Assessment of diurnal water demand patterns to determine supply reliability of plumbed rainwater tanks in South East Queensland

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ABSTRACT
Understanding the impact of rainwater tanks on household diurnal water demand patterns for new residential dwellings in South East Queensland is important for water system design. In this study, water demand patterns for 20 Class 1 residential dwellings with internally plumbed rainwater tanks in South East Queensland (SEQ), were monitored from April-August 2011. The monitored parameters included total mains water use, mains top-up to rainwater tanks and total water drawn from rainwater tanks for internal and external purposes. Preliminary results show that the total average household water demand for these dwellings was 133 Litres/person/day, which is significantly lower than the reported average water demand of 153 Litres/person/day for the same period, across the SEQ region. An assessment of the daily diurnal water demand pattern for the cluster-of-20 households revealed two water demand peaks; one each for the morning and evening. The mean volumetric reliability of the mandated rainwater tanks across the individual households was found to be 26%, which is the ratio of the rainwater available in the rainwater tank system to the total household water demand during the monitoring period. Subsequent water balance analysis on the dynamics of rainwater tanks found that the rainwater source alone could offset the peak hour water demand by 28%, with a daily average offset of 10%. The monitoring activity will be extended into the future to take seasonal effects into account. The findings from this study would provide information that would be significant for the future of urban water resources management in SEQ.

KEYWORDS
Diurnal water demand; Rainwater tanks; Plumbed end-uses; Integrated water management.

INTRODUCTION
Over the past few decades, there has been significant growth in population and constant changes in lifestyle due to rapid economic growth, which has had a great impact on urban water demand in Australia and across the world (Whittington et al., 2002; Johnson and Handmer, 2002). Calls to satisfy the growing demand on potable water resources have been met with numerous challenges owing to an expanding urban community and problems arising from potential impacts of climate change (Mwenge Kahinda et al., 2010; Zhang et al., 2009). The increasing scarcity of fresh water in Australia attributed to various factors has impelled state authorities to broaden the range of sustainable water management practices to meet the water demand in urban areas. In South East Queensland (SEQ), state and local governments have introduced various strategies such as imposing water restrictions and rebate programs like the WaterWise Rebate Scheme (2006) to encourage the uptake of water efficient household appliances. Most recently, the Queensland Development Code (QDC) MP 4.2 was established with aims to significantly reduce dependency on traditional mains water supply from the water grid. The introduction of QDC MP 4.2 has been one of the most significant steps taken to complement the state government's commitment to achieve potable water savings in new residential dwellings (DIP, 2010), leading to the use of various alternative water sources to supplement mainstream water supply sources on a fit–for-purpose basis. This has accentuated the potential inclusion of decentralised water supply systems, such as plumbed rainwater tanks, to relieve strain on traditional centralised water supply systems.

The recommended measures taken to conform to QDC Part MP 4.2 are through installation of a 5 kL rainwater tank connected to either a 100 m^2 roof catchment area or 50% of the total roof area (whichever is lesser of the two) in Class I dwellings (detached houses). Every household is expected to save 70kL of potable mains water through the internally plumbed rainwater tank systems in SEQ. The rainwater tank system (RTS) is plumbed to household appliances such as washing machine cold-water tap, toilet cisterns and at least one external irrigation tap. The internally connected fixtures where the water demand is met by the rainwater tank also require back-up water supply connections either through trickle top-up or automatic switching valve system to ensure continuous supply of water (DLGP, 2010). A number of studies have previously attempted to validate the potential mains water savings achievable through plumbed rainwater tanks through different methods such as: rainwater system tank modelling (Coombes and Kuzcera, 2003); paired statistical analysis using water billing data between household cohorts with and without plumbed rainwater tanks (Beal et al., 2011); and benchmarking the water usage in households having plumbed rainwater tanks to the corresponding regional water usage (Chong et al., 2011). However, the substantiation of these previous research outcomes to estimate the effectiveness of the newly adopted water saving strategies is imperative to make improvements in sustainable water management initiatives.

The aim of this study was to validate and provide substantiation by monitoring the actual water usage at 20 new residential households in SEQ with plumbed end-uses from mandated rainwater tanks. Smart water-flow monitoring systems were installed at each household to obtain continuous data of water usage from the mains water meter, water allocation between internally and externally plumbed end-uses and rainwater tank top-up supply from the mains at a fine pulse resolution. The 20 monitored households were selected from across four new greenfield urban residential developments in SEQ to quantify the effects of localised rainfall pattern and household occupancy rate. The continuous monitoring data obtained was analysed mainly for per capita water use pattern, mains water savings from installed mandated rainwater tanks, diurnal water usage patterns as well as the supply reliability of the rainwater tank system. Studies have shown that diurnal water use patterns help provide significant insight into peak hour mains water reductions achieved through usage of rainwater, which in turn help determine design criteria for urban water supply network infrastructure (Lucas et al., 2010). Hence, further analysis was carried out on the diurnal water demand pattern for the 20 monitored households as a cluster. This study is expected to help achieve a better understanding of the performance of mandated rainwater tanks in the *real world* as well as provide validation for mains water savings and demand profiles in comparison to other desktop studies. It is also expected that the findings from this study would provide important information for future urban water resource planning, given that a large number of mandated rainwater tanks are being adopted across Australia. However, as this study was conducted using a small data sample, further analysis involving a larger data set will be conducted to account for factors influencing variability in per capita consumption.

METHODS

Sample size and sample selection

A group of 20 detached residential homes built after 1 January 2007, including those applying for extension permits, were selected for this study to include only those homes that were required to comply with QDC Part MP 4.2. This ensured that all homes had internally plumbed rainwater tanks installed on their properties. The chosen samples of 20 homes were spread across four local government areas (LGAs) in the SEQ region namely, Pine Rivers, Caboolture (both part of the Moreton Bay Regional Council), Redland City Council and Gold Coast City Council.

Metering setup at 20 mandated households in SEQ
Each of the 20 homes is monitored at four relevant points in their rainwater systems to study the individual behavioural characteristics of rainwater consumption. Smart pulse meters were used to monitor the total water supply to the household through traditional mains and water flows in and out of the rainwater system. All pulse meters installed on the rainwater tanks and garden taps were calibrated at the rate of 0.5 L/pulse and all the potable mains water meters pulsed at 5 L/pulse except for two households where the potable mains meters were set to pulse at 100 L/pulse due to different types of mains meter setups. All meters were capable of providing continuous data to wired data loggers located on-site. Figure 1 depicts the points at which flow meters are installed at each household.

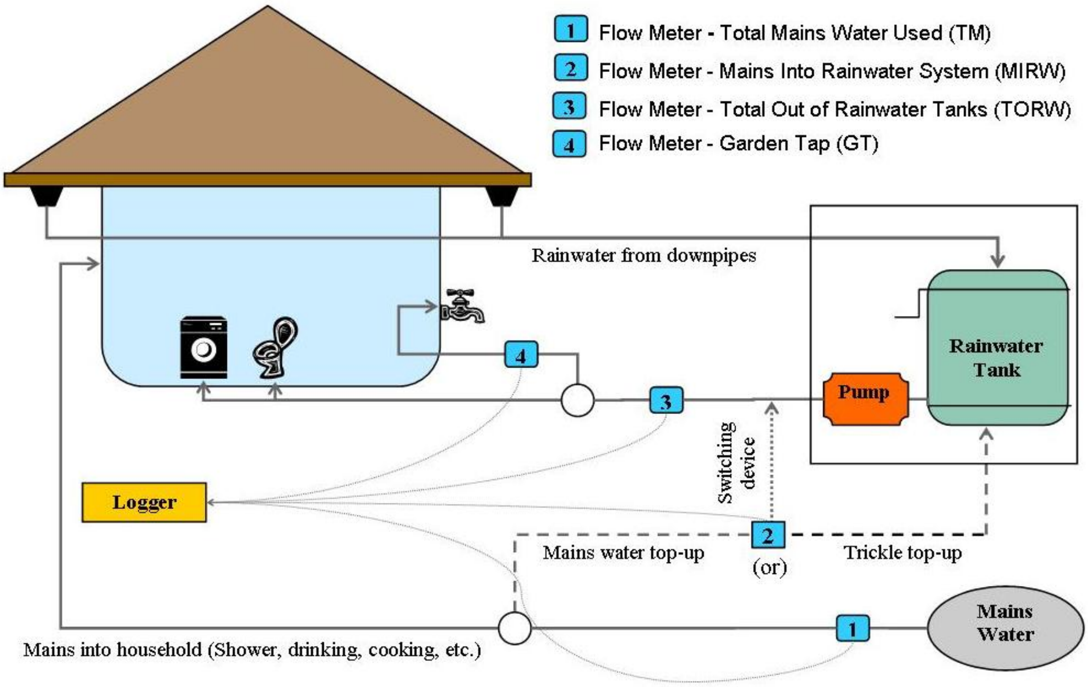


Figure 1. Illustrative diagram of metering system setup at each household.

Total Mains (TM). The total mains water is the total potable water being supplied from the mains water line. This is an important parameter to determine variations in total water usage and daily consumption patterns and characteristics. In dwellings with mandated rainwater tanks, TM acts as the sole potable water supply to most internal home fixtures such as showers, cooking/drinking, and internal faucets, with the exclusion of filling of toilet cisterns and operation of wash machines where rainwater is used as the priority source.

Mains Water Top-up into Rainwater System (MIRW). Mandated rainwater tank systems incorporate a mains water top-up system, which enable uninterrupted supply of water to the plumbed end-uses in the absence of rainwater. There are two types of top-up mechanisms usually installed at the 20 homes; 9 homes operate on the *"trickle top-up*" mechanism and 11 homes operate on a *"rainwater switch"* mechanism. The *trickle top-up* mechanism operates on a "float" arrangement when every time there is a drop in water level below a stipulated point in the rainwater tank, a fixed volume of mains water is delivered into the tank. Whereas in the *rainwater switch* system, mains water bypasses the tank and pump systems and delivers directly to the designated end-uses until there is sufficient rainwater available in the tank again.

Total Water Supplied from the Rainwater Tank (TORW). There is a difference in the metering of water supplied from a RWT system into the household based on the type of top-up employed at each household. In a *trickle top-up* mechanism, the water exiting the rainwater tank system was measured immediately after being pumped out of the RWT. In this system, water leaving the rainwater tank contains either rainwater or mains water (top-up) or a mixture of both. In a *rainwater switch* system, the water exiting the rainwater tank is comprised solely of rainwater collected by the system. Thus, the total water supply from the rainwater tanks is being metered accordingly.

Garden Tap (GT). The garden taps in all homes are supplied water through the RWT system. The water supplied to the garden tap (Flow Meter 4) was also metered to differentiate external from internal end-use water demand.

Data Validation and Analysis Procedures

A comprehensive validation of the data was carried out prior to periodic monthly analysis. A complete logger data set consists of four water demand/supply data series for all 20 homes (excluding 1 home where the mains water flow data series was not available). The data was validated in terms of data presence, consistency, range and format, both manually and by using the Microsoft Excel® 'macro' function to ensure ambiguous data was excluded from the analysis.

Diurnal Pattern and Peak Water Demand Analysis

The diurnal water demand patterns were plotted by converting the available "per-minute" data for each home into diurnal hourly demand values and consequently combining all patterns to generate a cluster-of-20 homes diurnal demand pattern. The diurnal water demand pattern was used to recognise peaks and trends in water usage and to generate further information for urban water planners.

Assessment of Mains Water Offset (Volumetric Reliability) in Diurnal Pattern Analysis. The volumetric reliability of the rainwater tanks is defined as the ratio of the rainwater available from the rainwater tank system to the total household water demand during the monitoring period. The volumetric reliabilities for the households indicate the percentage of mains water offset being achieved in the systems through the usage of captured rainwater as a supply source for designated plumbed end uses (e.g. filling the toilet cisterns, washing machine cold tap and external garden tap). The difference between flow meters 3 and 2 readings will be the rainwater supplied in this setup. The rainwater offset for each RWT system was calculated as follows:

$$Rv = \left(\frac{\sum_{t=1}^{T}(TORW - MIRW)}{\sum_{t=1}^{T} TM + \sum_{t=1}^{T}(TORW - MIRW)} \right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where:-

Rv = Volumetric Reliability of the system (%)

T = Total monitoring/assessment time period (4 months)

t = Minutely time step

TORW = Total water supplied from the rainwater tank system (kL)(flow meter 3)

MIRW = Mains water top-up into the rainwater tank system (kL) (flow meter 2)

TM = Total mains used in household (kL)

RESULTS AND DISCUSSION

Per Capita Water Consumption

Figure 2 shows that the average household per capita water use for the 20 monitored households was 133 litres/person/day (L/p/d), which is significantly lower than the reported per capita water demand of 153 L/p/d (QWC, 2011) in SEQ between April-August 2011. Results showed that most homes located in 'above average' to high rainfall climatic regions displayed relatively higher per capita water use that led to higher mains water savings from mandated rainwater tanks. This was particularly apparent in homes located in Redland (e.g. IPT5 and IPT15) and Gold Coast (IPT18) LGAs, where the recorded rainfall was found to be 260 mm and 161 mm, respectively. On the contrary, the monitored homes located in the 'below average' rainfall climatic regions (i.e. Caboolture) (e.g. IPT12, IPT13 and IPT14) showed significantly lower per capita water use and mains water savings from mandated rainwater tanks in comparison with the rest of the monitored homes. Homes located in the Pine Rivers area seem to have slightly varying levels of per capita water consumption patterns; these homes are in a climatic region with 'below average' rainfall (116 mm), hence the total mains water savings and rainwater consumption in this area has been lower than most other SEQ areas. Further rainwater tank modelling studies will be conducted to investigate the impact of various physical factors (i.e. roof area connectivity and effective tank size) and household characteristics (i.e. types of plumbed end-uses) associated with the rainwater uptake. This would be an attempt to develop a more in-depth understanding of the performance of mandated rainwater tanks supplying rainwater as an alternative water source.

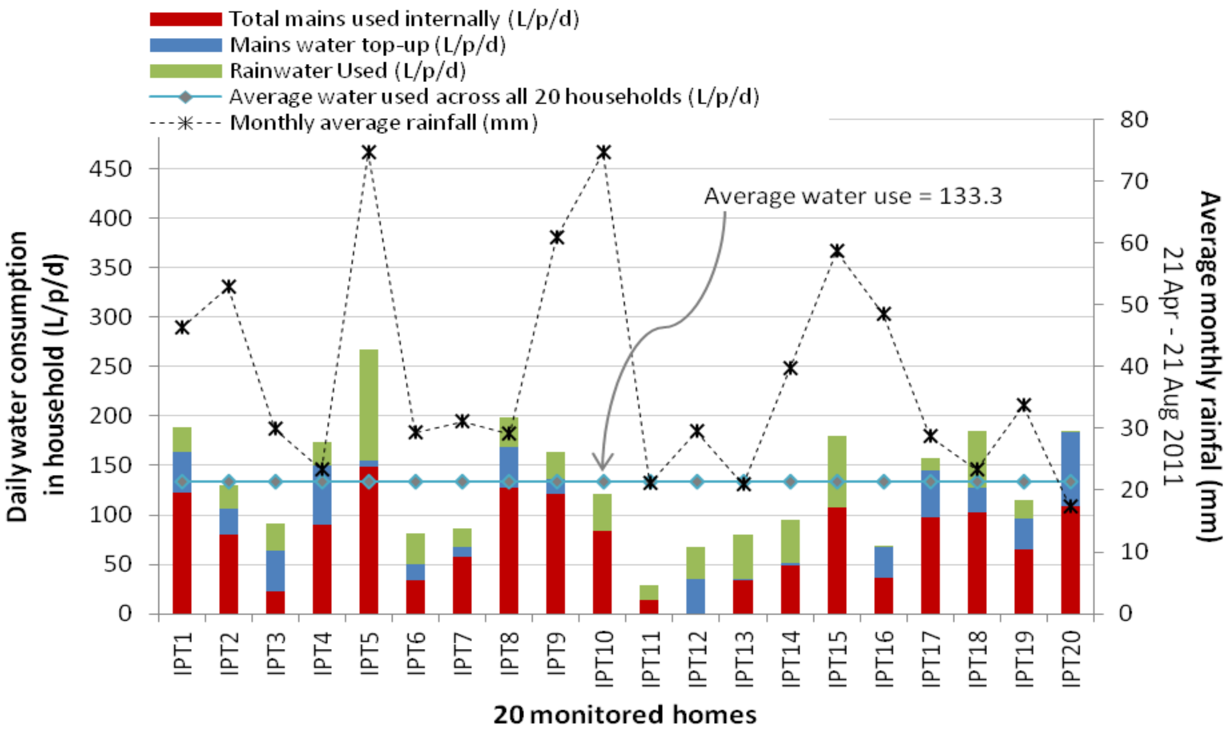
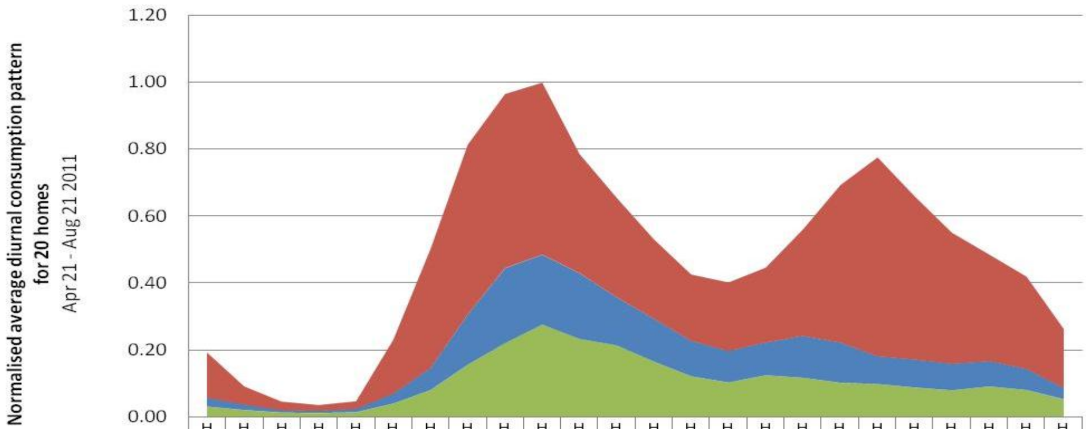


Figure 2. Per capita water consumption across the 20 monitored homes.

Diurnal Water Demand Pattern Analysis: Figure 3 demonstrates the diurnal pattern for water consumption in the cluster-of-20 homes (recorded over a 4-month period) normalised against the peak daily water demand. This facilitates an easy interpretation of the water balance fractions between the monitored streams of Direct Mains Water (DMW, which is the difference between the total mains used in the household and the mains water top-up into the rainwater tank), Mains into the Rainwater Tank (MIRW) and Total Rainwater Supplied from the Rainwater Tank System (TRW).



	H 1	H 2	H 3	H 4	H 5	H 6	H 7	H 8	H 9	H 10	H 11	H 12	H 13	H 14	H 15	H 16	H 17	H 18	H 19	H 20	H 21	H 22	H 23	H 24
DMW - Direct Mains Water (Internal Use)	0.14	0.05	0.03	0.02	0.02	0.16	0.36	0.51	0.52	0.51	0.36	0.30	0.24	0.20	0.21	0.22	0.32	0.47	0.60	0.49	0.39	0.32	0.28	0.18
MIRW - Mains Into Rainwater System	0.03	0.02	0.01	0.01	0.01	0.03	0.07	0.15	0.23	0.21	0.20	0.14	0.13	0.11	0.09	0.10	0.13	0.12	0.08	0.08	0.08	0.08	0.06	0.03
TRW - Total Rain Water Used	0.03	0.02	0.01	0.01	0.01	0.04	0.08	0.16	0.22	0.28	0.23	0.21	0.16	0.12	0.10	0.12	0.12	0.10	0.10	0.09	0.08	0.09	0.08	0.05

Time (0.00 hours)

Figure 3. Normalised average diurnal water consumption patterns for a cluster-of-20 monitored homes.

From Figure 3, it can be observed that there are two distinct water demand peaks, which are seen to represent the morning and evening peak water usage. The morning peak occurs between 8:00 and 11:00 hours, while the evening peak water consumption occurs between 18:00 and 20:00 hours with significantly higher usage of internal mains water supply and declining demand in rainwater supply. From the figure, it can be seen that around 49% of the average hourly household water demand during the morning water peak (at 10:00 hours) is met through the mandated rainwater tank supply system (either by captured rainwater or mains water top-up or both). Out of the total demand met during the morning peak hour, 28% is met solely through the rainwater available in the tanks.

On the contrary, only 18% of the average hourly household water demands for the evening water peak (at 19:00 hours) was substituted from the mandated rainwater tank supply system, where the contribution from rainwater as a source is around 10%. This finding shows that the evening water peak is mainly attributed to end use fixtures that draw water directly from the mains water supply (i.e., shower roses, kitchen taps/drinking water supply, dishwasher, etc).

Previously, Thyer *et al*. (2007) found that increase in typical end uses such as toilets and showers provided the greatest increase in average water use resulting in higher peak hour mains water demand. In this study, the morning peak hour demands for the cluster-of-20 homes is directly influenced by more prominent and consistent water supply from the rainwater tanks to typical end uses such as toilet flushing, clothes washing and garden tap. However, the evening peak was seen to be a factor of other typical end-uses (e.g., shower, kitchen taps/drinking water, dishwasher) that were dependant on mains water supply.

Volumetric Reliability of Rainwater Tank System: Figure 4 shows the range of volumetric reliabilities of rainwater tanks for the 20 households. The average of the volumetric reliability across the 20 individual homes was determined to be 27%. The higher average volumetric reliability for the 20 homes is a result of higher rainwater consumption at individual houses (IPT3, IPT5, IPT6, IPT11, IPT13, and IPT14). In a previous study by Chong *et al.* (2011), a benchmark analysis was conducted to establish the average mains water offset achieved in IPT households (n=691) across Pine Rivers, Caboolture, Gold Coast and Redland, relative to the daily average water consumption in the SEQ region on the whole. For 2009, the mains water offset achieved through rainwater use in IPT homes was found to be 15%, 18%, 34% and 36% for the four areas respectively, with the overall average rainwater offset achieved in IPT households across all four areas being ~26%. Similarly for 2010, the rainwater offsetting the mains water in the same set of

IPT homes was 22%, 25%, 33% and 31% respectively with an average offset of ~28%. Thus, these figures are easily comparable to the average rainwater offset (volumetric reliability) of 27% currently achieved at the 20 homes.

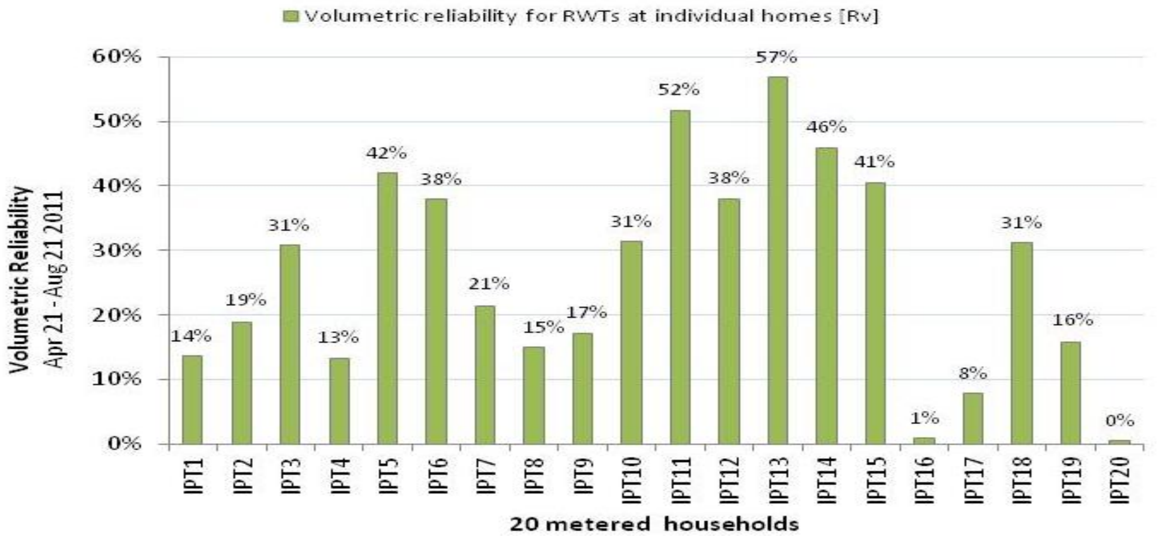


Figure 4. Estimated volumetric reliability of rainwater tank systems at 20 monitored homes.

From the analysis, it was also observed that the availability of rainwater had considerable influence on the supply reliability of rainwater tank systems over a longer period of time. It was found that rainfall events did not influence the internal daily water demand from the rainwater tank systems, with the exception in homes where the external garden tap was regularly used. This was supported by the long-term monitoring data which showed that there was little or no water drawn from the external garden tap during most rainfall events. The seasonal effects on the rainwater savings achieved at the 20 homes will be studied further as more complete data for the total monitoring period (a minimum of 12 months) becomes available, allowing a more comprehensive analysis of the behaviours of rainwater tank systems.

CONCLUSIONS

The study has provided improved insight into the real world performance of mandated rainwater tanks in SEQ. As the implementation of mandated rainwater tanks is still in its infancy, any monitored information on their contribution towards mains water savings is important for water professionals and policy makers. Results showed the average household per capita water use for the 20 monitored households was 133 L/p/d, which is significantly lower than the reported annual per capita water demand in SEQ where the annual per capita water demand was 153 L/p/d for the same period, which could be attributed towards lower rainfall during the analysis period. Two distinct water demand peaks that are representative of the morning and evening peak water usage are evident from the diurnal water demand pattern of the cluster of 20 monitored homes. The average volumetric reliability of the rainwater tank systems to meet daily household water demands (27%) is comparable to previous analyses conducted to determine the mains water offset by the tanks. From diurnal pattern analysis, it was also determined that the collected rainwater contributed towards a 10% offset in mains water consumption over the analysis period. Differences in household water usage based on local rainfall patterns were also found, wherein lower water consumption in areas with lower rainfall could possibly be attributed to diligence of people in these areas. Based on known parameters such as roof area, tank size and water consumption in each home, modelling will be conducted to determine the expected water saving outcomes in each individual dwelling for comparison with measured results. The final findings from this study would provide information that would be significant for the future of urban water resources management and planning in SEQ, or even Australia wide.

ACKNOWLEDGEMENT

This research is being conducted as part of the Urban Water Security Research Alliance (UWSRA), aresearch collaboration between the Queensland Government, CSIRO, The University of Queensland and Griffith University. Authors would also like to acknowledge Don Begbie, Director UWSRA for his continual support.

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