RAINWATER HARVESTING: REVEALING THE DETAIL

S A Lucas, P J Coombes, M J Hardy, P M Geary

Abstract

The Probabilistic Urban Rainfall and wastewater Reuse Simulator (PURRS v7.2), the Model for Urban Stormwater Improvement Conceptualisation (MUSIC v3) and Spreadsheet modelling tools were compared for evaluating rainwater harvesting strategies. Input data included climate files, suggested water demands and time-steps. Models were run with climate data of unequal duration and time-step, which highlighted significant differences between modelled outcomes. Using climate data of equal duration still resulted in major differences. The reasons for these differences are explained as a function of the duration and time-step of climate data, the time-step and diurnal patterns of indoor/outdoor water demand and tank configuration. Results imply that the length and time-step of climate inputs, the distribution and time-step of daily water demand and rainwater tank configuration are significant factors in robustly evaluating mains water savings for a range of Australian climates.

Keywords: modelling, water demands, time-steps, rainwater harvesting

Introduction

Computer modelling tools are often used to determine the mains water savings gained from rainwater harvesting strategies. The models MUSIC (v3) by the Cooperative Research Centre for Catchment Hydrology (CRCCH, 2005) and PURRS (v7.2) by Coombes and Kuczera (2002), and the use of spreadsheets are methods currently employed in the water industry to evaluate rainwater harvesting strategies. Inputs commonly used in MUSIC, PURRS and spreadsheet methods are shown in Table 1.

Table 1 shows that a range of time steps and durations are used for both rainfall and water demand inputs to the selected models.

It may be perceived that the time-step and duration of these inputs have negligible impact on modelled outcomes. For example, modelling results have been reported without stating the duration of the rainfall series used (Mitchell *et al*, 2000; Liebman *et al*, 2004; Tanner and King, 2004) whilst others have employed one year of climate data (Hallmann *et al*, 2003; Melbourne Water, 2004). Constant daily water demand is also commonly applied to modelling rainwater harvesting strategies (Mitchell, 2000; McLean, 2004; Phillips *et al*, 2004). We consider that for a robust evaluation of rainwater harvesting strategies the time steps of both rainfall and demand are significant factors.

Table 1. Common inputs to MUSIC, PURRS and spreadsheet methods used to evaluate rainwater harvesting strategies.

Method	Rainfall time step (duration)	Other climate	Water demand: Indoor	Water demand: Outdoor
MUSIC	6 minute (1 year template or construct template from provided long record)	Potential evapotranspiration (PET)	Daily constant	Annual scaled to daily by PET
PURRS	6 minute (long records as provided or DRIP model with choice of duration)	Daily minimum and maximum temperature	Monthly daily average with 6 minute diurnal pattern	Probabilistic climate dependent with 6 minute diurnal pattern
Spread-sheet	Daily (1 to 20 years)	NA	Annual daily average	Annual daily average

This study has two parts. Firstly, it endeavours to understand the relative reliability of the common use of MUSIC, PURRS and spreadsheets, which employ rainfall records with different durations, to evaluate the performance of rainwater harvesting strategies in Adelaide, Brisbane, Melbourne and Sydney. Secondly, this study evaluates the relative reliability of the selected models for estimating mains water savings using rainfall records of equal duration at each location.

Significant differences between modelled outcomes were observed.

Method

The reliability of the common uses of MUSIC, PURRS and Spreadsheet models for estimating mains water savings derived from rainwater harvesting strategies was analysed by conducting continuous simulation in accordance with the criteria shown in Table 1. The simulations were then repeated using rainfall records of equal duration at each location to remove the impact of using rainfall records of different durations on the results from the selected models. All simulations use water demands from 3 person households, a roof area of 200 m^2 connected to rainwater tanks and rainwater tank sizes of 1, 2, 3, 4, 5 and 10 kL. Household uses drawn from the rainwater tank include outdoor, toilet, laundry and hot water demand, which was assumed to represent 85% of indoor demand and 100% of outdoor demand. Given that MUSIC was originally developed to evaluate planning strategies for stormwater management and PURRS was created to evaluate the detailed design of rainwater harvesting strategies, the results from PURRS are used as a reference.

Climate data

Climate data sourced from the Bureau of Meteorology (BOM) and provided in MUSIC and PURRS was employed in the "common use" simulations are shown in Table 2.

The simulations to evaluate the impact of using rainfall records of equal duration utilised BOM climate data provided in MUSIC as shown in Table 3.

The BOM rainfall files provided in MUSIC (shown in Table 2) contained many sections of hidden missing data that were not highlighted by the data analysis tool within the model. Subsequent detailed analysis of these files to prepare the rainfall records shown in Table 3 revealed the sections of missing data, which were removed from the records. Note that PURRS BOM records had gaps removed before use.

Table 2. Duration and length of climate provided with MUSIC (v3) and PURRS (v7.2).

Location	Model	Rainfall duration	Years	Description
Sydney Observatory Hill	MUSIC	1/1/1959 to 31/12/1959	1	Template
Adelaide Airport	MUSIC	1/1/1970 to 31/12/1970	1	Template
Melbourne Regional office	MUSIC	1/1/1959 to 31/12/1959	1	Template
Brisbane Airport	MUSIC	1/1/1990 to 31/12/1990	1	Template
Sydney Observatory Hill	MUSIC	31/7/1913 to 10/12/2001	88	Template constructed using provided BOM data
Adelaide Airport	MUSIC	13/1/1967 to 8/4/2001	34	Template constructed using provided BOM data
Melbourne Regional office	MUSIC	30/4/1873 to 30/11/2001	128	Template constructed using provided BOM data
Brisbane Airport	MUSIC	31/5/1949 to 16/2/2000	51	Template constructed using provided BOM data
Sydney Observatory Hill	PURRS	3/1/1913 to 31/12/1992	79	BOM data
Adelaide Airport	PURRS	13/1/1969 to 17/12/1991	22	BOM data
Melbourne Regional office	PURRS	12/1/1925 to 28/11/2001	76	BOM data
Brisbane Airport	PURRS	9/1/1950 to 14/2/2000	50	BOM data

Water demand

The total water demands used in each model at Sydney, Melbourne, Brisbane and Adelaide were sourced from Coombes and Kuczera (2003) and are summarised in Figure 1.

Tank configuration

The configuration of the rainwater tanks used in each model is shown in Figure 2.

In each of the models rainfall was directed from roofs via first flush devices with a volume of 20 L to the rainwater tanks. An initial loss of 0.5 mm was assumed from the roofs. In the PURRS model the tanks are topped up by mains water at a rate of 40 L/hr when the water levels were drawn below a minimum water level located 0.3 m from the base of the tank as shown in case A (Figure 2). The rainwater tank configuration shown as case B (Figure 2) was adopted in MUSIC and the spreadsheet because the use of daily water demands does not allow direct simulation of the mains water top up process. In this situation it was assumed that the proportion of the tank volume below the minimum water level always contained mains water.

Use of the selected models

PURRS

Continuous simulation of the performance of rainwater tanks was conducted in PURRS at 6-minute time-steps using rainfall over periods depending on the location as shown in Table 2. PURRS employ climate dependent water demands derived from Figure 1 and a diurnal pattern to disaggregate water demand into 6-minute time steps. Full details on the use and operation of the PURRS model

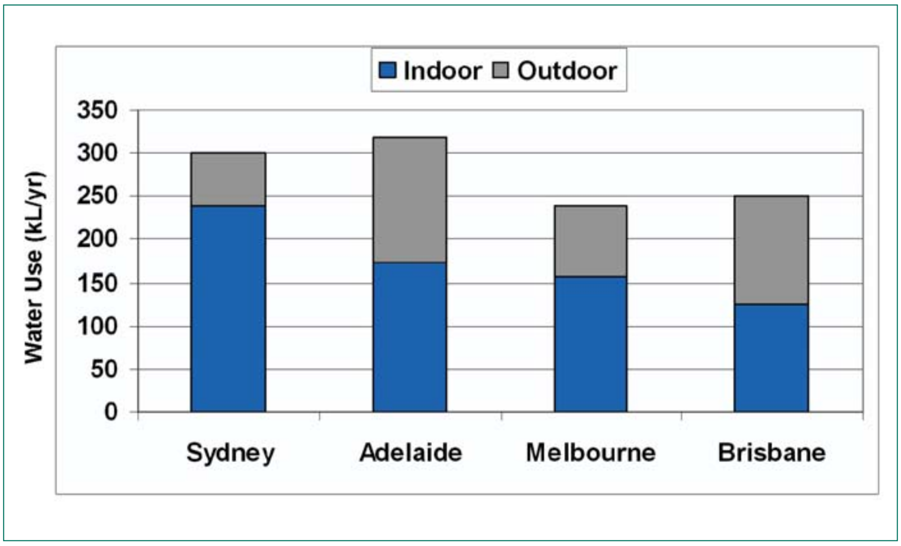

Figure 1. Indoor/outdoor water use for 3 person dwellings (Coombes and Kuczera, 2003).

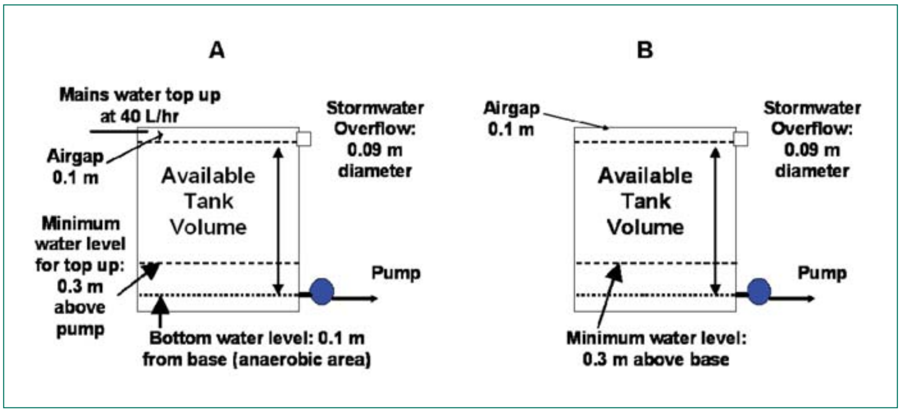

Figure 2. Configuration of tanks used in PURRS (A), and MUSIC and Spreadsheet (B).

Table 3. Climate files used in each model to enable direct comparison.

Location	Duration	Years	Comment
Sydney Observatory Hill	3/1/1913 to 31/12/1992	79	Removed sections of missing data
Adelaide Airport	13/1/1969 to 17/12/1991	22	Removed sections of missing data
Melbourne Regional Office	12/1/1925 to 28/11/2001	76	Removed sections of missing data
Brisbane Airport	9/1/1950 to 14/2/2000	50	Removed sections of missing data

can be found in Coombes and Kuczera (2001).

MUSIC v3

Climate data was selected from the meteorological templates and rainfall records provided in MUSIC. The one year climate templates that utilise 6-minute rainfall and the longer BOM 6 minute records were used for each location as shown in Table 2. The MUSIC model structure used in this study is shown in Figure 3. Urban Node 1 represents the roof area. The roof area was designated as 100% impervious and the rainfall threshold was adjusted to mimic a first flush device of 20 L and an initial loss of 0.5 mm. In the Rainwater Tank node the details of storage properties (tank size), outflow pipe diameter (90 mm) and reuse properties (water demand) were set.

Outdoor water demand was simulated using the "water demand scaled by PET" option and indoor water demand was modelled using the "daily demand" option. Mains water savings were calculated by subtracting the rainwater tank outflow from the rainwater tank inflow that was found in the "Statistics/All Data" directory after running the model. Water demand data from the PURRS simulations were used to condition the water demand inputs to MUSIC. Further details about the use of MUSIC (v3) are provided in the MUSIC User Guide (CRCCH, 2005).

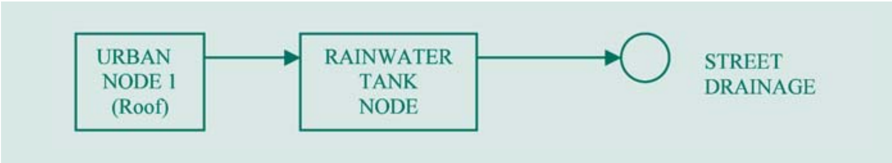

Figure 3. Generic structure of MUSIC models used to simulate rainwater harvesting from roofs.

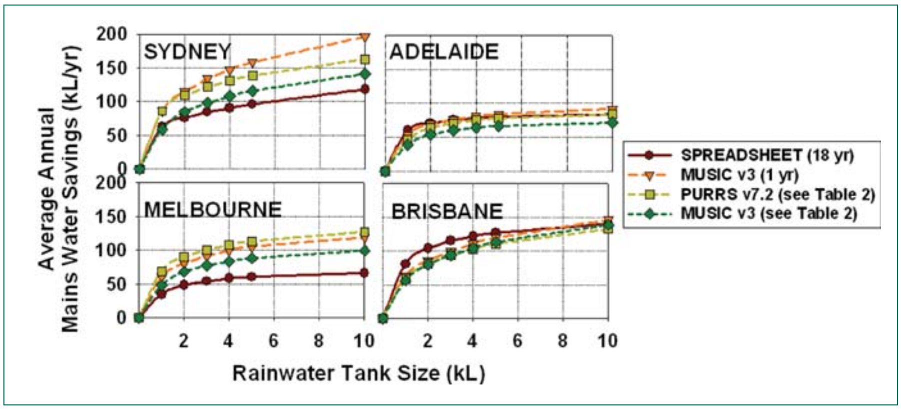

Figure 4. Comparisons of mains water savings derived from common uses of the selected models.

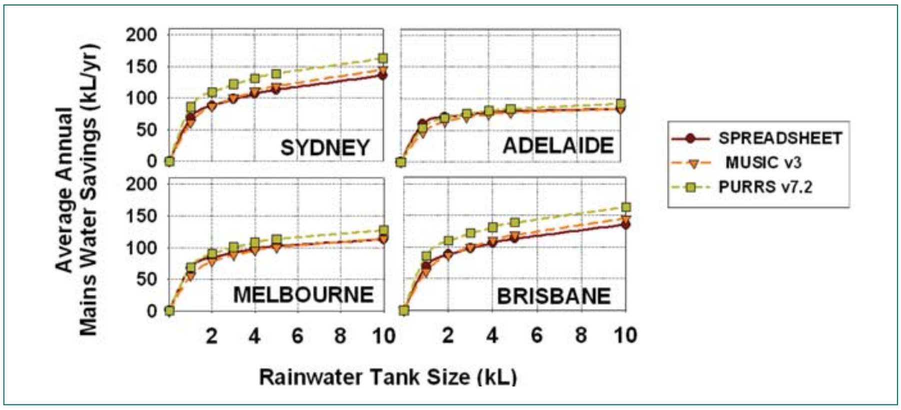

Figure 5. Results from use of climate records of equal duration at each location in models.

Spreadsheet

A simple Spreadsheet program was established to simulate the performance of the rainwater tanks that comprised a series of simple water balance calculations based on the rainwater storage TV_t on each day t which is resolved as a function of the rainwater storage TV_{t-1} on the previous day t-1 as follows:

$$TV_t = TV_{t-1} + HR_t - OF_t - MWS_t \qquad (1)$$

where HRt is the harvestable roof runoff, OF_t is the tank overflow and MWS_t is the daily mains water savings. The harvestable roof runoff HR_t is dependent on potential roof runoff RR_t less roof losses of 0.5 mm and the first flush separation of 20 litres:

$$HR_t = \begin{cases} RR_t - (200 \times 0.0005) - 0.02, (m^3) & RR_t \geq 0.095 \\ 0, & Otherwise \end{cases} \qquad (2)$$

The daily main water savings MWS_t were derived as a function of daily water demand DD_t on the rainwater tanks using:

$$MWS_t = \begin{cases} DD_t, & DD_t \leq TV_{t-1} + HR_t - OF_t \\ TV_{t-1} + HR_t - OF_t, & \text{Otherwise} \end{cases} \qquad (3)$$

To account for the minimum water level of 300 mm and the overflow outlet diameter of 90 mm in the Spreadsheet, an available rainwater storage volume (kL) was calculated based on an area of 1 m^2 (x 1 m high) for a 1 kL tank and height of 2 m for larger tank sizes (using variable plan areas). Available tank volumes for the various tank sizes are as follows: 1kL = 0.61 kL, 2kL = 1.61 kL, 3 kL = 2.415 kL, 4kL = 3.22 kL, 5 kL = 4.025 kL and 10 kL = 8.05 kL. Water demand data from the PURRS simulations were used to condition the water demand inputs to the spreadsheet.

Results

Mains water savings resulting from the water industry's "common use" of the models is shown in Figure 4.

Figure 4 shows that the use of meteorological templates that employ one year of rainfall in MUSIC resulted in an over-estimation of mains water savings for Sydney and Brisbane, and an under-estimation of mains water savings for Melbourne and Adelaide in comparison to the PURRS results.

The use of meteorological templates based on the longer BOM records provided in MUSIC resulted in a consistent under-estimation of mains water savings at each location. A proportion of the under-estimation of mains water savings can be attributed to the period of "hidden" missing data in each of the BOM records provided in MUSIC.

Results from the spreadsheet analysis reveal an under-estimation of mains water savings for Sydney and Melbourne, and an over-estimation of mains water savings for Adelaide and Brisbane.

The BOM files provided in MUSIC were analysed to remove missing data and to create climate files of equivalent duration for each location as shown in Table 3. The use of climate files of equivalent duration at each location in the models will eliminate the variability of mains water savings caused by the use of climate files of differing length. Results of the use of climate files of equivalent durations at each location in MUSIC, PURRS and the spreadsheet are shown in Figure 5.

Figure 5 reveals that the use of longer climate records which are free of missing data in MUSIC resulted in similar mains water savings for Adelaide and an under-estimation of mains water savings at Sydney, Melbourne and Brisbane in comparison to the PURRS results. The spreadsheet analysis using the same climate data was able to approximate the mains water savings for Adelaide and under-estimated the mains water savings for Sydney, Melbourne and Brisbane in comparison to the PURRS results.

Discussion

The mains water savings derived from the water industry's "common" use of MUSIC and spreadsheets for evaluating rainwater harvesting strategies are compared to the PURRS results in Figure 6. Figure 6 shows that analysis of rainwater harvesting using one year of climate data in MUSIC has over-estimated main water savings from 15% to 30% for Sydney and under-estimated mains water savings from 10% to 15% for Melbourne, from 0% to 20% in Adelaide, and by about 10% in Brisbane. Analysis of rainwater harvesting over a period of a single year produces unacceptable errors in the assessment of mains water savings from rainwater harvesting.

The use of longer BOM climates files as provided in the MUSIC analysis, including "hidden" missing data, has under-estimated mains water savings by 15% to 40% in Sydney, by 20% to 40% in Melbourne, by 20% to 30% in Adelaide and by up to 5% in Brisbane. Clearly the periods of missing data in the rainfall records has contributed to these differences. Analysis of the performance of rainwater harvesting using 18 years of climate data in a spreadsheet has over-estimated mains water savings by 5% to 40% in Brisbane and has under-estimated mains water savings by about 30% in Sydney and by 45% to 50% in Melbourne. In Adelaide, mains water savings were over-estimated by 0% to 10% for tank sizes ≤ 3 kL and under-estimated mains water savings by 0% to 5% for larger tank sizes.

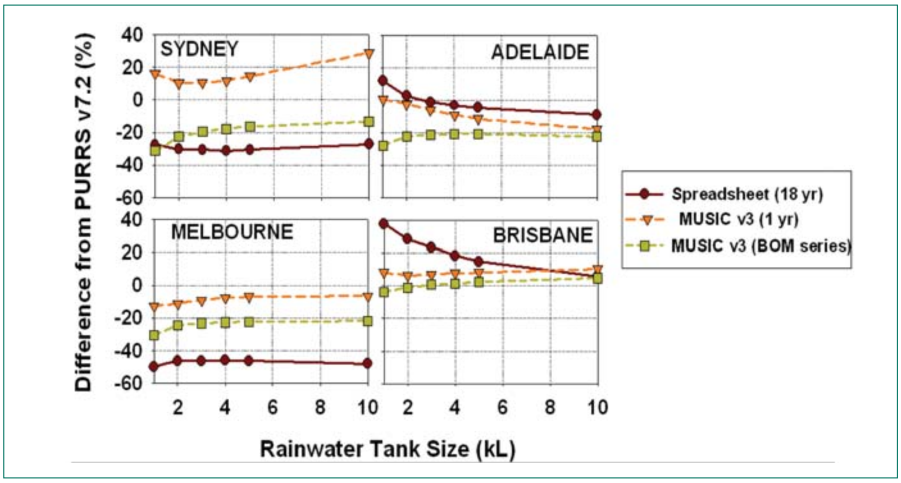

Figure 6. Difference in results from the common use of Spreadsheet and MUSIC in comparison to PURRS results.

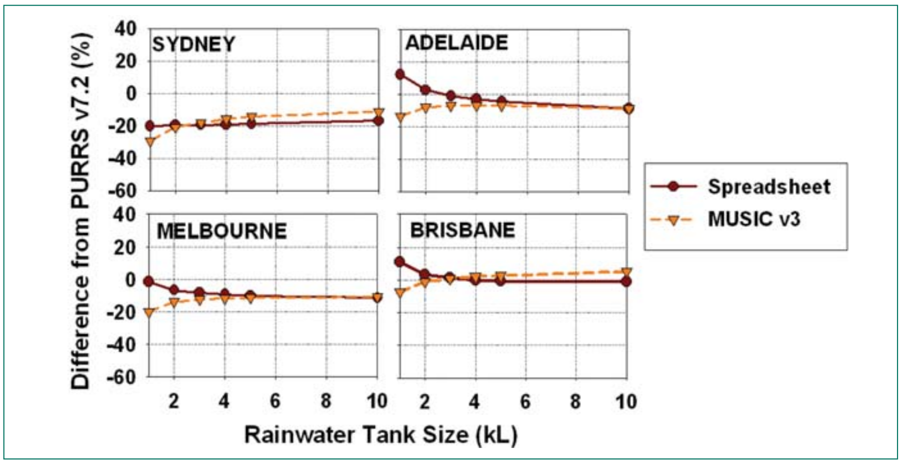

Figure 7. Difference in results from the use of equal rainfall durations in Spreadsheet and MUSIC when compared to PURRS.

The range of the under/over estimations produced by the water industry's common use of the models is considerable and the magnitude of these errors would be unacceptable for water planning and evaluation of rainwater harvesting strategies. These differences observed between the common use of models and the PURRS results are most likely a consequence of using climate records of different durations with missing data in some of the climate records. The different treatment of water demand inputs, the time step of simulation and the configuration of the tanks used in the models will also contribute to the variability of results.

The different climate durations and missing data in climate records was deemed to contribute to the observed errors and as such, climate files were truncated to provide relatively complete, long-term climate files in an attempt to reduce the observed differences between selected models. Results from analysis in the models using climate files of equal duration at the different locations are shown in Figure 7.

Figure 7 shows that the differences resulting in analysis using rainfall data of equal lengths are generally lower than those observed from the water industry's "common use" of the models. Analysis of rainwater harvesting using MUSIC resulted in under-estimation of mains water savings by 15% to 5% in Adelaide and under-estimation of mains water savings by 10% to 30% in Sydney and by 10% to 20% in Melbourne. Differences of ± 5% were observed for Brisbane. The analysis of rainwater harvesting using the spreadsheet results in an over-estimation of mains water savings of up to 10% in Brisbane and under-estimates mains water savings by 20% in Sydney and by up to 10% in Melbourne.

Differences of ± 15% were observed for Adelaide. Although the magnitude of differences has been reduced by use of rainfall records of equal durations that have a minimum of missing data in the models, the magnitude of differences remain unacceptable for robust assessment of rainwater harvesting. Nevertheless, the results indicate that simulation of the performance of rainwater harvesting systems is critically dependent on the duration of rainfall used in models. The selection of rainfall records that are complete and have an adequate duration is important for more reliable simulation of rainwater harvesting.

Variation of the magnitude of errors between locations also indicated that simulation of rainwater harvesting was dependent on the ability of the models to account for the climate regime at each location. Reliability of a model in different climate regimes will be dependent on the time step of simulation, treatment of water demand inputs and the representation of the configuration of rainwater tanks.

At a location that is subject to a greater proportion low intensity rainfall events and/or an even distribution of rainfall (such as Melbourne and Sydney), models that operate at a daily time step are more likely to under-estimate mains water savings because they cannot account for intra-daily water demands that occur during rainfall events. For example, Figure 7 shows that the Spreadsheet and MUSIC simulations that utilise daily water demand and similar tank configurations have under-estimated mains water savings at Melbourne and Sydney.

At the Brisbane location, for tank sizes greater than 2 kL, the Spreadsheet and MUSIC models produce similar results that trend towards over-estimation of mains water savings for larger tank sizes. This result is likely to be due to higher annual rainfall depth, available tank storage and summer rainfall distribution that overwhelmed any differences in the model process. Nevertheless, for smaller tank sizes in Brisbane considerable differences between MUSIC and the Spreadsheet were observed. The difference between Spreadsheet and MUSIC simulations was the use of 6-minute rainfall and a PET-scaled outdoor demand in MUSIC. The configuration of MUSIC utilises 6-minute rainfall inputs to the tank and daily demand extractions from the tank, resulting in an over-estimation of tank overflow and therefore under-estimation of mains water savings from smaller tanks. In contrast, the use of daily rainfall and water demand in the Spreadsheet under-estimates tank overflows, thus over-estimates mains water savings for smaller tank sizes.

At the Adelaide location, for tank sizes greater than 2 kL, the Spreadsheet and MUSIC models produce similar results that trend towards under-estimation of mains

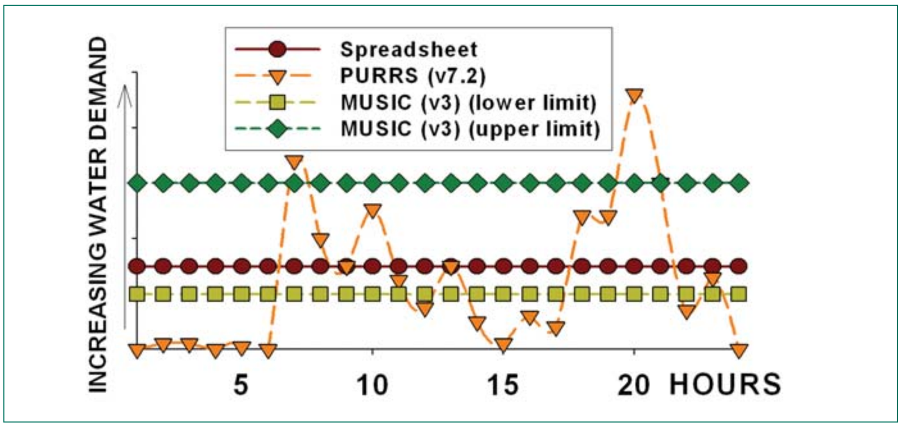

Figure 8: Water use patterns used in the selected models.

water savings with larger tank sizes. This result is likely to be due to lower annual rainfall depth, winter rainfall distribution and summer water demand that has highlighted differences between models. However, considerable differences between MUSIC and the Spreadsheet were observed for smaller tank sizes in Adelaide. The 6-minute rainfall inputs to the tank coupled with daily demand extractions from the tank results in an over-estimate of overflows from the tank and therefore under-estimate water savings from the smaller tanks. In contrast, the use of daily rainfall and water demand in the Spreadsheet will under-estimate tank overflows, thus over-estimating mains water savings for smaller tank sizes. Figure 7 highlights the need to utilise both continuous rainfall and water demand (6-minute), in conjunction with realistic diurnal water use patterns, in order to reduce these errors for smaller tank sizes.

PURRS utilises 6-minute rainfall, 6-minute water demand based on a diurnal water pattern and a climate dependent outdoor use model. Figure 8 conceptualises the daily water use demand patterns as used in the selected models.

The use of a diurnal pattern (such as PURRS) is more likely to realistically simulate water demand from rainwater tanks. Figure 8 highlights the significant variation in water demand from tanks using MUSIC and a constant water demand, which is simulated with the Spreadsheet. Modelled results imply the significance of simulating tank configurations at 6-minute times-steps to capture intra-daily demand for robust results.

For example, if rainfall enters the tank in the morning it is immediately available for use and as more water is drawn from the tank there is increasing tank volume available to capture further rain that day. Also, the use of a diurnal water use pattern is more realistic than using constant daily demands, as these patterns govern intra-daily available tank volume. Therefore, continuous simulation of rainfall, water demand and diurnal water use patterns must be considered for robustly evaluating rainwater harvesting strategies.

In addition, a non-parameteric nearest neighbourhood scheme has been developed to create synthetic rainfall records that can be used in continuous simulation models such as PURRS (Coombes, 2004). The methodology relies on the use of a target site with a daily rainfall record, and nearby pluviograph records that are used as reference files to disaggregate the daily rainfall into a continuous series of storm events and dry periods. This method has been successfully verified against observed pluviograph records at Brisbane Airport, Sydney Airport and Wellington Research Station, with good replication of IFD curves and dry periods, indicating that reliable synthetic rainfall records were produced (Coombes, 2004).

The practical considerations of selecting an optimum size tank for a given development or subdivision will depend on the physical limitations of the site (lot-size, slope, etc), comparative life-cycle costs (compared to centralised water systems) and the social/cost/environmental impacts analysed during the integrated water cycle management (IWCM) process. As such, the detail required to comment further on affordability, life-cycle costing and security are outside the scope of this paper - however the article by Coombes in Water (March 2005) highlights the complexity in analysing scales of water management and the solutions preferred by the water authorities.

Conclusion

The PURRS, MUSIC and Spreadsheet modelling tools have been discussed in the context of how they are commonly used in the water industry to evaluate rainwater harvesting strategies. Significant differences were observed (-50% to +60%). Even when climate files of equal duration were used in each model, major differences still existed (-30% to +15%). The selection of rainfall records that are complete and have an adequate duration is important for more reliable simulation of rainwater harvesting, as well as the models' ability to account for variable climate regimes. The differences between models were explained in terms of the duration and time-step of climate data, use of a diurnal pattern for water demand and simulating tank configuration at a 6-minute time-step. Reducing time-steps to mimic realistic flows and using a detailed tank configuration and diurnal water use pattern to simulate tank drawdown promote robust evaluation of rainwater harvesting strategies. Both MUSIC and the Spreadsheet were unable to reliably simulate available tank volume due to inadequate intra-daily water demand time-steps, particularly for smaller tanks sizes.

The Authors

Steven A Lucas is a postdoctoral research associate with the Integrated Water Cycle Management Group, School of Environmental & Life Sciences, at the University of Newcastle, email Steven.Lucas@newcastle.edu.au; **Associate Professor P J Coombes** (integrated water systems) and **Dr P M Geary** (on-site wastewater systems) are senior members of this group. **M J Hardy** is a doctoral student with the Urban Water Research Group, School of Engineering, at the University of Newcastle.

References

Coombes, P.J. (2005) *Integrated Water Cycle Management: Analysis of Resource Security*, WATER (AWA), Mar 2005.

Coombes, P.J. (2004) A non-parametric nearest neighbourhood scheme for the development of synthetic pluviograph rainfall. *International Water Sensitive Urban Design Conference 2004*, Adelaide, SA, Australia.

Coombes, P. J. and Kuczera, G. (2003). Analysis of the performance of rainwater tanks in Australian capital locations. *Proceedings of the 28th International Hydrology and Water Resources Symposium,* Wollongong, NSW, Australia.

Coombes, P. J. and Kuczera, G. (2001). Rainwater tank design for water supply and stormwater management. *Stormwater Industry Association 2001 Regional Conference,* Port Stephens , NSW, Australia.

CRCCH (2005). MUSIC (v3) User Guide. MUSIC Development Team. CRC for Catchment Hydrology, Monash University, Victoria, Australia.

Liebman M., Garraway, E., Bain, L., Brown, M. and Dallmer Roach, L. (2004) How sustainable are stormwater management targets?, *Proceedings of the 2004 International Conference on Water Sensitive Urban Design,* Adelaide, Australia.

McLean, J. (2004) Aurora – Delivering a Sustainable Urban Water System for a New Suburb, *Proceedings of the 2004 International Conference on Water Sensitive Urban Design,* Adelaide, Australia.

Phillips, B.C., Wade, W., Howard, T. and Breen, M. (2004) Towards the Introduction of Rainwater Tanks across the City of Caloundra, Queensland, Proceedings of the 2004 International Conference on Water Sensitive Urban Design, Adelaide, Australia.

Tanner, C and King, A. (2004) Integrated Water Management At 599 Payne Rd, The Gap, Proceedings of the 2004 Sustainable Water in the Urban Environment, Brisbane, Australia.

Mitchell, V.G., Gray, S. and Farley, T. (2000) *Accounting for Water Contaminants in Urban Areas,* 10th World Water Congress, Melbourne, Australia.

Melbourne Water (2004) *Revised MUSIC Input Parameters Guidelines.*

Hallmann, M., Grant, T. and Alsop, N. (2003) Yarra Valley Water – Life Cycle Costing of Water Tanks as a Supplement to Mains Water Supply, Centre for Design at RMIT University, Melbourne.