How supply system design can reduce the energy footprint of rainwater supply in urban areas in Australia

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G. Tjandraatmadja, C. Pollard, A. Sharma and T. Gardner

ABSTRACT

In Australia rainwater tanks are used in cities to reduce demand of mains water and increase the resilience of cities to drought. Rainwater is collected in a tank and supplied to a dwelling through a small pump. Typically the energy footprint for rainwater supply (in kWh/kL) is higher than for centralised water supply, but it can also vary markedly from dwelling to dwelling (0.4–11 kWh/kL). This study aimed to understand how the design of the rainwater supply system from the collection tank to the household can reduce the energy consumption of pumping. We examined the operation of a range of system components for rainwater supply, such as pumps, switches and pressure vessels, in a controlled residential environment (a model house) to understand their impact on the energy required for rainwater supply in urban dwellings. Results show that urban rainwater applications have flow and volume requirements which cause pumps to operate at high energy for rainwater delivery. Matching pump sizes to end use requirements and adoption of ancillary devices (pressure vessels and header tanks) have the potential to lower the energy footprint for rainwater supply. However, the energy savings can be constrained by dwelling characteristics, appliances and system design.

Key words | pump energy use, rainwater systems, urban water supply

G. Tjandraatmadja (corresponding author)
C. Pollard
A. Sharma
CSIRO,
PO Box 56,
Highett,
Victoria, 3190,
Australia
E-mail: *grace.tjandra@csiro.au*

T. Gardner
CSIRO,
GPO Box 2583,
Brisbane,
Qld 4001 and Central Queensland University,
Noosa campus,
PO Box 1128 Noosaville BC,
Qld, 4566,
Australia

INTRODUCTION

Rainwater harvesting and collection through tanks has been adopted in many countries around the world, e.g. Uganda, China, Australia, Spain, the USA, France, Greece (Baguma *et al.* 2010; Zhou *et al.* 2010; Ahmed *et al.* 2011; Farreny *et al.* 2011; Mendez *et al.* 2011; Vialle *et al.* 2011; Gikas & Tsihrintzis 2012), mostly when centralised water supply has not been available. Since 2005, in Australia, rainwater tanks have been widely promoted in urban areas as a supplementary water source for non potable uses, to increase resilience to drought and to alleviate the demand of centralised potable water supply. Through the aid of financial incentives and also of legislation encouraging installation of rainwater tanks in new housing in states such as Queensland, South Australia and New South Wales, rainwater tank uptake has risen in urban areas as shown in Figure 1, with high uptake in capital cities, such as Brisbane, but also in high growth regions, such as South East Queensland, where respectively 43 and 36% of suitable dwellings have a rainwater tank (Australian Bureau of Statistics 2010).

In urban dwellings rainwater collected in a tank is supplied on demand to various end uses, typically toilet flushing, washing machine cold tap and outdoor taps, via a fixed speed pump (Talebpour *et al.* 2011). A number of Australian studies have examined the energy burden associated with such mode of supply via desktop (Marsden Jacob Associates 2007; Lane *et al.* 2010; Hall *et al.* 2011) or *in-situ* studies. Hall *et al.* (2011) estimated that in areas of high rainwater tank uptake, such as South East Queensland, 'rainwater tanks might potentially consume the same amount of energy as the centralised water supply system' in the future, yet they also recognised that there was high uncertainty (±50%) in estimates of energy for rainwater supply. This is reinforced in the recent *in-situ* studies of actual energy consumption in Australian dwellings shown

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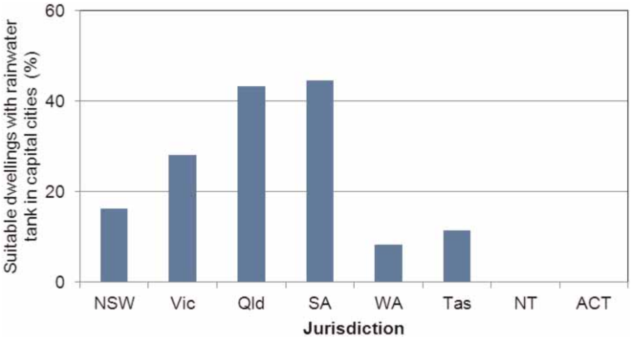

Figure 1 | Rainwater tank uptake in Australian capital cities in New South Wales (NSW), Victoria (Vic), Queensland (Qld), South Australia (SA), Western Australia (WA), Tasmania (Tas), Northern Territory (NT) and Australian Capital Territory (ACT). (Australian Bureau of Statistics 2010).

in Table 1. The energy footprint or the specific energy, i.e. the amount of energy used for pumping divided by the amount of water supplied in kilowatt hours per kilolitre (kWh/kL), reported in those studies ranged from 0.59 to 11.6 kWh/kL of rainwater supplied. However, the dwellings monitored differed in system set-up, number of householders, dwelling characteristics (e.g. single or double storey) and end uses. In Queensland, the energy recorded for rainwater supply to six high value houses with individual rainwater tanks ranged from 2.1 to 3.8 kWh/kL (Gardner *et al.* 2006; Beal *et al.* 2008), whilst for 40 houses of various sizes (one, two or three bedrooms) in an ecovillage the energy required was lower at 1.4 kWh/kL (Hood *et al.* 2010). In Victoria and New South Wales, a wide spread from 0.4 to 11.61 kWh/kL was recorded for 40 dwellings fitted with various pumps types, systems and occupancy, recorded (Retamal *et al*. 2009; SEWL 2009, 2010).

The role of individual system components has also been explored in previous studies. Retamal *et al.* (2009) and Hauber-Davidson & Shortt (2011) verified that different pump types (e.g. external, variable speed and submersible) produced different specific energy requirements. The specific energy was also observed to differ for pumps with same engine capacity but of different brands (SEWL 2010; Hauber-Davidson & Shortt 2011). Hauber-Davidson & Shortt (2011) also evaluated the impact of an automatic rainwater to mains switch, pressure controllers and a 5 L pressure vessel in the energy for supply of rainwater to selected end uses (toilet cistern, front loader washing machine, shower head and garden hose) in a two-storey dwelling. The adoption of an automatic switch from rainwater to mains water and the 5 L pressure vessels were seen as beneficial by the researchers, as they prevented pump start-ups for low volumes of water, such as small leaks or dripping taps, however the reduction in energy for the system was minimal with the components tested. Most researchers expect that the adoption of a header tank will significantly reduce the pumping energy, however this set-up still has to be verified experimentally for the common range of rainwater appliances (Cunio & Sproul 2009; Retamal *et al.* 2009; Hauber-Davidson & Shortt 2011).

This study aimed to understand how the design of the rainwater supply system from the collection tank to the household can reduce the energy consumption of pumping. To do so we examined the operation of a range of system components for rainwater supply, such as pumps with control switches (pressure or automatic rainwater to mains water switch), with and without pressure vessels, or

Table 1 | Australian *in-situ* studies of energy for pumping rainwater to urban dwellings

Location in Australia	Energy for rainwater supply per dwelling (kWh/kL)	Number of dwellings	End use type	References
Payne Rd, The Gap, Queensland	2.1–3.8	4–6	Potable and non-potable	Gardner *et al.* (2006); Beal *et al.* (2008)
Currumbin Ecovillage, Queensland	1.4 (median)	40	Potable and non-potable	Hood *et al.* (2010)
Gold Coast, Queensland	1.04–1.67 (depending on end use type)	5	Non-potable	Talebpour *et al.* (2011)
Sydney and Newcastle, New South Wales	0.9–2.3	8	Non-potable	Retamal *et al.* (2009)
Sydney, New South Wales	0.4–1.6	1	Non-potable	SEWL (2010)
Melbourne, Victoria	0.59–11.61 (average 1.98)	31	Non-potable	SEWL (2009)

header tanks, to understand their impact on the energy footprint for rainwater supply in urban dwellings.

MATERIALS AND METHODS

A model house was constructed in the CSIRO laboratories. An 850 L rainwater tank supplied water via an external pump through 18 mm diameter polyethylene pipe to a range of common household appliances: a top loading washing machine, a tap, a dishwasher and a dual flush toilet cistern (shown in Figure 2). System components adopted included three external constant speed pumps A, B and C, with respective motor capacities of 0.20, 0.55 and 0.75 kW; pressure vessels with nominal capacities of 8, 18, 40 and 80 L and a 300 L header tank with a float valve. Pump B was installed with an automatic rainwater to mains water switch and the other two with pressure switches. Three alternative set-ups were adopted: (i) direct supply from pumps to appliances; (ii) pump supply to pressure vessel and pressure vessel to appliances; and (iii) pump supply to a header tank located at ceiling height (2.7 m) and gravity supply from the header tank to appliances. Pressure and flow within the water supply system and the energy consumed by the pump were monitored in intervals of 0.2 s and logged every 1 s using, respectively, pressure transducers (ABB 2699T ±0.15% Full Scale Deflection), an ABB magnetic flowmeter (±0.16% of reading at 20 °C) and current and power transducers (LEM AC/ AWT190 AC ±0.5%).

The system was monitored for the operation of individual appliances. The specific energy of water supply (in kWh/kL) was estimated as the energy used by the pump for a rainwater supply event divided by the volume of water delivered.

RESULTS

This section summarises the experimental results obtained from this study.

Service requirements

In Australia, mains water supply is pressurised, in addition, due to water scarcity, household appliances and fittings have evolved to function at high water efficiency. Fittings, such as taps, showerheads and irrigation devices, are designed to limit the flow of water use (Australian Government 2011) and household appliances, such as washing machines and dishwashers are designed to operate within a specific range of flow and/or pressure conditions. Table 2 shows

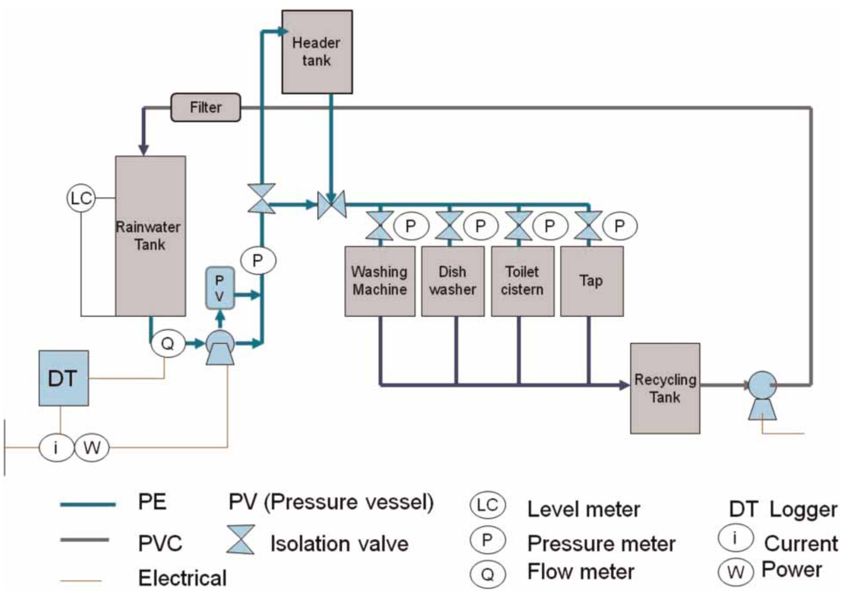

Figure 2 | Diagram of rainwater supply system and monitoring set-up in the model house.

Table 2 | Design and operating requirements for appliances and fittings

	General specifications		Service conditions[d]	
Appliances	Minimum pressure (kPa)[a]	Maximum pressure (kPa)	Measured flow rate (L/min)	Volume of water (L/use)
Washing machine	40–100[a]	800–1,000[a]	<13	113
Dishwasher	30–150[a]	800–1,000[a]	<4.1	16
Toilet cistern	40–150[b]	400[b]	<6.3	3 (half flush), 5 (full flush)
Tap (WELS 4–6 stars)	n.a.	n.a. 2–7 L/min[c]	<35	<35 L/min (no flow restrictors)

Note: [a]Manufacturer specifications.
[b]Standards Australia (1999).
[c]Australian Government (2011).
[d]Measured (adapted from Tjandraatmadja et al. 2011).

the typical design service conditions and those measured experimentally for the appliances adopted in our investigation. Typically, the minimum operating pressure for a washing machine ranges from 40 to 100 KPa depending on appliance make and model. Whilst flow from a water efficient (four to six star Water Efficient Labelling Scheme (WELS)) tap is restricted by design to range from 2 to 7 L/min (Australian Government 2011).

The pattern of water supply for individual appliances also differs. Filling of a toilet cistern requires supply of 3 or 6 L of water as a continuous event, whereas, the operation of the washing machine and the dishwasher is characterised by water supply in multiple events of various volumes and intervals. This is exemplified in Figure 3 for the washing machine where water was delivered in seven stages (three main supply events (53, 28, 22 L), and the remainder as small supply events (<3.5 L/each), thus causing the pump to start multiple times.

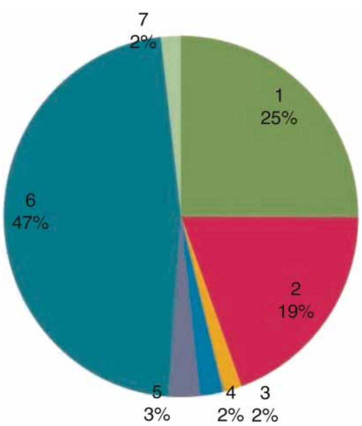

Figure 3 | Breakdown of water delivery during water supply to a washing machine.

Pump operation

Fixed speed pumps are the most common type of pump adopted for rainwater systems in Australian urban dwellings (Retamal et al. 2009). The pumps selected are representative of the typical range observed in the studies in Table 1, where 44 and 33% of pump motor size were within the ranges of 0.41–0.6kW and 0.61–0.81 kW, respectively. Figure 4 shows the specific energy (kWh/kL) for pumping rainwater at a range of flow rates for each pump A, B and C. The figure also shows the range of service flows measured during water supply to the dishwasher, the filling of the toilet cistern and the filling of the washing machine, which were respectively 3.3–4.1 L/min, 4–6.3 L/min and 9.6–13 L/min, in this study. As seen in the figure, the energy required for pumping decreases as flow rate increases, with low flow applications, such as filling a toilet cistern, having a higher specific energy than higher flow applications, such as the washing machine. Thus, energy

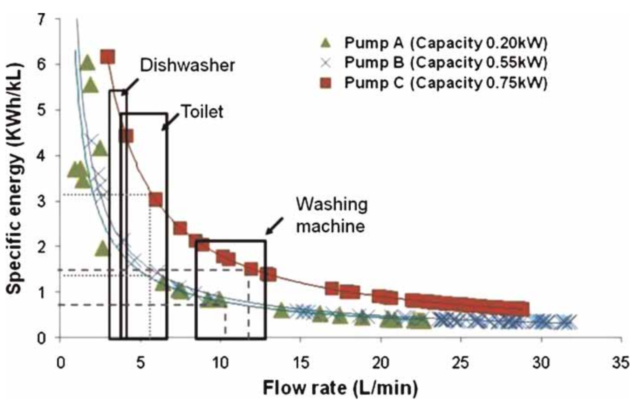

Figure 4 | Relationship between specific energy for pump operation and flow rate requirements for various household appliances.

requirements can be minimised by either operating pumps at high flow rates or by selecting pumps with low specific energy curves such as pump A in preference to pump C.

Figure 5 shows the specific energy required for pumping water to the appliances investigated. The header tank, which is controlled by a float ball valve, has the lowest energy requirement at 0.4–0.6 kWh/kL, depending on pump size, filling also took place at high flow rates (>25 L/min) for an effective volume of 260 ± 4.7 L in a single event. Such volume is sufficient to supply the typical rainwater end uses (washing machine, toilet and irrigation) of 137–233 L per day reported for dwellings in South East Queensland (Beal *et al.* 2010). However, when examining the service pressure generated by gravity, 20 kPa, the pressure generated was below the minimum required for operation of many appliances (Figure 6). This could be improved by increasing the height of the header tank, but this would exceed the height of the roof cavity (2.7 m) in a single storey household. On the other hand, all three pumps exceeded the required minimum pressure for appliance operation. Hence, to adopt a header tank, it would be necessary to either increase the height of the tank or alter the design pressure of the water inlet in current appliances. A discussion with manufacturers would be required to explore if appliances can operate at low pressure and the changes required.

Ancillary devices

Two pressure vessels, 8 and 18 L, were examined (Tjandraatmadja *et al.* 2012). Pressure vessels are designed to

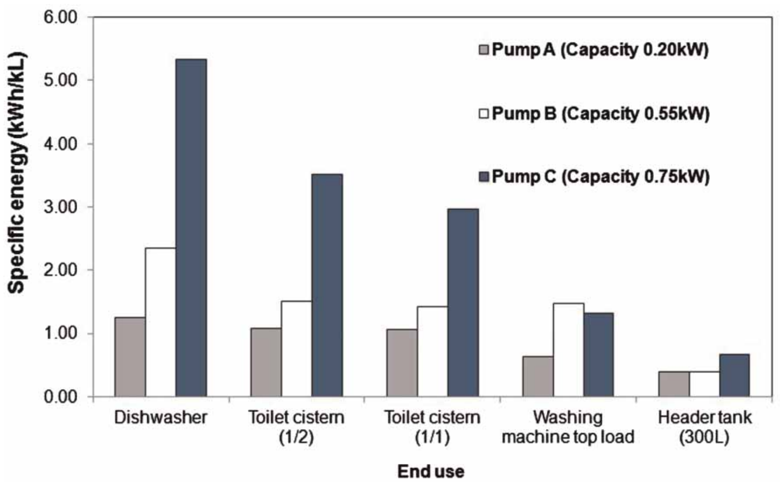

Figure 5 | Energy required for water delivery to appliances.

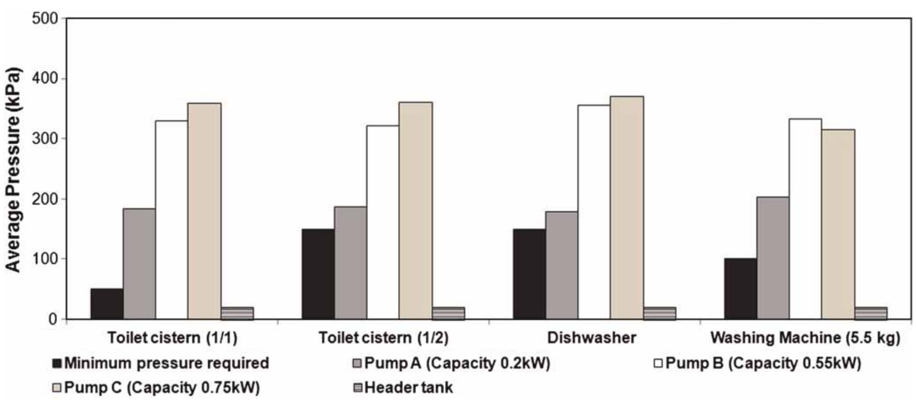

Figure 6 | Pressure supplied by pumps upon operation.

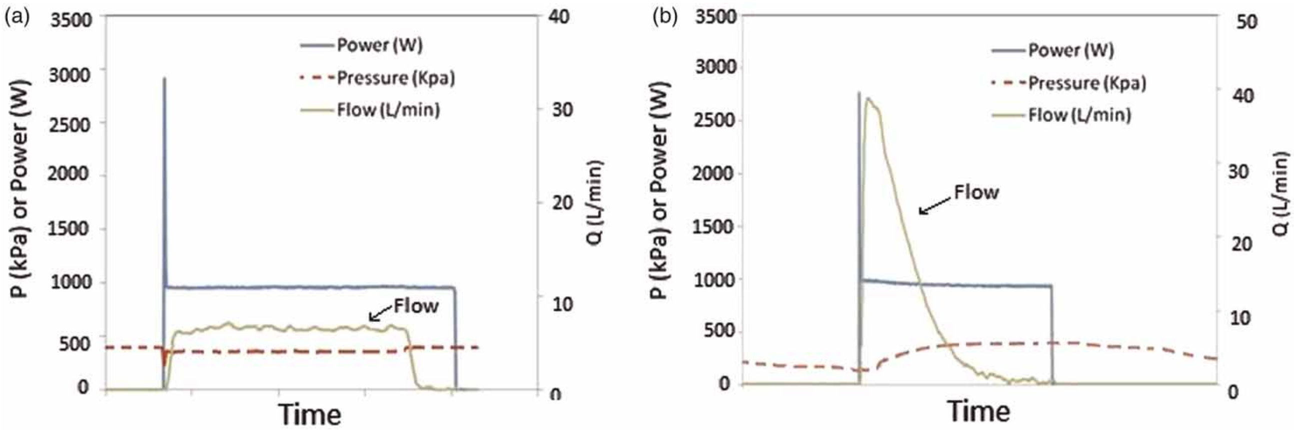

Figure 7 | Pump operation (0.75 kW) during water supply to: (a) toilet cistern, (b) pressure vessel. The *x*-axis for (a) and (b) are not in the same scale.

release a set amount of water under pressure before requiring refill, thus reducing the number of pump start-ups. In addition, the mode of water supply by a pump during refill of a pressure vessel differed from that of direct rainwater supply to an appliance as exemplified in Figure 7 for pump C (0.75 kW). The figure shows the power consumed by the pump, the flow of rainwater delivered and the pressure changes in the system. In both instances, the pump starts up and draws power during pumping. Filling a pressure vessel started at a high flow rate (38 L/min) which decreased as pressure within the vessel increased. Whilst in direct supply to the toilet cistern the average flow rate is lower and remains at 6.3 ± 0.05 L/min during pump operation, as the flow is constrained by the inlet valve to the cistern, causing the pump to run longer (Figure 7(a)).

The effectiveness of a pressure vessel is dictated by the volume of water it can release prior to refill and the volume of water required for the appliances supplied by the pump. Figure 8 shows how the amount of water released varies with increasing pressure vessel size, from 8 to 80 L, for pumps A and C. For the 0.75 kW pump C, the 8 L pressure vessel released 3 ± 0.1 L of water before the pump started up, but as most appliances required a larger amount of water, the small pressure vessel did little to reduce the energy use. The 18 L pressure vessel released 6.3 ± 0.1 L before the pump restarted, which allowed filling of the cistern twice before refill of the vessel. The reduction in energy that can be achieved by addition of an 18 L pressure vessel is compared in Figure 9. The vessel was most effective in reducing the energy required for supply of high energy intensity and low volume (<6 L) end uses, such as the opening of a tap for short periods, the dishwasher and the toilet cistern, bringing the specific energy for water supply to less than 2.5 kWh/kL for all the individual activities. For the washing machine, which adopts larger volumes of water the reduction in energy is less marked, as the pressure vessel is able to supply the low volume requirements, but it has little impact on delivery of larger volume required for filling and rinsing stages previously shown in Figure 2. For the 0.2 kW pump A, the volume of water released and the energy savings by the 8 and 18 L vessels were negligible.

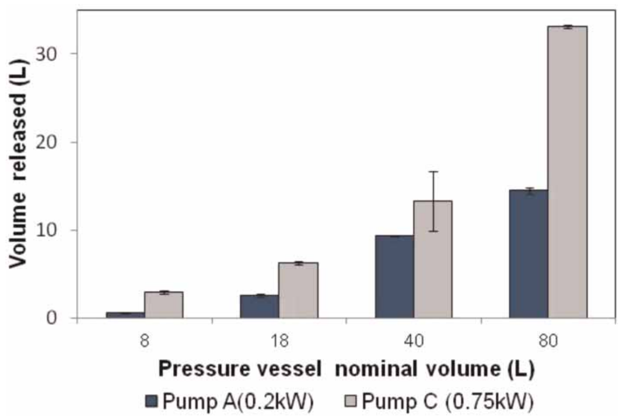

Figure 8 | Volume of water released before pump start-up for pumps A and C and pressure vessels of various sizes.

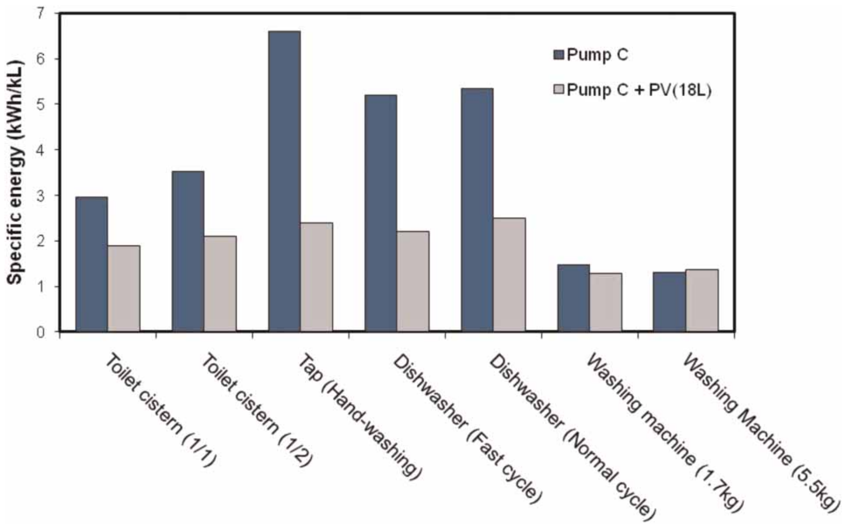

Figure 9 | Energy for rainwater delivery for a system with pump C (0.75 kW) and an 18 L pressure vessel. (Source: Tjandraatmadja *et al.* 2012).

This explains why a small pressure vessel is not effective in reducing the energy consumption for rainwater supply as observed in Hauber-Davidson & Shortt (2011). In addition, it also suggests that pressure vessels should be selected based on the required end use volumes.

Pump B which was equipped with an automatic mains switch could not be operated under the pressure vessel set-up we trialled, as the switch tended to preferentially supply mains water instead of rainwater to the pressure vessel.

CONCLUSIONS

In conclusion, pumps are most energy efficient when performing at high flow rates (>25 L/min), at which energy requirements are minimised. However, limits to the flow that can be achieved are exerted by the design of water inlet valves for appliances sold in Australia, which are designed for high pressure mains water supply. It was shown that a number of options could be attempted to reduce the energy use for pumping.

- Pump selection: among the three pumps adopted – all three pumps deliver suitable service, however, pump A (0.2 kW motor capacity) had the lowest specific energy requirements. Yet, as previously shown in Hauber-Davidson & Shortt (2011), pump brand in addition to pump motor capacity needs to be considered in pump selection.
- Pressure vessels: need to be selected with consideration of the volumes required by appliances supplied with rainwater. They are effective to maintain service pressure, whilst also reducing the energy required for low volume end uses when adequately sized. However, their performance also depends on other system components such as switch type and pump capacity.
- Supply of water from header tanks by gravity are constrained by the height at which a tank can be placed and by the appliance design in Australia. Thus, their use would require modification of either of the two, which would require redesign of the building or of the appliances. They may, however, be considered for double storey housing.

Proper selection of system components could thus reduce the overall energy footprint for rainwater pumping.

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REFERENCES

Ahmed, W., Gardner, T. & Toze, S. 2011 Microbiological quality of roof-harvested rainwater and health risks: a review. *J. Environ. Qual.* **40**, 13–21.

Australian Bureau of Statistics 2010 Environmental Issues: Water Conservation, Australia, Report 4602.0.55.003, Australian Bureau of Statistics. Available from: http://www.ausstats.abs.gov.au/ausstats/subscriber.nsf/0/878BECBA37E23738CA2577DF00155293/$File/4602055003_mar%202010.pdf (accessed 10 September 2012).

Australian Government 2011 Water Efficiency Labelling and Standards (WELS) Scheme: Water efficiency. http://www.waterrating.gov.au/consumers/efficiency.html (accessed 12 September 2012).

Baguma, D., Loiskandl, W. & Jung, H. 2010 Water management, rainwater harvesting and predictive variables in rural households. *Water Resour. Manage.* **24**, 3333–3348.

Beal, C. D., Hood, B., Gardner, T., Lane, J. & Christiansen, C. 2008 Energy and water metabolism of a sustainable subdivision in South East Queensland: a reality check. In: *Proceedings Enviro 2008*, Melbourne, Australia, 5 to 7 May.

Beal, C., Stewart, R. & Huang, T. 2010 South East Queensland residential end use study: Baseline results – Winter 2010, Urban Water Research Alliance report 31, http://www.urbanwateralliance.org.au/publications/UWSRA-tr31.pdf, accessed November 2012.

Cunio, L. N. & Sproul, A. B. 2009 Low energy pumping systems for rainwater tanks. In: *Solar09- 47th Annual Conference of Australian and New Zealand Solar Energy Society (ANZSES)*, Townsville, 29 September – 22 October.

Farreny, R., Morales-Pinzón, T., Guisasola, A., Tayà, C., Rieradevall, J. & Gabarrell, X. 2011 Roof selection for rainwater harvesting: quantity and quality assessments in Spain. *Water Res.* **45**, 3245–3254.

Gardner, E. A., Millar, G. E., Christiansen, C., Vieritz, A. M. & Chapman, H. 2006 Energy and water use at a WSUD subdivision in Brisbane, Australia. *Aust. J. Water Resour.* **10** (3), 283–291.

Gikas, G. D. & Tsihrintzis, V. A. 2012 Assessment of water quality of first-flush roof runoff and harvested rainwater. *J. Hydrol.* **466–467**, 115–126.

Hall, M., West, J., Sherman, B., Lane, J. & de Haas, D. 2011 Long-term trends and opportunities for managing regional water supply and wastewater greenhouse gas emissions. *Environ. Sci. Technol.* **45** (12), 5434–5440.

Hauber-Davidson, G. & Shortt, J. 2011 Energy consumption of domestic rainwater tanks – why supplying rainwater uses more energy than it should. *Water* **38** (3), 72–76.

Hood, B., Gardner, T., Barton, R., Gardiner, R., Beal, C., Hyde, R. & Walton, C. 2010 The ecovillage at Currumbin–a model decentralised development. In: *Ozwater 2010 Proceedings*, Brisbane, Australia, 8–10 March.

Lane, J., de Haas, D. & Lant, P. 2010 Life cycle impacts on the Gold Coast urban water cycle. In: *Ozwater 2010 Proceedings*, Brisbane, Australia, 8–10 March.

Marsden Jacob Associates 2007 *The Economics of Rainwater Tanks and Alternative Water Supply Options*. Australian Conservation Foundation, Nature Conservation Council (NSW) and Environment Victoria, April.

Mendez, C. B., Klenzendorf, J. B., Afshar, B. R., Simmons, M. T., Barrett, M. E., Kinney, K. A. & Kirisits, M. J. 2011 The effect of roofing material on the quality of harvested rainwater. *Water Res.* **45** (5), 2049–2059.

Retamal, M., Glassmire, J., Abeysuriya, K., Turner, A. & White, S. 2009 The Water-Energy Nexus: Investigation into the Energy Implications of Household Rainwater Systems. Report CSIRO-Institute for Sustainable Futures, University of Technology, Sydney.

SEWL 2009 Energy consumption in domestic rainwater harvesting. Report prepared by Water Conservation Group for South East Water Limited, South East Water Limited, Australia.

SEWL 2010 Energy consumption of domestic rainwater harvesting. Report prepared by Water Conservation Group for South East Water Limited, South East Water Limited, Australia.

Standards Australia 1999 *AS 1172.2 Water Closet (WC) Pans of 6/3 L Capacity or Proven Equivalent- Part 2: Cistern*. Standards Australia, Australia.

Talebpour, M. R., Stewart, R. A., Beal, C. D., Dowling, B., Sharma, A. & Fane, S. 2011 Rainwater energy tank end usage and energy demand: a pilot study. *Water* **38** (1), 97–101.

Tjandraatmadja, G., Pollard, C., Sharma, A. & Gardner, E. 2011 Dissecting rainwater pump energy use in urban households. In: *Proceedings. Science Forum and Stakeholder Engagement: Building Linkages, Collaboration and Science Quality* (D. K. Begbie & S. L. Wakem, eds.). Urban Water Security Research Alliance, 14–15 September, Brisbane, Queensland.

Tjandraatmadja, G., Pollard, C., Sharma, A. & Gardner, E. 2012 Rainwater system design for urban residential households – the role of header tanks and pressure vessels in improving energy efficiency. In: *Proceedings. Science Forum and Stakeholder Engagement: Building Linkages, Collaboration and Science Quality* (D. K. Begbie, S. J. Kenway, S. M. Biermann & S. L. Wakem, eds.). Urban Water Security Research Alliance, Brisbane, 19–20 June, Brisbane, Australia.

Vialle, C., Sablayrolles, C., Lovera, M., Huau, M.-C. & Montrejaud-Vignoles, M. 2011 Monitoring of water quality from roof runoff: interpretation using multivariate analysis. *Water Res.* **45**, 3765–3775.

Zhou, Y. C., Shao, W. Y. & Zhang, T. Q. 2010 Analysis of rainwater harvesting system for domestic water supply in Zhoushan, China. *J. Zhejiang Univ.-Sci. A (Appl. Phys. Eng.)* **11** (5), 342–348.

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