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Performance Analysis of a Communal Residential Rainwater System for Potable Supply: A Case Study in Brisbane, Australia

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Abstract Cities in developed countries have increasingly adopted rainwater tanks as an alternative water source over the last 15 years. The rapid uptake of rainwater tanks has been driven by the need to reduce demand for centralised water services that are under pressure to adapt to population growth and climate change impacts. Rainwater tanks are part of integrated urban water management approach that considers the whole water cycle to provide water services on a fit for purpose basis that minimises the impact on the local environment and receiving waters. Rainwater tanks are typically applied at the household scale for non-potable water source uses such as toilet flushing and garden irrigation. However, this paper reports on a communal approach to rainwater harvesting, where the water is treated for potable use. A communal approach to rainwater harvesting can offer benefits, such as: economies of scale for capital costs, reduced land footprint, centralised disinfection and flexibility in matching supply and demand for different households. The analysis showed that the communal approach could provide a reliable potable water source to a small urban development. However, there was an energy penalty associated with this water source compared to centralised systems that could be addressed through more appropriate pump sizing. The outputs from this monitoring and modelling study demonstrated rainwater harvesting can be expanded beyond the current mainstream practices of household systems for non-potable use in certain development contexts. The analysis contained in this paper can be used for the improved planning and design of communal approaches to rainwater harvesting.

Keywords Rainwater harvesting · Decentralised systems · Integrated urban water management · Energy-water nexus

1 Introduction

Rainwater harvesting has been used as a water source since the beginning of urbanised society (AbdelKhaleq and Alhaj Ahmed 2007). However, the adoption of rainwater harvesting as a

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mainstream practice in modern cities in complement to conventional water supply sources is novel (Abdulla and Al-Shareef 2009; Aladenola and Adeboye 2010; Tam et al. 2010). There are a range of studies that have modelled the likely performance of rainwater tanks as an alternative supply source (Coombes and Kuczera 2003; Imteaz et al. 2011; Jones and Hunt 2010; Khastagir and Jayasuriya 2010; Mitchell et al. 2008; Vialle et al. 2011; Imteaz et al. 2013). However, there is the need for observations from monitoring studies to understand the potential of rainwater harvesting in a range of developments contexts.

The uptake of rainwater harvesting has been primarily to supplement traditional urban water supply sources in cities with projected water scarcity issues due to the likely impacts of climate change on rainfall patterns and growth in demand (Marlow et al. 2010; Moglia et al. 2011; Ruth et al. 2007; Sharma et al. 2009). Rainwater harvesting can form part of a strategy to diversify water supply sources by reducing reliance on traditional water catchments and centralised infrastructure, and can also offer benefits to other parts of the water cycle, including: moderating peak stormwater runoff, reducing discharge of nutrients to receiving waters, and improving ecological health (Hall et al. 2011; Khastagir and Jayasuriya 2010; Kim and Furumai 2012; Villarreal and Dixon 2005; Farreny et al. 2011). Coombes et al. (2000) showed that a communal approach to rainwater harvesting could reduce mains water use by around 60 % while also reducing stormwater discharge. Rainwater harvesting in cities has mostly been implemented at the household scale. However, it has been found that there are a number of limitations with household scale rainwater systems. This includes a lack of householder understanding of health risks (Domènech and Saurí 2011) and also inadequate maintenance of systems that can result in failure (Moglia et al. 2013). This paper focuses on the potential application of communal rainwater tanks in providing an alternative residential water source in cities as part of an integrated urban water management approach (Sharma et al. 2012).

We define communal rainwater systems as systems that collect roof runoff from a cluster of houses, and then store and treat water centrally before reticulating back to households. Compared to individual household rainwater tanks, communal rainwater systems remain novel with a lack of published studies to validate their volumetric reliability and water quality performance, and associated energy demand. Volumetric reliability is defined as the water supplied from the rainwater tank divided by the sum of the water demand requested from the rainwater tank over the monitoring period (Neumann et al. 2011). This paper reports on a monitoring study of a communal rainwater system in South East Queensland, Australia. The results in this paper are relevant to developing improved guidelines for the design of communal rainwater systems to provide volumetric reliability and minimise energy demand.

2 Methodology

Figure 1 depicts the methodology used to validate the performance of a communal rainwater harvesting system. Following sections contain more information on the analysis of metered water and energy fluxes, and the water balance modelling components of the methodology.

3 Case Study

Capo di Monte (CDM) is a 46 home development at Mount Tambourine located on the peri-urban fringe of Greater Brisbane, Australia. The development site lies outside of the area serviced by municipal water and wastewater services, so for the development to proceed it had to commission decentralised water and wastewater systems. The communal rainwater

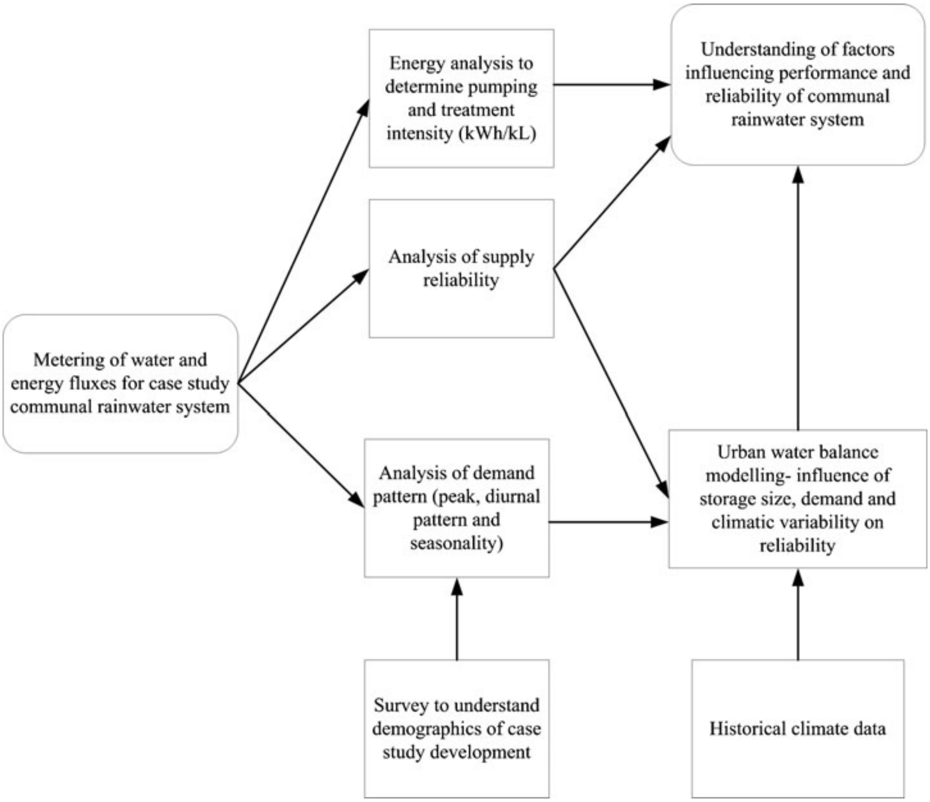


Fig. 1 Methodology for the validation of communal rainwater harvesting performance

system was designed to meet household uses that require potable water quality: kitchen, bathroom and laundry. A wastewater recycling scheme is used to satisfy non-potable demands: toilet flushing and garden irrigation. A local bore is used to supplement both systems in times when demand is higher than supply capacity.

CDM was planned as a retirement village, therefore residents are mostly 60 years or older and retired. The CDM population is 75 people, with an average household occupancy of 1.65 persons compared to overall Brisbane average of 2.6 persons per dwelling. CDM is located near the Mount Tambourine weather station, which recorded an average annual precipitation of 1,318 mm/year over the period 1982 to 2005. Analysis of the rainfall record showed a pattern of relatively wet years, with up to 2,000 mm in rainfall, interspersed with drier years, with rainfall of around 1,000 mm. This weather station is located less than 5 km from CDM and is the closest weather station with a long-term climate record.

The communal rainwater system collects roof runoff through a network of household downpipes that feed into collector pipes which transfer the water by gravity to two 200 kL storage tanks. The total connected roof area is around 10,700 m^2, with houses having an average roof area of 222 m^2, and a community centre that provides another 488 m^2 of connected roof area.

A water treatment plant, comprising sand filtration, UV sterilisation and chlorination sends water to a 40 kL balance tank for subsequent distribution of *potable water* to each house and a small community centre. A local bore provides supplemental water in times of insufficient rainfall, or excess demand. The communal 200 kL tanks at CDM are operated to

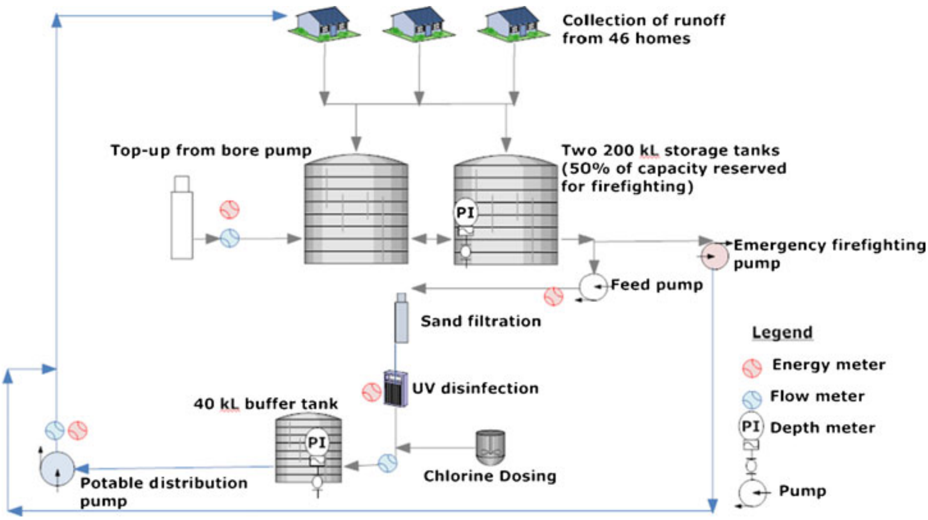


Fig. 2 Capo di Monte hydraulic circuit, and water and energy meters

retain at least 50 % capacity to allow for emergency fire-fighting capability. The system is managed by an appropriately trained person who is directly responsible to a body corporate entity. Figure 2 depicts the CDM hydraulic circuit.

3.1 Monitoring System

Monitoring of energy and water fluxes through the communal rainwater system were undertaken using a high-frequency logging device that recorded flows or energy pulses within 5 min time intervals. A data logging system stored the data in 5 min, hourly and daily data files. Manual recordings taken monthly from the water and energy meters were used to calibrate the electronically logged data.

3.2 Water Balance Modelling

Simulations were undertaken to explore the likely performance of the case study communal rainwater system under different operating configurations and conditions. The long term reliability of the communal rainwater system was modelled using the Urban Volume and Quality (UVQ) model. The UVQ model quantifies urban water and contaminant balance at a daily time-step; enabling the user to track flow paths and contaminant concentrations through the urban water cycle (Mitchell and Diaper 2006).

4 Results

4.1 Demand

The communal rainwater system is used to meet potable demand at CDM. The demand for potable water supplied the following internal household demand: kitchen, laundry and bathroom. Table 1 depicts the average household daily and yearly water use at CDM for the

Table 1 Average household water use by source

End uses	Water supply source	Average daily per capita demand (L/capita /day)	Average yearly household demand (kL/household/year)
Potable (communal rainwater system)	Rainwater	60	36
	Bore-Top-up	12	7
	Total (potable)	72	43
Non-Potable	Recycled and bore top-up	91	55
Overall household		163	98

18 months (March 2010 to August 2011) that the system was monitored. The average per capita water use at CDM was marginally higher than the average water demand reported for this region of 150 l a day (Queensland Government 2011). This disparity may in part be due to the older demographic profile of CDM, as older households are likely to spend significant time at home leading to increased in the home toilet flushing and other uses (Willis et al. 2009b). The CDM monitored demand was compared with two comprehensive Australian end use studies: Roberts (2004) and Willis et al. (2009a). This comparison found that potable demand was much lower at CDM than the other two studies, while non-potable demand was higher. The supply of recycled wastewater for irrigation at CDM may mean there is less emphasis on water conservation for outdoor uses. The inherent heterogeneity of household water use is worth noting in using the average CDM household water demand to compare with other water demand studies. Beal et al. (2010) made the point that water demand patterns vary significantly between households on the basis of socio-demographics, house size, climate, and cultural practices.

Figure 3 depicts the average diurnal demand pattern for potable water use in CDM households, which uses data from both summer and winter monitoring periods. This depicts a typical bimodal distribution for household water use where there is very little water use before 6 in the morning and then a morning peak associated with showering and another peak in the early evening that can be attributed to meal preparation, dishwashing and showering. There is no significant seasonal variation in potable water demand for CDM, which is to be expected as indoor water demand is not significantly influenced by climate. Daily household potable water demand was not found to vary significantly between different days of the week, over the monitoring period.

Table 2 shows the peaking factors for the CDM communal rainwater system in comparison to government guidelines for water supply planning. This shows that mean day maximum month peaking factor is slightly lower than the guideline value, which could be

Fig. 3 Diurnal flow pattern

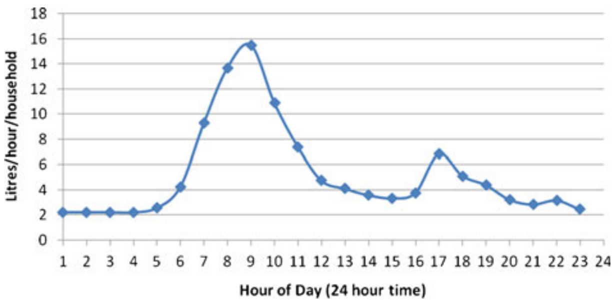


Table 2 Peaking factors for CDM communal rainwater system (potable use)

	Capo di Monte peaking results	Suggested water supply planning ranges for peaking factors[a]
Mean day maximum month	1.33	1.5–1.7
Peak day demand	2.91	1.9–2.3
Peak hour demand	3.33	3.6–4.5

[a] Queensland Department of Energy and Water Supply (2010) Planning guidelines for water supply and sewerage – Table 5.4, p 56

explained by the fact that the communal rainwater system is used for potable demand, which is not particularly responsive to climate conditions compared to outdoor water demand.

4.2 Supply

The monitoring data shows that over the period January 2010 to November 2011 an average 5 kL per day was supplied from the communal rainwater system for potable use. Rainwater harvested from roofs was able to meet around 90 % of the demand, with the remainder supplied from an onsite bore. Bore pumping was greatest during June 2010, the driest month over this monitoring period where only 13 mm of rainfall was recorded. Around 160 kL of water needed to be supplied through bore pumping during this period, which represented 80 % of the potable demand in June 2010.

Figure 4 depicts the daily input and output flows for the communal rainwater system, and storage levels, over a 9 month monitoring period. This shows a consistent daily demand and that the regular rainfall over the monitoring period meant that bore top-up was only required

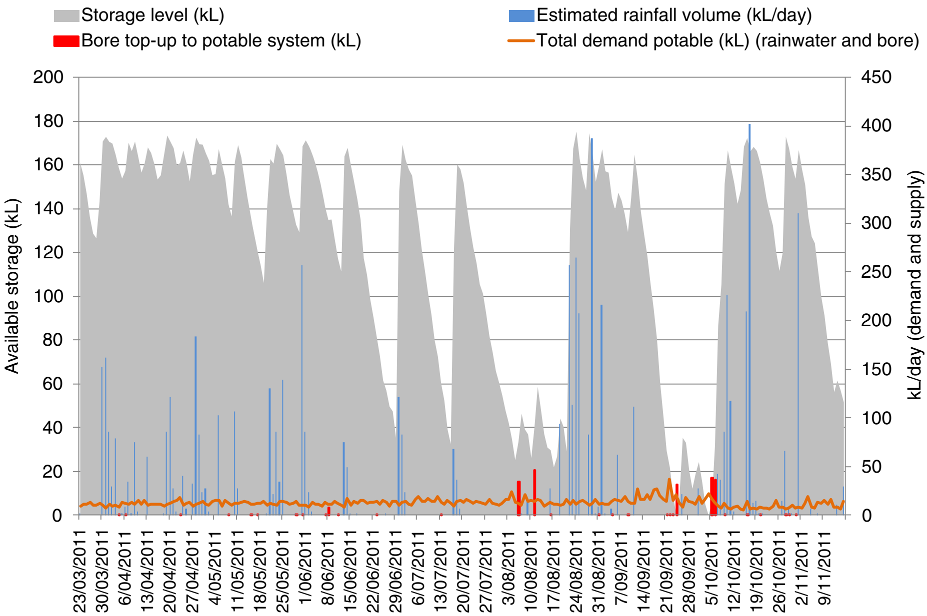


Fig. 4 Daily flows and storage level for CDM communal rainwater system

infrequently. The bore top-up for CDM occurs manually at the discretion of the operations manager. Discussions with the operations manager indicated that bore pumping is activated when remaining supply reaches around 20 % of the 200 kL capacity. Thus the effective storage volume for rainwater collection is only 160 kL, with a further 200 kL quarantined for fire-fighting. This means that the reserve storage is at least a week's supply based on the average daily potable demand for the development of just over 5 kL. Figure 4 shows that the lowest point of the effective storage capacity was only reached once, which triggered top-up bore pumping. Other significant bore pumping events occurred when there was still 20 kL of effective storage still available. These results indicate that bore pumping could be further reduced if the effective storage was allowed to reach the reserve level before top-up occurred.

4.3 Water Balance Modelling

Water balance modelling in UVQ was undertaken to explore the reliability of the communal rainwater system at CDM under different operational configurations and its resilience to drier years.

Historical rainfall record at a 6 min time step was used from the nearby Mount Tambourine weather station for the period 1982 to 2005. The water balance model aggregated six minute rainfall intensity data to daily records, but the values were adjusted to reflect the effective rainfall. Effective rainfall is the runoff from the connected roof area that can be captured by the downpipe system at CDM. For the CDM system, it has been calculated that the maximum rainfall intensity that can be harvested is 1.8 mm per minute. This was based on the calculated maximum discharge from roof runoff of one litre per second, which was a function of the diameter of the downpipes. Theoretical runoff was estimated using the rational equation:

$$Q = ciA$$

Where:

- Q is the peak discharge
- c is the rational method runoff coefficient (0.9 was used for roof area)
- i is the rainfall intensity (millimetres per hour); and
- A is the rainfall catchment roof area for roof runoff.

The rational runoff coefficient of 0.9 has been found to accurately simulate initial losses from roofs during a rainfall event (Imteaz et al. 2012). The effective rainfall showed that on average over a year the potential rainfall for harvesting is 16 % less than actual rainfall. The difference is greatest in summer months, which are characterised by more intense rainfall events. The average annual rainfall, over the 24 year climate record, was 1,318 mm. This shows a pattern of relatively wet years, around 2,000 mm rainfall, interspersed with drier years, with rainfall of around 1,000 mm. The monitoring period for this study has coincided with a relatively wet period. Rainfall for 2010 was 2,300 mm, which is in the 95th percentile. Therefore, it is worth exploring through water balance modelling how the CDM communal rainwater system is likely to perform in drier years.

For the water balance modelling, it was assumed that the available rainwater storage of 200 kL was full at the start of the simulation. It was also assumed that top up with bore water occurred when the available storage reached 20 % of effective capacity (40 kL). Therefore, an active available storage of 160 kL is assumed based on local information. The results in Fig. 5 are presented as annual averages over the simulation period of 24 years to

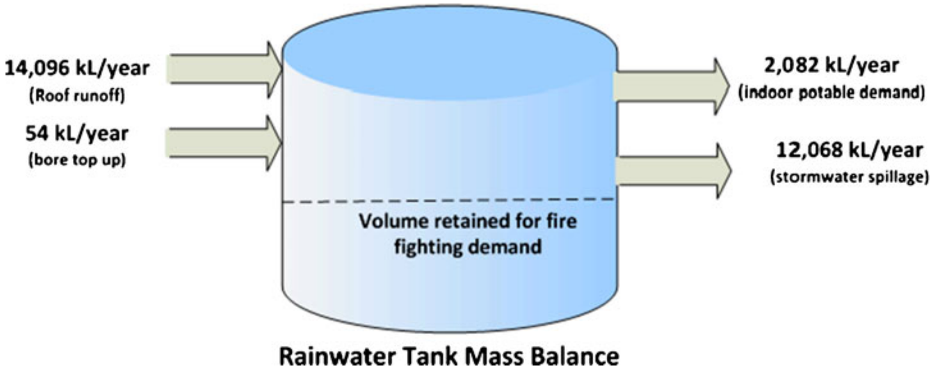


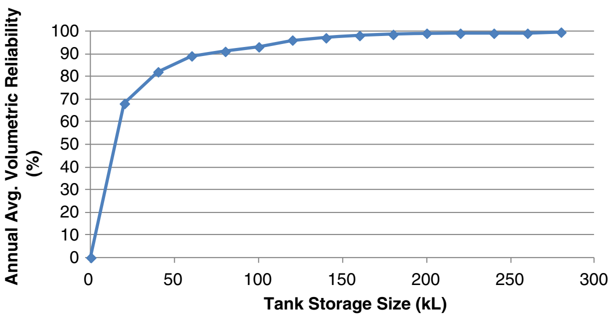
Fig. 5 Average annual mass balance CDM rainwater system (1982 to 2005)

account for both seasonal and yearly fluctuations in rainfall. The results, summarised, demonstrate that bore top-up is only needed to satisfy a small proportion of the demand. This also highlights that, on average, around 86 % of the roof runoff ends up as stormwater overflow.

We have defined volumetric reliability as the water supplied from the rainwater tank divided by the sum of the water demand requested from the rainwater tank over the monitoring period. First we explored the influence of storage size on reliability. Figure 6 depicts the simulated annual average volumetric rainwater yield for different active storage sizes. This shows that for the active storage at CDM (160 kL) that on average demand could have been satisfied from rainwater inputs on 98 % of the days over this 24 year period. To increase the reliability to 99.5 %, without resorting to bore top-up, would have required a storage size of 280 kL. However, the average annual values can obscure reliability performance during periods of uncommonly low rainfall. The simulation of the 280 kL storage still showed that the rainfall system would have failed for 21 days in 1991, 13 days in 2002, and 10 days in 2004. To avoid supply failure in 1991 420 kL would have been required. This demonstrates the difficulty of providing adequate rainwater storage to provide 100 % reliability. The CDM rainwater system was designed for a high volumetric reliability as the development was located outside of the area serviced by mains water supply and the use of water for potable demands meant that the roof runoff was the preferred water source over bore water due to water quality considerations.

Figure 7 depicts the relationship between connected roof area and annual average volumetric reliability. This was modelled using the effective storage size of 160 kL and a

Fig. 6 Volumetric reliability of CDM communal rainwater system for different storage sizes



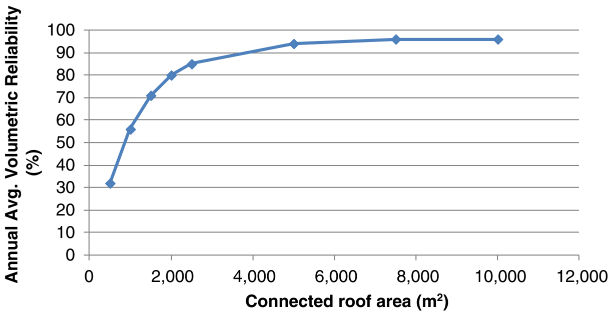


Fig. 7 Annual average volumetric reliability and connected roof area

constant demand of 5.4 kL per day. This analysis showed that halving the connected roof area at CDM from the actual 10,000 m^2 would only reduce the harvested rainwater on average from 2,006 kL a year to 1,949 kL a year. This correspondingly reduced volumetric reliability from 96 % to 94 %.

Our analysis showed the CDM system has been configured to provide, on average, greater than 90 % of potable demand from harvested rainwater. The connected roof area could be reduced with only marginal reductions in the yield, and further increases in the storage capacity would only realise small increases in volumetric reliability.

4.4 Energy

Recent monitoring of individual rainwater tanks estimated a typical energy intensity of 1.5 kWh/kL, with a range of 0.9 to 1.7 kWh/kL (Retamal et al. 2009). While other studies of rainwater systems on steep terrain found an energy intensity of 5 kWh/kL, which is ten times the energy required for centralised water supply (Gardner et al. 2006; Beal et al. 2008). Energy intensity of rainwater systems is determined by the specific characteristics of each site with factors such as system configuration, equipment selection, water use and topography influencing energy demand (Retamal et al. 2009; Beal et al. 2008).

A summary of energy use by the CDM potable communal rainwater system is shown in Table 3. This shows that energy consumption at CDM is dominated by pumping of treated rainwater to households, with around three quarters of energy demand for pumping. The pump system is an on-demand system with a small pressure vessel so any use triggers a pumping event. The topography of the CDM site means there is a pump head requirement of 44 m. The pump has a 4,000 W power capacity and flow capacity of 0.3 m^3/h. Analysis by Sullivan (2011) for this system indicated that the pump is oversized for the system requirements. They showed that a 750 W pump could still meet the head and flow requirements but would reduce the specific energy for pumping by around 50 %.

Table 3 Breakdown of specific energy for CDM communal rainwater system - kWh per KL supplied

	Specific energy (kWh/kL)
Potable pressure pump	3.02
Bore top-up pump	0.08
Feed pump for sand filter	0.65
UV disinfection	0.26
Total specific energy (kWh/kL)	4.01

5 Conclusions

Communal rainwater systems are an alternative method for developers to provide potable water services to developments that are not connected to municipal supplies i.e. decentralised developments. These systems may also be suitable for urban infill developments where existing infrastructure is already at capacity and upgrading may prove to be economically or logistically non-viable. However the performance of communal systems to deliver safe, reliable supplies of water is largely untested.

Results of monitoring at CDM have shown that with a small amount of top-up from groundwater the water system can meet the potable demand of the 75 residents supplied by the system. Modelling using historical climate data showed that the system is configured to be resilient even in relatively dry years, with most of the potable demand being satisfied from harvested roof runoff.

However, this decentralised water supply comes at an energy cost. The system requires around 4.0 kWh/kL to treat and supply the rainwater/groundwater for potable demand. This equates to around 4 times the energy required for centralised potable water treatment and pumping in South East Queensland, and is marginally more than the 3.2 kWh/kL required producing desalinated water by reverse osmosis (WaterSecure 2011). There are opportunities to substantially improve the energy efficiency of this system through smaller pump sizing.

Communal rainwater systems offer a number of advantages over other alternative water sources at the development scale (i.e. stormwater, recycled water and desalinated water) as roof runoff can provide a relatively high quality water source, which can be directly used for non-potable uses, or with filtration and disinfection for potable uses. The results reported in this paper have demonstrated that a communal rainwater system can reliably provide an alternative water source, with minimal reliance on back-up supply, but that there is the need to optimise the energy efficiency. A communal approach to harvesting and treating rainwater means that individual householders do not have to maintain and operate their own tank, and treatment system if being used for potable demand. A communal system, such as the one studied at CDM, is managed by the body corporate. This means that the management burden is not imposed on each household who may lack the skills or motivation to maintain their rainwater system correctly. Also, communal rainwater system may be more appropriate in medium density developments where there is high building ratio to allotment area, which limits space available for storage tanks. Further work is being undertaken to validate the hydraulic efficiency of communal versus individual storages for rainwater harvesting and economic analysis of the two systems.

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