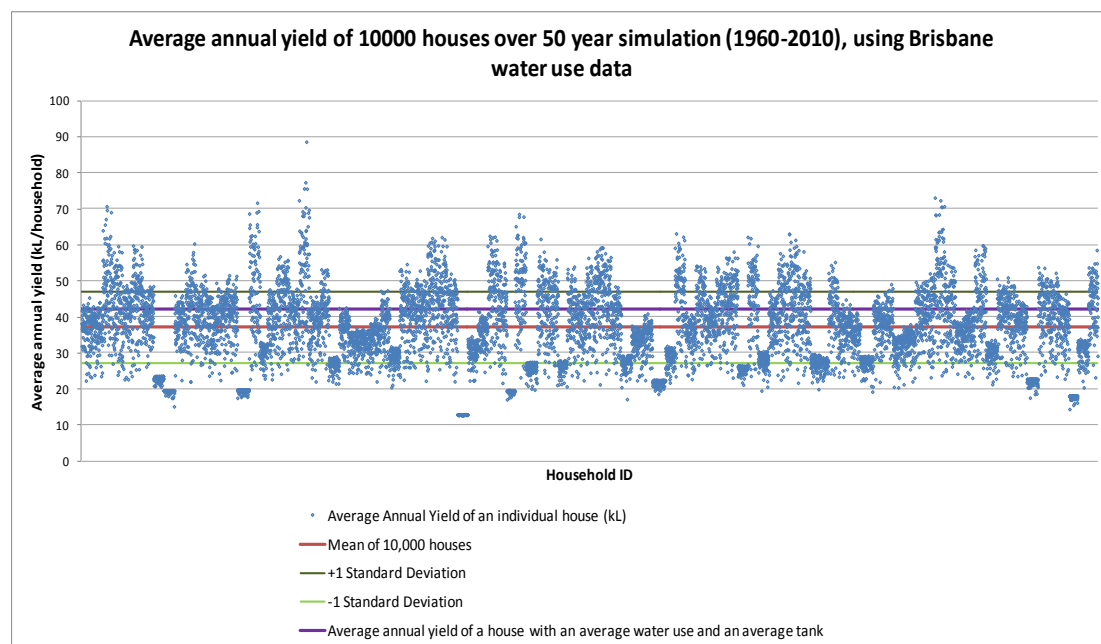


Figure 4 .Monte Carlo simulation of 10,000 domestic rainwater tanks with each tank's behaviour simulated on a daily basis over 50 years

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 1841 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 1721 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 and 481 litres/household/day, 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 litres/person/day (or 36.55 kl/hh/year based on the average occupancy rate of 2.6, which is the same for the sample of 61 houses used in our study).



In summary, our study indicated 39.09 litres/person/day (or 37.12 kl/hh/year), as the rainwater tank yield in SEQ, which is of similar order of magnitude to the QWC's study which indicated 38.46 litres/person/day (or 36.55 kl/hh/year) 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 litres/person/day), 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 South East Queensland 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 37.12 kl/hh/year, which is of similar order of magnitude to the tank yield estimated from the billing records by the Queensland Water Commission.

It should however 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, 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 when generalising outcomes of this study to 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.

Acknowledgement

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References

- Basinger, M., Montalto, F. and Lall, U (2010) A rainwater harvesting system reliability model based on nonparametric stochastic rainfall generator, *Journal of Hydrology*, 392: 105-118.
- Beal, C. and Stewart, R. (2011) South East Queensland Residential End Use Study: Draft Final Report, Urban Water Security Research Alliance Technical Report No. 47, Urban Water Security Research Alliance (<http://www.urbanwateralliance.org.au/>), 53 Albert Street, Brisbane, Australia.
- Beal C. D., Gardner, T., Sharma, A., Chong, M. (2012) A desktop analysis of potable water savings from internally plumbed rainwater tanks in south-east Queensland, Australia. *Water Resources Management*, 26 (6), 1577-1590



- Chong, M. N., Umapathi, S., Mankad, A., Sharma, A. and Gardner, T. (2011a). Baseline Characteristics of Mandated Rainwater Tank Users in South East Queensland - Phase 1, Urban Water Security Research Alliance Technical Report No 48, Urban Water Security Research Alliance (<http://www.urbanwateralliance.org.au/>), 53 Albert Street, Brisbane, Australia.
- Chong, M. N., Umapathi, S., Mankad, A., Sharma, A. and Gardner, T. (2011b). A benchmark analysis of water savings by mandated rainwater tank users in South East Queensland – Phase 2, Urban Water Security Research Alliance Technical Report No 49, Urban Water Security Research Alliance (<http://www.urbanwateralliance.org.au/>), 53 Albert Street, Brisbane, Australia.
- Coombes, P.J. & Barry M.E. (2007) The effect of selection of time steps and average assumptions on the continuous simulation of rainwater harvesting strategies, *Water Science and Technology*, 55(4), 125-133.
- Coultas, E.H., Maheepala, S. and Mirza, F. (2011) Towards the quantification of water quantity and quality impacts of rainwater tanks in South East Queensland, Paper submitted to MODSIM 2011, International Congress on Modelling and Simulation, 12-16 December, Perth Australia
- Duncan, H.P. & Mitchell, V.G. (2008) A Stochastic Demand Generator for Domestic Water Use, Conference Proceedings of Water Down Under, 15-17 April 2008, Adelaide, South Australia, published by the Institution of Engineers, Australia.
- Fewkes, A & Butler, D. (2000) Simulating the performance of rainwater collection and reuse systems using behavioural models.", *Building Services Engineering Research & Technology*, 21: 99-106.
- Fewkes, A. & Warm, P. (2000) Method of modelling the performance of rainwater collection systems in the United Kingdom.", *Building Services Engineering Research & Technology*, 21: 257-265
- Ghisi, E. (2010) Parameters influencing the sizing of rainwater tanks for use in houses, *Journal of Water Resources Management*, 24:2381-2403.
- Khastagir, A. and Jayasuriya, N. (2010) Optimal sizing of rainwater tanks for domestic water conservation, *Journal of Hydrology*, 381: 181-188.
- Kroese, D. P.; Taimre, T.; Botev, Z.I. (2011). *Handbook of Monte Carlo Methods*. New York: John Wiley & Sons, ISBN 0-470-17793-4.
- Neumann, L. E., Coultas, E. H., Moglia M. and Mashford, J. (2011). Errors in yield and overflow estimation in rainwater tank cluster modelling, 12th International Conference on Urban Drainage, Porto Alegre/Brazil, 11-16 September 2011.
- Maheepala, S., Loonat, N., Mirza, F. and Coultas, E. (2011). Quantifying potable water savings of rainwater tanks at a city scale by considering the effect of spatial lumping, OzWater 2011 conference, May 9-11, 2011, Adelaide, Australia, Published by Water Services Association of Australia.
- Mashford, J., Maheepala, S. Neumann, L. and Coultas, E., (2011) Computation of the expected value and variance of the average annual yield for a stochastic simulation of rainwater tank clusters, Proc. of the 2011 International Conference on Modeling, Simulation and Visualization Methods, 2011, pp. 303-309.
- Mitchell, V.G. (2007) How important is the selection of computational analysis method to the accuracy of rainwater tank behaviour modelling?, *Journal of Hydrologic Processes*, 21, 2850-2861.
- Mitchell V.G., Siriwardene N., Duncan H. & Rahilly M. (2008). Impact of temporal and spatial lumping on rainwater tank system modelling, Conference Proceedings of Water Down Under, 15-17 April 2008, Adelaide, South Australia, published by the Institution of Engineers, Australia.
- Palla, A., Gnecco, I and Lanza, L.G. (2011) Non-dimensional design parameters and performance assessment of rainwater harvesting systems, *Journal of Hydrology* 401: 65-76.
- Queensland Development Code (2008) MP4.2 Water Savings Target, Publication Date: 22 October 2008, Queensland Government, Australia, <http://www.dlqp.qld.gov.au/resources/laws/queensland-development-code/current-parts/mp-4-2-water-savings-targets.pdf> .
- Queensland Water Commission. (2010) South East Queensland Water Strategy, Queensland Water Commission, Brisbane, Queensland, Australia.
- Roberts, P. (2005) Yarra Valley Water 2004 Residential End Use Measurement study, Yarra Valley Water, Melbourne, Australia.
- Willis, R., Stewart, R. A., Panuwatwanich, K., Capati, B. and Giurco, D. (2009) Gold Coast Domestic water study, *Journal of Water*, September 2009. Australian Water Association, Australia.
- Xu, H., Rahilly, M. and Maheepala, S. (2010) Assessing the impact of spatial lumping on rainwater tank performance using daily modelling", Proceedings of the 9th International Conference on Hydroinformatics, September 7-11, 2010, Chinese Academy of Sciences, China.