Optimisation of Energy Use in Household Rainwater Supply Systems

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Description: Rainwater tank in South East Queensland.
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FOREWORD

Water is fundamental to our quality of life, to economic growth and to the environment. With its booming economy and growing population, Australia's South East Queensland (SEQ) region faces increasing pressure on its water resources. These pressures are compounded by the impact of climate variability and accelerating climate change.

The Urban Water Security Research Alliance, through targeted, multidisciplinary research initiatives, has been formed to address the region's emerging urban water issues.

As the largest regionally focused urban water research program in Australia, the Alliance is focused on water security and recycling, but will align research where appropriate with other water research programs such as those of other SEQ water agencies, CSIRO's Water for a Healthy Country National Research Flagship, Water Quality Research Australia, eWater CRC and the Water Services Association of Australia (WSAA).

The Alliance is a partnership between the Queensland Government, CSIRO's Water for a Healthy Country National Research Flagship, The University of Queensland and Griffith University. It brings new research capacity to SEQ, tailored to tackling existing and anticipated future risks, assumptions and uncertainties facing water supply strategy. It is a $50 million partnership over five years.

Alliance research is examining fundamental issues necessary to deliver the region's water needs, including:

- ensuring the reliability and safety of recycled water systems.
- advising on infrastructure and technology for the recycling of wastewater and stormwater.
- building scientific knowledge into the management of health and safety risks in the water supply system.
- increasing community confidence in the future of water supply.

This report is part of a series summarising the output from the Urban Water Security Research Alliance. All reports and additional information about the Alliance can be found at http://www.urbanwateralliance.org.au/about.html.

C. Davis

Chris Davis
Chair, Urban Water Security Research Alliance

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EXECUTIVE SUMMARY

Rainwater tanks in urban areas are one of the strategies to reduce the overall mains water consumption in households, and are currently mandated for new dwellings in South Australia and New South Wales; and were mandated in South East Queensland (SEQ) from 2007 up to January 2013. Rainwater tanks were also promoted across the country via rebate schemes up to 2011. Whilst the effectiveness of rainwater tanks in saving mains water is now well recognised, (Beal *et al.* 2011; Chong *et al.* 2011, 2012; Umapathi *et al.* 2012) limited characterisation has been conducted on the energy usage with rainwater supply.

The energy usage by rainwater supply systems reported in the literature has a wide spread of figures. Desktop studies typically assumed between 0.9 to 2.3 kilowatt-hours per kilolitre (kWh/kL) of rainwater supplied, however, in-situ studies conducted in Australia since 2003 have shown that, in individual households, the energy spread is much larger, ranging from 0.4 kWh/kL to 11.6 kWh/kL. In comparison, traditional potable water supply from catchment reservoirs, which is often gravity assisted, is much less energy intensive than rainwater supply, requiring less than 0.9 kWh/kL. Other alternative potable water supplies, such as indirect potable reuse and desalinated water, require more than 2.8 kWh/kL.

The large spread in energy usage for rainwater supply systems suggests that there is a potential to reduce the energy requirements for such systems, and hence opportunities to optimise the design of rainwater supply systems should be explored. One key challenge has been comparing the outcomes from the various studies in view of the diversity of rainwater supply system configurations, components and water use patterns.

To objectively evaluate the energy needs for rainwater supply in residential settings for urban areas and the performance of the range of systems used for rainwater supply, evaluation of their performance in a comparable and reproducible environment is required.

At the CSIRO laboratories in Melbourne, the energy performance of a variety of rainwater supply systems was evaluated by monitoring the supply of rainwater to a purpose built “model house” with common household appliances operated under controlled conditions. The project aimed to understand the impact of various system components and configurations for rainwater and to optimise the design of rainwater systems for energy use.

To achieve this, we reviewed the literature on energy requirements for rainwater supply, policies and guidelines on rainwater tank set-up for residential dwellings. This was followed by the experimental examination of a range of common system configurations in the laboratory. In summary, the research examined:

- A sample of new dwelling floor plans and tank set-up to determine location and pipeline diameters and lengths typically adopted;
- Pump types available in the Australian market and commonly used in households;
- Service requirements (flow, volume and pressure) for typical household water end uses;
- The operating characteristics of fixed speed external and submersible pumps and their impact on the rainwater supply system in a dwelling;
- Combinations of pumps of various sizes, pressure switches and automatic mains switches, pressure vessels, header tanks and infrastructure variation, to determine their impact on service conditions and energy requirements for rainwater supply to a dwelling; and
- The costs associated with the various configurations.

The results indicate that optimisation of residential rainwater pumping systems can be achieved as there is a mismatch between water end use requirements and typical pump best operating performance, particularly in urban areas with mandated tanks. The following conclusions are made based on the investigations:

Mismatch between rainwater end uses and the pump operating requirements

- Domestic appliances and fittings are currently designed for high water efficiency, i.e. the total volume and/or flow rate of water supply is restricted by design. This applies to appliances that are typically supplied by rainwater (toilet cistern and washing machines). Appliances also have minimum water pressure requirements for operation.
- When constant speed pumps are operating in their best efficiency range, their energy requirements are at a minimum. Such a range occurs at high flow rates (>20 L/min) for those types of pump typically installed in urban dwellings. In contrast, the majority of household water end uses occurs at low water flows (e.g., toilet cistern 4-6 L/min, washing machine 9-14 L/min), causing pumps to operate in the low energy efficiency range.

Need to further develop an understanding of pump energy requirements

- Energy efficiency varies with pump type, capacity and manufacturer. The relationship between the energy used for water delivery by a pump (i.e., the specific energy of water supply in units of kWh/kL) versus flow rate can be used to compare end use requirements and energy efficiency.
- Reduction in pumping energy can be achieved by either increasing the flow rate requirements for the end uses (appliances) or by using pumps that have the lowest energy requirements for the required service provision.
- Correct pump sizing and informed selection of system components could improve energy efficiency significantly to values of around 1.5 kWh/kL, which would make rainwater the least energy intensive alternative water source compared to desalination and indirect potable reuse.

Need for increased focus on rainwater supply system design as a unit

- The typical rainwater system configuration adopted in urban dwellings is the direct supply from a tank to the various household end uses via a submersible or external fixed speed pump. Header tanks and pressure vessels are not usually installed in rainwater systems for urban dwellings.
- Design of the rainwater pumping system and proper selection of ancillary components can help to reduce the energy usage for rainwater pumping. To achieve optimal energy usage for rainwater supply, it is necessary to understand the operation and limitations of the various system components.
- Header tanks followed by gravity supply had a marked reduction on the pumping energy to a dwelling. However, this set-up, where a header tank is placed in the roof cavity of a single storey dwelling, generates insufficient pressure for the operation of solenoids and valves in washing machines and toilet cisterns. Hence this configuration is unable to meet the minimum operating pressure requirements for appliances currently available in the market. Adoption of header tanks and gravity feed systems could be revisited if manufacturers redesign appliances with water inlet valves suitable for low pressure/flow supply.
- Pressure vessels, if properly sized, have the potential to reduce the energy consumption and maintain suitable pressure and flow for appliances. They reduce the frequency of pump activation for low-flow, low-volume, high-energy intensity water requirements, whilst maintaining system pressure when properly sized. In selecting a pressure vessel, it is necessary to match the volume of water released to the end use water requirements. Pump settings will also impact the volume of water released from pressure vessels and should be further explored in discussions with manufacturers. For the configurations we examined, pressure vessels had to be installed with pumps that adopted pressure switches, as the automatic rainwater to mains supply switching valve malfunctioned, by-passing the rainwater supply and thereby favouring mains water use to fill the pressure vessel.

Increase access to information on rainwater systems and their components

- There is a significant gap in awareness of and information on the energy aspects of rainwater systems at present. Overall, increasing access to the information on how system components operate and the water requirements of the various appliances in urban dwellings is the most effective available tool to improve the design of rainwater systems for energy efficiency. This would create opportunities for design improvement to pumps and overall rainwater tank supply systems, development of better guidelines and customer advocacy, and reduce the energy and environmental burden of a distributed rainwater supply.

1. INTRODUCTION

This report is an output of the Decentralised Systems Project in the Urban Water Security Research Alliance. The Decentralised Systems project is focussed on addressing knowledge gaps in the strategic planning and implementation of rainwater tanks.

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. Financial incentives and also legislation enforcing installation of rainwater tanks in new housing in various Australian jurisdictions have been key tools to promote the uptake of rainwater tanks in urban areas:

- The South East Queensland (SEQ) Water Strategy (November 2009) advocates reduction of mains water consumption for households to increase security of water supply. Rainwater tank installation and rainwater connection to outdoor and indoor non-potable uses, such as toilet flushing and/or laundry use, has been one of the most common means to achieve the mandated water savings in new dwellings. In SEQ alone, in compliance with the Queensland Development Code Part 25 MP 4.2 – Water saving target (QDC MP 4.2), approximately 50,000 homes with rainwater tanks have been built since 2007, and an additional 745,000 new dwellings with 5 kL rainwater tanks are expected by 2031[1].
- In New South Wales (NSW), under the BASIX (Building Sustainability Index) program every home requiring building approval is required to reduce its potable water and energy consumption by 40%. Installing a 5 kL rainwater tank is the most common solution to meet the water consumption target. By June 2008 alone, 45,000 homes had been built in compliance with the scheme (NSW Government 2005).
- In Victoria, the 6 star energy rating required new dwellings to install either a rainwater tank connected to a toilet, or install a solar hot water system (Building Commission Victoria 2011).
- In South Australia, since 2011 every new dwelling is required to install an additional water supply, besides mains water, connected to at least a toilet or a water heater or all cold water laundry tap outlets. This is most commonly fulfilled with a minimum 1 kL volume rainwater tank (Government of South Australia 2011).

Rainwater tank systems are effective in reducing potable water demand (Coombes *et al.* 2002, Ghisi and Ferreira 2007, Tam *et al.* 2010, Eroksuz and Rahman, 2010); but more recently, interest has increased on the energy required for rainwater supply to urban households (Apostolidis 2010, Retamal 2009).

Desktop studies on the water-energy nexus in Australia have found that the energy required for rainwater harvesting should not be taken lightly when implications to overall society were considered (Apostolidis 2010, Hall *et al.* 2011, Tam *et al.* 2010, Retamal *et al.* 2009). The energy intensity for conventional water supply to Brisbane and the Gold Coast was estimated to be respectively 0.68 and 0.21 kWh/kL in 2006–07 (Kenway *et al.* 2008). This is significantly lower than the 1.5 kWh/kL typically assumed for pumping from a rainwater tank (Hall *et al.* 2009). On the other hand, rainwater supply is less energy intensive than desalination or indirect potable reuse (IPR), which require on average 3.2 and 2.8 kWh/kL respectively (NSW LC 2006, Apostolidis 2010, Retamal *et al.* 2009, Hall *et al.* 2011) (Figure 1).

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[1] Buildings in Qld no longer have to meet compulsory water savings targets, following the repeal of laws mandating the installation of water supply systems on 1 February 2013. Previously, all new homes and commercial and industrial buildings in Queensland were required to install rainwater tanks or other water supply systems such as grey water treatment plants. Provisions have been made for local governments to opt-in to water savings requirements in recognition of Queensland's varying climatic conditions and regional circumstances. Builders in these local government areas will still need to comply with water savings requirements. Water supply systems such as rainwater tanks and grey water treatment plants can still be installed voluntarily by homeowners and builders in all areas of the state. Builders who install a water saving system (either voluntarily or to meet local government requirements) must comply with the health and safety standards set out in the Queensland Development Code Part 4.2 – Rainwater tanks and other supplementary water supply systems (for residential – class 1, 2 and 10 - buildings) and Part 4.3 – Supplementary water sources – commercial buildings (for commercial and industrial - class 3-9 - buildings). (Source: Department of Housing and Public Works, 2013.)

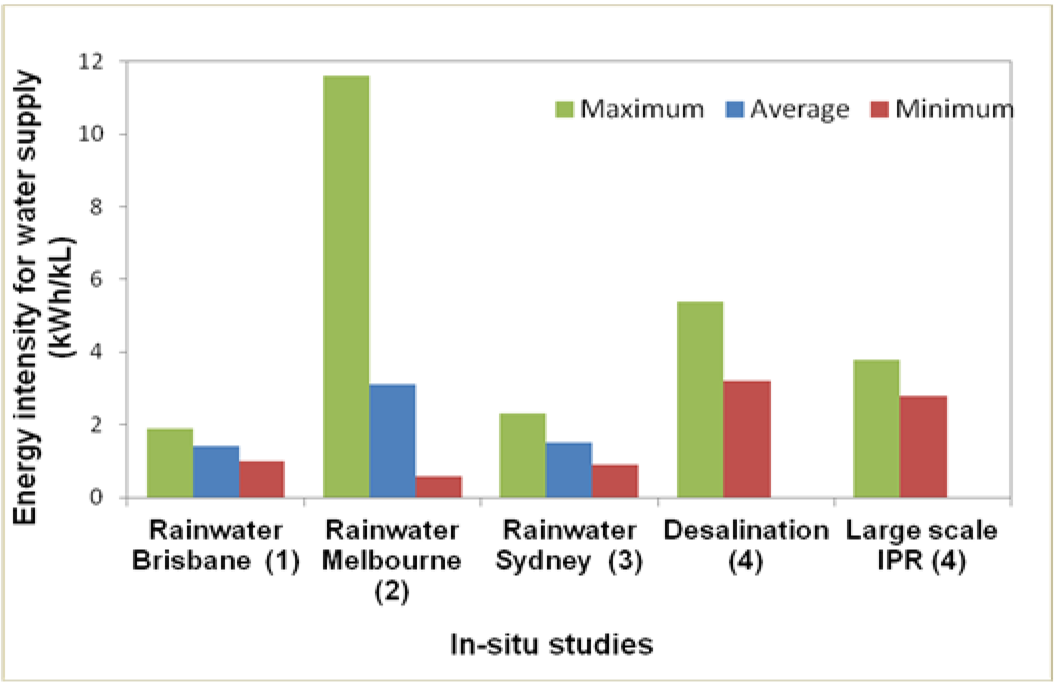

Figure 1: **Energy intensity for alternative sources of water supply. References (1) Gardner *et al.* 2006, (2) SEWL (2009), (3) Retamal *et al.* (2009), (4) NSW Government (2006).**

Hall *et al.* (2011) examined the energy requirements for areas of high rainwater tank uptake, such as SEQ, and concluded that the cumulative impact of individual "rainwater tanks might potentially consume the same amount of energy as the centralised water supply system by 2056". In addition, the uncertainty associated with rainwater supply is larger than for centralised supply. Energy estimates for centralised systems have typically an uncertainty of ± 15%, whilst for distributed rainwater supply this is typically ± 50% (Hall *et al.* 2008). Preliminary estimates for rainwater tank adoption and energy use for SEQ, indicate that, if rainwater tanks remain at the existing low energy efficiency they will contribute to about 20% of the greenhouse gas (GHG) burden of the water supply cycle, yet contributing to less than 10% of the water supply by 2056 (Hall *et al.* 2011).

In the literature, desktop studies have adopted values ranging from 0.96 kWh/kL to 2.3 kWh/kL to estimate the energy burden of rainwater harvesting (Marsden Jacob Associates, 2007, Lane *et al.* 2010, Apostolidis 2010), however, in-situ evaluation values range from 0.4 to 11 kWh/kL for individual homes (SEWL 2010).

The variability in energy requirements is associated with the various system configurations, technologies, and operation regimens adopted in urban dwellings, but limited information is available on how to optimise their performance (Beal *et al.* 2008; Retamal *et al.* 2009, SEWL 2010, Talebpour *et al.* 2011). It is also recognised that there are energy inefficiencies in the current manner rainwater harvesting schemes are set up (Apostolidis 2010, SEWL 2009, Retamal 2009).

In view of the large variability in energy associated with rainwater pumping systems and the potential impact that rainwater systems can have on the future energy requirements and GHG emissions, it is important to determine how to optimise the energy for rainwater delivery in urban areas.

However, one of the major challenges in optimising the energy used in rainwater harvesting is comparing the efficiency of the different systems in view of the various configurations of household and tank set-up and water use patterns across households, which vary with occupancy, end uses and the type of appliances adopted in each household.

2. RESEARCH OBJECTIVES AND ACTIVITIES

The main aim of the research was to understand how to minimise the energy required for water supply from rainwater tanks to households as specified under the South East Queensland (SEQ) Water Strategy, through monitoring, validation and modelling of a rainwater supply system set-up to a dwelling in a controlled and reproducible environment.

To achieve such objectives the project aimed to:

- Understand the typical service requirements for indoor and outdoor rainwater use;
- Understand the energy consumption of rainwater supply systems under the same baseline conditions;
- Determine how system configuration, including system components (accessories), storage and pipe sizes impact the overall energy consumption for rainwater pumping;
- Develop strategies to reduce the energy required for rainwater pumping; and
- Identify an optimal configuration under various supply conditions to minimise the energy requirements of rainwater systems.

By understanding the energy consumption and hydraulic performance of rainwater systems, a range of benefits could be achieved:

- The information would assist the water industry to assess with increased certainty the impact of distributed systems on the overall energy consumption and its carbon footprint;
- Allow pump and equipment manufacturers to gain more understanding of the operating requirements for pumps in urban areas and hence to optimise rainwater system design creating better products;
- Provide government and consumer advocacy groups with scientifically based evidence on the performance of rainwater systems;
- Allow regulatory and planning agencies to assess the impact of distributed rainwater systems on energy and GHG mitigation policies based on scientific information; and
- Assist the public to better understand the energy consumption and associated costs of their systems and hence to make more informed choices in the selection of their rainwater systems.

The key research activities undertaken included a review of the scientific literature, examination of standards and guidelines for determination of the status of knowledge on rainwater systems configurations, typical set-up and energy performance. The review was also used to select the system configurations and options for verification in the laboratory. The research activities described in this report include:

- Section 3 - Background: Review of literature on rainwater tank uptake, legislation, design and state of knowledge on rainwater supply and the energy associated with rainwater supply and end use needs;
- Section 4 - Experimental Methodology: Description of the experimental set-up and methodology adopted for energy evaluation;
- Section 5 - Results and discussion: covers the gamut of rainwater system components and their performance;
- Section 6 – Energy consumption at households;
- Section 7 – Implications to policy; and
- Section 8 – Conclusions and recommendations.

Appendices, supplementary material and a list of references are included at the end of the report.

3. BACKGROUND

3.1. Rainwater Tank Uptake

Rainwater harvesting and storage is adopted in many countries around the world (Ahmed *et al.* 2011, Farreny *et al.* 2011, Mendez *et al.* 2011). Adoption is typically driven by necessity, either due to lack of access to mains water or by the need for increased sustainability and security of water supply at households (Baguma *et al.* 2010, Han 2010). Historically in urban cities around the world, when a reliable supply of mains water becomes available, rainwater harvesting at the household becomes obsolete and is superseded. However, in many countries, such as Australia, rainwater tanks are finding renewed acceptance in urban areas and their uptake has been promoted through legislation and rebate schemes (Queensland Government 2005).

In Australia, rainwater tank uptake has increased markedly, in particular in high population growth areas across Queensland (see Figure 2). From 2007 to 2009, the uptake of rainwater tanks in Queensland increased by 15.9%, with rainwater tanks installed in 38% of households (Australian Bureau of Statistics 2007; Australian Bureau of Statistics 2009). Brisbane experienced the largest uptake with rainwater tanks in 43% of suitable dwellings (Australian Bureau of Statistics 2010), whilst in SEQ over 36% of detached dwellings have rainwater tanks. Rebate programs contributed to over 230,000 domestic rainwater tanks installed between 2006 and 2008 (Queensland Government 2005). From 2007 to 2010, QDC MP4.2 resulted in an additional 30,000 tanks installed in new homes (Gardiner 2010). Rainwater tank uptake was highest in new dwellings, with 57% of new houses less than 1 year old connected to a rainwater tank (Australian Bureau of Statistics 2010). In 2005, it was estimated that by 2026, an additional 575,000 new dwellings would be required within the State and, at the time of writing this report, each of them is likely to have a mandated tank (Queensland Government 2005). However, in February 2013, the MP4.2 requirements for alternative water supplies for new dwellings, such as rainwater tanks, were removed from the QDC[2].

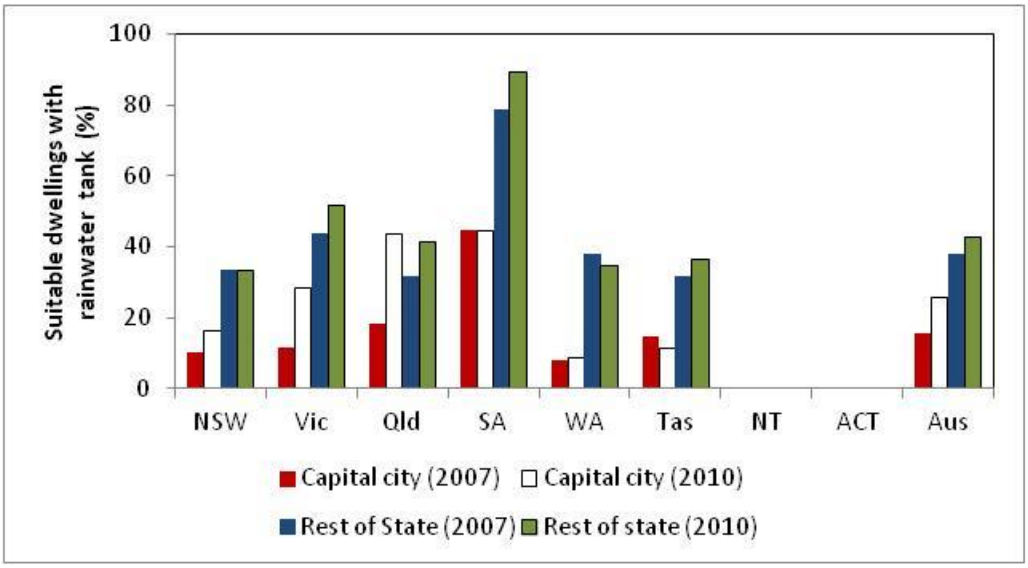

Figure 2: Installation of rainwater tanks in capital cities across Australia (ABS 2010).

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[2] Buildings in Qld no longer have to meet compulsory water savings targets, following the repeal of laws mandating the installation of water supply systems on 1 February 2013.

3.2. Legislation and Guidelines on Rainwater Tanks

Across Australia legislation on rainwater tanks has focused on tank uptake, compliance with standards for product manufacture and installation, and monitoring for public health observance.

3.2.1. Uptake

In Queensland, the installation of rainwater tanks and the allowable rainwater uses in new dwellings was promulgated in the Queensland Development Code MP4.2 (Queensland Government, 2009). This code requires new dwellings to achieve minimum water saving targets, which are most commonly achieved by the installation of 5 kL rainwater tanks (see footnotes 1 and 2).

Rainwater tanks are the easiest means to achieve the mandated water demand reductions in new housing in New South Wales (NSW Government, 2005) and South Australia (Government of South Australia, 2011).

Across other jurisdictions, uptake of rainwater tanks in dwellings has been mainly voluntary. In Victoria, the Six Star Standard for new dwellings allows the option of installing either a rainwater tank connected to toilet or a solar hot water system (Building Commission of Victoria 2011). Up to June 2011, most capital cities also offered rebate programs for installation of an internally plumbed rainwater tank to existing dwellings (ACT Government 2011, Queensland Government 2011, Government of South Australia 2011, Northern Territory Government 2007, State Government of Victoria 2011, NSW Government 2011, Water Corporation 2011, Hobart City Council 2011). In addition, the Commonwealth government also offered rebates for rainwater tanks systems retrofitted to existing residences up to November 2011 through its National Rainwater and Greywater Initiative (Australian government 2009, Commonwealth of Australia 2011)

3.2.2. Standards

Minimum standards apply to individual system components such as rainwater tanks materials, pumps and valves for product durability and operating requirements. A summary of standard requirements is provided in Appendix A. In addition, a range of plumbing products used in rainwater systems are also required to be independently certified under the Watermark program to demonstrate compliance with the standards.

3.2.3. System Design and Installation

The *Rainwater tank design and installation handbook -HB230A* is the most comprehensive document on rainwater system design, installation and operation in Australia (Standards Australia 2008). Relevant sections of the guidelines have been incorporated in a number of building, construction and plumbing codes across the country to promote adherence to installation guidelines.

HB-230A outlines the basic requirements for rainwater design, installation and connection to a dwelling, certification requirements and maintenance advice. The document also outlines the relevant standard requirements, e.g. materials of construction, and the relevant guidelines adopted in each jurisdiction across Australia. The handbook offers advice on pump location, typical rainwater usage and performance based on required flow rates, pressure ranges and electrical safety. However, the handbook offers no specific guidelines on pump selection regarding energy consumption.

Likewise, the various building codes across Australia (Table 1), aimed at increasing the sustainability of housing stock, focus on the uptake of rainwater tanks for reduction of water consumption and do not consider the energy associated with rainwater pumping.

Table 1: Sustainable housing rating systems in Australia (Standards Australia 2008).

State/Territory	System	Website
National	Building Code of Australia	www.nabers.com.au
ACT	Requirements for sustainable water management	www.actpla.act.gov.au/topics/design_build/siting/water_efficiency
NSW	BASIX	www.basix.nsw.gov.au
Qld	Building Code of Queensland	www.hpw.qld.gov.au/construction/BuildingPlumbing/Building/WaterSupplySystems/Pages/default.aspx
SA	Building sustainability and efficiency, Planning SA	www.planning.sa.gov.au/go/rainwater-tanks
Vic	5 Star Standard	www.5starhouse.vic.gov.au/
WA	Five Star plus	www.5starplus.wa.gov.au/
Tas	Check with local regulatory authority	
NT	Check with local regulatory authority	www.nt.gov.au/infrastructure/bss/strategies/buildingcode.shtml

A similar scenario is observed internationally, with the majority of the literature on rainwater tanks focused on water savings. Uptake of rainwater tanks in urban centres is also promoted in Japan, parts of the USA, Germany, parts of India, etc (Herrman and Schmida 2000).

Internationally, the focus of most codes and guidelines is on water quality and treatment needs, as well as design and installation of the system for maximising rainwater recovery. Typically none of the guidelines examined address energy optimisation for rainwater pumps.

3.3. Rainwater Systems in Urban Areas

A wide range of options are available for the configuration of a rainwater system. As this paper focuses mainly on the energy associated with water pumping, it will examine only the rainwater supply from the tank to the dwelling, and ignore the collection of rainwater from the roof which is typically gravity based.

The range of system components that can be adopted in a rainwater supply system is exemplified in Table 2. The system configurations created by combining pumps, switching valves, back-up systems, ancillaries and end uses are numerous and various combinations have been observed in-situ around Australia (Retamal *et al.* 2009, Cunio and Sproul 2009, SEWL 2009, Umapathi *et al.* 2012).

Retamal *et al.* (2009) provides a review of key system components and configurations adopted in rainwater supply. The most common systems observed in greenfield urban areas are fixed speed pumps (either external or submersible) with a trickle top-up or automatic switching valve accessing the mains water back-up system.

Table 2: Rainwater system components for pumping water to households (Retamal *et al.* 2009, Standards Australia 2008).

System Components	Examples
Tank	Manufactured in a range of materials (polymer, sheet metal, concrete); shapes (round, slimline, bladder, etc) and self-standing or underground
Pumps	Fixed speed external, fixed speed submersible, variable speed, jet pump, venturi pump, etc
Switches	Pressure switch, differential flow switch
Mains back-up	Trickle-top into tank, automatic mains switching valve
Pipelines	Polyethylene (diameter 19 mm) Copper (diameter 19mm)
Ancillaries	Pressure vessel Header tank (uncommon in urban Australia) Water treatment: reverse osmosis, filters, UV disinfection
End use connections	Outdoor tap Indoor type I: toilet cistern, laundry/washing machine Indoor type II: hot water system, dishwasher, shower, other potable

3.3.1. Pumps and Switches

Pumps are typically sold with a pump activation switch as a package. Three major types of switches are available; (a) pressure switches, (a) level switches and (c) differential flow switches. Pressure switches are activated by a drop in pressure in the system. The cut-in pressure is pre-set by the manufacturer at the factory. Level switches are typically mounted in submersible pumps and are designed to activate the pump if the water level in the tank falls below a threshold value. Differential flow switches are installed in automatic rainwater-to-mains back-up switch systems. They measure the flow in the rainwater supply line and switch between mains water or tank water based on the availability of rainwater.

Pumps range in type (mechanism), brands and motor capacities (or maximum water delivery capacity). The most common pump types adopted in urban areas are fixed speed external and submersible pumps. Other pumps types (variable speed drive, venturi and jet stream) are much less commonly used, and tend to be more costly (Retamal *et al.* 2009). Variable speed drives (VSD) adjust the speed of the pump to match the energy required to the delivery of required flow rate (Retamal *et al.* 2009). They are usually sold as larger capacity pumps (kW) which attract a higher price premium.

Retamal *et al.* (2009) and Hauber-Davidson and Shortt (2011) verified that different pump types had different specific energy requirements. Figure 3 illustrates the variability in energy associated with various pump types (external, variable speed and submersible) (Retamal *et al.* 2009). Two dwellings using pumps with VSD drives were examined in Retamal *et al.* (2009). Suprisingly, the energy intensities recorded were 50% higher compared to a dwelling with a fixed speed pump. In addition, it was not possible to distinguish the impact of the VSD alone as other factors such as occupancy, water use, system configuration, etc differed amongst the dwellings (Retamal *et al.* 2009).

In SEWL (2011) a comparison was made of a single pump (Davey HM60-10) with and without a VSD. The VSD reduced the specific energy required for operation of the pump by 15%, but the stand-by energy exceeded the reduction in operating energy (SEWL 2010).

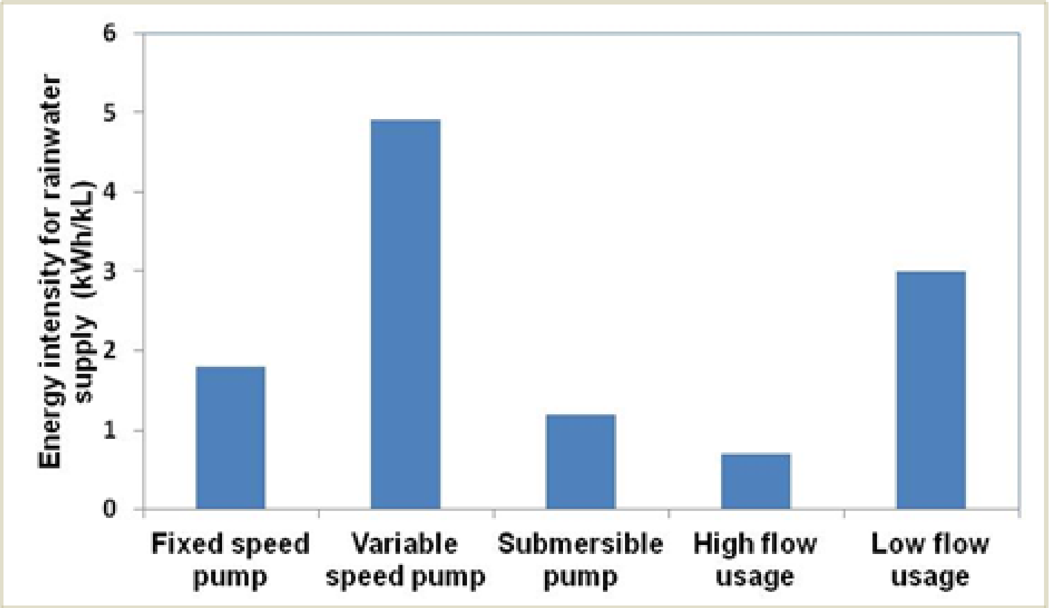


Figure 3: **Variation in specific energy use by rainwater supply pumps installed in Sydney homes (Retamal *et al.* 2009).**

Hauber-Davidson and Shortt (2011) and SEWL (2010), tested a sample of eight different pumps and verified that pump design also had a significant effect, and that different brand pumps with similar motor capacity (kW) could at times display very different energy requirements (kWh/kL).

Pump size also matters. Cunio and Sproul (2009) showed that under-sizing a pump runs the risk of limiting the supply service. They showed that a small pump (0.18 kW motor) was unable to provide sufficient pressure to fill a toilet cistern in a rural dwelling.

We examined the pumps adopted in a sample of 50 dwellings monitored across Australia by various researchers (Beal *et al.* 2008, Gardner *et al.* 2008, Retamal *et al.* 2009, SEWL 2009 and 2010). Figure 4 shows that the pumps ranged in motor capacity from 0.25 kW to 1.25 kW. In particular, the most common pump sizes were in the ranges of 0.41 to 0.6 kW and 0.61 to 0.81 kW, corresponding to 44% and 33% of the sample size respectively.

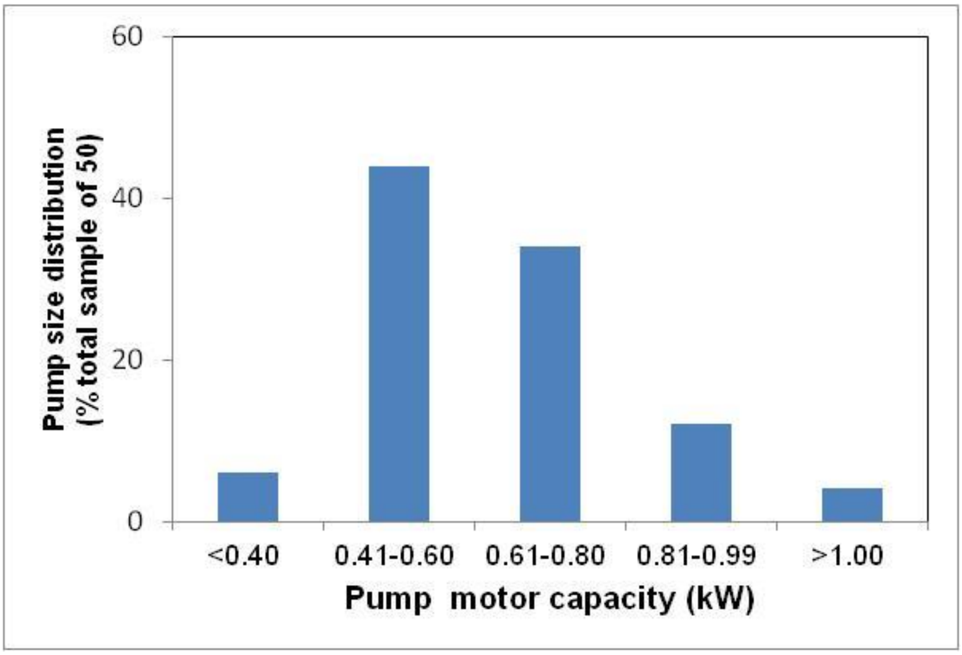


Figure 4: Motor capacity of pumps installed in 50 dwellings from Australian in-situ studies.

3.3.2. Pipelines

Polyethylene pipe (3/4 inches or 19 mm diameter) is the predominant material adopted for connection from a rainwater tank to end uses in a dwelling because of its lower cost compared to copper pipe. The length of pipe and the path from the tank to the dwelling is determined by the location of the tank at the property and the dwelling configuration. Despite examination of the literature and attempts to consult large building companies, no information was available on the location of tanks and the range of lengths of pipe used.

Therefore, to establish a baseline for our experimental examination we estimated the length of pipe from a rainwater tank to a dwelling by examining the floor plans of thirty entry level single floor dwellings sold in Queensland and New South Wales. The assumptions adopted and the estimation procedure is outlined in the Appendix B. Tanks were located as close to the dwelling as permitted. The mean length of pipe from a rainwater tank to the closest end use was 22.9 ± 9.6 m and the range verified was 2 to 44.8m.

The pumping energy associated with friction losses in infrastructure is influenced by flow path characteristics (number of bends, constrictions, length, diameter), pipe material, fluid type and velocity, and can be estimated using the Darcy-Weisbach equation (equation 1) (Sinnott *et al.* 2005).

$$\Delta p = \lambda(L/d)(\rho\ V^2/2) \qquad \text{Equation 1}$$

Where:

Δp	Pressure loss (Pa)
λ	D'Arcy Weisbach friction coefficient
d	Pipe internal diameter (m)
L	Pipe length (m)
ρ	Fluid density (kg/m^3)
V	fluid velocity (m/s)

Retamal *et al.* (2009) estimated that infrastructure pipe friction losses would in theory be minor and contribute on average only 2% of energy losses in pumping systems. On the other hand, Cunio and Sproul (2009) verified that shifting from a high pressure system (0.45 kW pump) with 19mm diameter pipe to low pressure pumps (0.18 and 0.22 kW) with 40mm diameter pipe could increase pumping efficiency by over 50% (from 1.7 to 0.79 kWh/kL) for supply to a toilet cistern. Whilst they did not verify the influence of pipe size and pump size separately, they also estimated that by increasing pipe diameter from 12.5mm to 25mm diameter, a system with 20m length had the potential to reduce power use by 95% (Cunio and Sproul 2008).

3.3.3. Ancillaries

A number of ancillary devices can be incorporated into a rainwater supply system. Examples include pressure vessels and, if water is used for potable uses in a dwelling, water treatment devices.

Ancillary devices such as pressure vessels and header tanks are expected in theory to reduce the overall energy required for pumping rainwater (Retamal *et al.* 2009). However characterisation of the benefits derived from the addition of such components to a system have been challenging to quantify in-situ.

Pressure Vessels

A pressure vessel is designed to release a certain volume of water whilst maintaining the pressure in the line from the pump to the vessel above a threshold value, preventing the activation of the pump for small events such as filling a glass. They are commonly incorporated in systems with variable speed drive pumps. Use of pressure vessels with fixed speed pumps is also possible, but it is not a common configuration observed in new dwellings with mandated tanks urban areas.

Retamal *et al.* (2009) examined the overall energy consumed for dwellings having pressure vessels. Hauber-Davidson and Shortt (2011) evaluated the impact of a 5 L pressure vessel on the energy consumption for supplying rainwater to selected end uses (toilet cistern, front loader washing machine, shower head and garden hose) in a two storey dwelling.

Retamal *et al.* (2009) monitored three pressure vessel set-ups: two dwellings with 8 L pressure vessels (Newcastle, Concord) and one with a 50 L pressure vessel (Enmore). The dwelling in Enmore adopted a fixed speed pump and was tested with and without the 50 L pressure vessel. It experienced a 32% reduction in overall energy intensity with the pressure vessel. However, the volume of water used during the monitored period had also changed by 10% during the two monitored periods. Hence, the authors concluded that the savings between the two periods could not be compared as water use and volume patterns differed. The impact of the pressure vessel on the other two dwellings could not be isolated due to the impact of other system variables, as both dwellings were equipped with variable speed pumps.

Hauber-Davidson and Shortt examined a system with a 5 L pressure vessel that provided low volumes of water (1 to 2 L) before the pump started (Hauber-Davidson and Shortt 2011). They concluded that the energy reduction from the 5 L pressure vessel was not significant for such a small size vessel. Larger size pressure vessels were not trialled in their study.

In summary, further investigation is required to understand the full extent of energy savings and also the level of service that a pressure vessel would provide.

Header Tanks

Header tanks are commonly used in a range of Asian countries for water supply, but they are not usually adopted in Australian cities. Most researchers expect that the adoption of a header tank will significantly reduce the pumping energy. However this set-up has to be verified experimentally for the common range of appliances adopting rainwater (Retamal *et al.* 2009, Cunio and Sproul 2009, Hauber-Davidson and Shott 2011).

Rainwater Filtration

Water treatment devices such as filter cartridges, reverse osmosis and UV disinfection devices are adopted when water is used for potable purposes mainly and are usually not common in non-potable urban systems. SEWL (2010) reported an increase in resistance to pumping as rainwater filters became clogged, but they did not report the value of the change.

3.4. Rainwater End Uses

Rainwater tanks are traditionally adopted in rural areas and on remote properties in Australia as the sole supply of water for all applications in the dwelling, including drinking. In urban areas, rainwater use is promoted for non-potable applications, such as outdoor uses, supply of washing machine cold water and filling of toilet cisterns, as shown in Table 3 and Table 4. Rainwater end uses vary across the country, partly due to the end uses promoted in each State, but also because of household characteristics, time of construction, home owner motivation and preferences (Gardiner *et al.* 2008, Gardiner 2009). Note that SA is the only state that promotes rainwater for hot water systems.

The pattern and flow rate of water use in a dwelling has a marked influence on pumping energy requirements. Retamal *et al.* (2009) estimated that the energy intensity associated with individual end uses varied from 0.4 to 2.9 kWh/KL for pumps with motor capacity between 0.5 to 0.9 kW. Talebpour *et al.* (2011) examined the energy associated with individual end uses in five dwellings in the Gold Coast equipped with the popular Davey pump and Rainbank switch and measured energy intensities from 1.04 to 1.67 kWh/kL from irrigation to toilet flushing respectively (see Table 8). Hauber-Davidson and Shortt (2011) determined the energy associated with the operation of a washing machine, trigger spray, toilet cistern and hot-cold water mixing and found specific energies ranging from 1.13 to 4.73 kWh/kL. All three studies realised that the flow rate associated with end uses influenced the energy intensity of pump operation, with low flow end uses typically using more energy per kL than high flow uses.

Thus, it is necessary to understand how water is used in a dwelling to understand its impact on pump operation and energy use. Data on the specific end uses of water is scarce. Majority of studies reporting end use report the total volume of water use in a dwelling over time. For example, across Australia, overall water consumption is reported to range from 112 to 169 L/p/d (litres per person per day) based on studies conducted since 2000 (Roberts, 2005; Mead 2008; Willis *et al.* 2009a,b in Beal *et al.* 2010; Beal *et al.* 2010, Umapathi *et al.* 2012). Recently, Beal *et al.* (2010) examined the water use pattern of a sample of 252 houses in the Gold Coast, Brisbane, Ipswich and Sunshine Coast during the winter of 2010 and established that the average household and per capita consumption for SEQ were 370.7 L/hh/d (litres per household per day) or 145.3 L/p/d. However, there were some differences between local government areas, particularly for showers, leaks and irrigation, which were attributed to differences in water restriction levels. The largest end uses observed were shower, tap and clothes washer at respectively 42.7 L/p/d, 27.5 L/p/d and 31 L/p/d. Their sample did not include households with internally plumbed rainwater tanks. Another study, Umapathi *et al.* (2012), recorded a slightly lower consumption rate of 139 L/p/d for a sample of 20 dwellings from April to November 2011.

Table 3: Allowable rainwater end uses according to legislation across Australia.

Jurisdiction	Application	Reference
Commonwealth	From March 2009, home owners were eligible for rebates of $400 to $500 for the installation of a rainwater tank connected to a toilet and/or laundry of an existing home.	National Rainwater and Greywater Initiative http://www.raincycle.com.au/img/files/factsheet.pdf
ACT	Since 31 March 2008, new buildings, redevelopments or extensions need to meet 40% water efficiency target. Options include rainwater tanks connected to at least to toilet, laundry cold water and all external uses. Rebate for connection to either toilet and/or laundry.	ACTPLA http://www.actpla.act.gov.au/topics/design_build/siting/water_efficiency http://www.watertankco.com.au/rebates.html#TAS
NSW	Developments need to achieve up to 40% reduction in potable water depending on climatic zone under BASIX. A rainwater tank is required for all new developments. The rainwater tank can be connected to toilets, garden and lawns, laundry, all hot water, pool (if required) and spa (if required) and drinking. The first three options are the most commonly selected. NSW health does not recommend use for drinking. Rebates for connection to toilet and washing machine.	BASIX (www.basix.nsw.gov.au)
Qld	Buildings connected to reticulated town supply have the option to achieve target water savings by use of a rainwater tank, a greywater system, an alternative water substitution measure or a combination of the above. Acceptable uses for rainwater include connection to toilet cistern and wash machine cold taps, other uses are subject to local government discretion. As from 1 March 2006, councils have the option to mandate rainwater tanks for new houses in their region.	Queensland Development Code MP 4.2 http://www.dsdip.qld.gov.au/resources/laws/queensland-development-code/current-parts/mp-4-2-water-savings-targets.pdf
SA	Since 1 July 2006, all new dwellings (or extensions >50m^2) are required to have additional water supply to supplement mains water. This added water supply has to be plumbed to a toilet, to a water heater or to all cold water outlets in the laundry of a new home. Rebates for retrofit to toilet, clothes washing or hot water supply.	Building sustainability and efficiency Planning SA http://www.planning.sa.gov.au/go/rainwater-tanks
Tas	Rebate for connection to toilet.	http://www.watertankco.com.au/rebates.html#TAS
Vic	Since 1 July 2005, all new houses (or extensions >25% of existing floor area or >1000m^2 whichever is lesser) are required to have either a rainwater tank for toilet flushing or a solar hot water system. Rebate for connection to toilet.	5 Star Standard www.buildingcommission.com.au http://www.buildingcommission.com.au/resources/documents/14161_BC_5_Star_House_c13.pdf
WA	No specific rainwater tank regulation, check with local council regulations. No rebates for indoor connections.	Five Star Plus www.5starplus.wa,giv.au
NT	No specific rainwater tank regulation, check with local council regulations. Rebate for connection to toilet or washing machine by GreenPlumber (Alice Springs and Central Australia)	http://www.nt.gov.au/lands/building/index.shtml

Table 4: Summary of recommended rainwater end uses in Australia.

Jurisdiction	Outdoor / Garden	Toilet	Laundry Cold Water	Hot Water System	Comments
ACT	√	√	√		Rebate for toilet and/or laundry
NSW	√	√	√		Rebate for toilet and/or washing machine
NT					No specific rainwater tank regulation, check with local council regulations. Rebate for connection to toilet or washing machine by GreenPlumber (Alice Springs and Central Australia)
SA	√	√	√	√	Rebates for retrofit.
Tas	√	√			Rebate for connection to toilet
Qld	√	√	√		Other uses subject to council discretion.
Vic	√	√			Option of rainwater to toilet or solar hot water system
WA					No specific rainwater tank regulation, check with local council regulations. No rebates for indoor connections.

Other studies on rainwater end use in SEQ include Gardiner *et al.* (2008), Gardiner (2009) and Talebpour *et al.* (2011). Figure 5 compares the type of rainwater end uses in urban areas for retrofit and mandated tanks in greenfield areas in SEQ from a survey of 600 residents in peri-urban, retrofit and greenfield developments reported in Gardiner *et al.* (2008). At the time, over 58% of tank owners used rainwater for garden irrigation, whilst laundry, washing machine and toilet flushing had a lower and more variable uptake among urban dwellers (Gardiner *et al.* 2008).

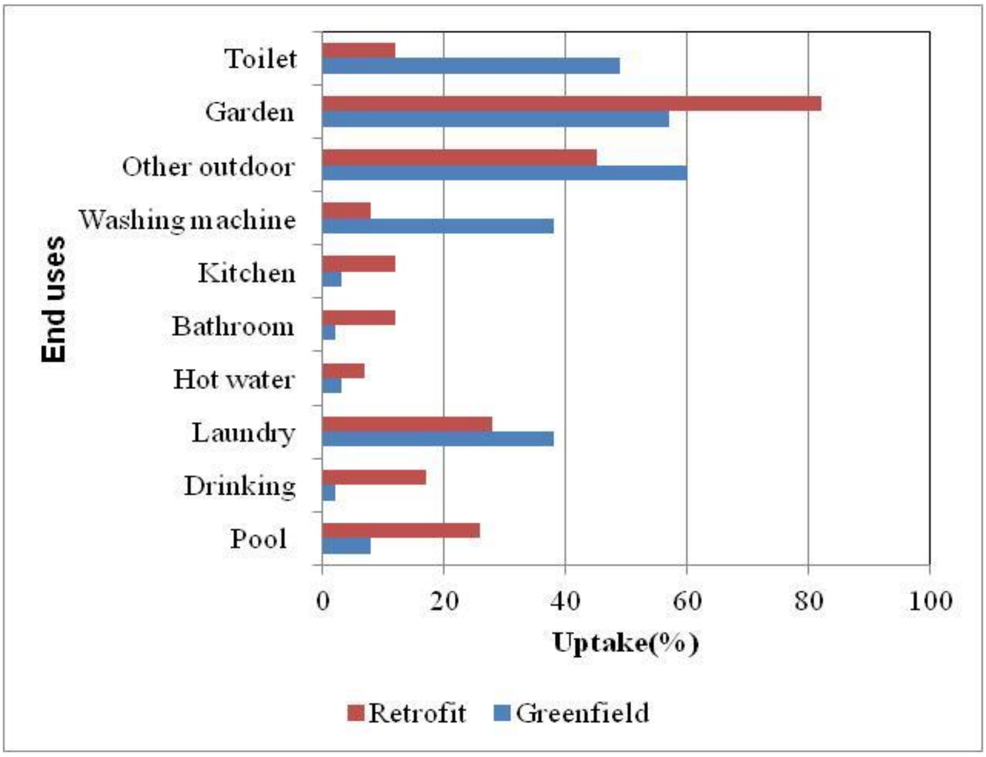


Figure 5: End uses of rainwater tank (adapted from Gardiner *et al.* 2008).

In the greenfield developments, rainwater was commonly adopted for outdoor end uses, toilet cistern filling and washing machine/laundry by respectively over 58%, 48% and 38% of tank owners, as shown in Figure 5. In retrofitted dwellings, over 80% used rainwater for outdoor end use, but less than 30% and 10% of the sample used rainwater for toilet flushing and washing machine supply respectively.

In contrast, a more recent study, Talebpour *et al.* (2011), quantified the rainwater use from five dwellings with 5 kL rainwater tanks in the Gold Coast. In their sample, the largest volumes of rainwater use were, in decreasing order, clothes washing, toilet and irrigation which corresponded to 71%, 23% and 6% of the total volume of rainwater consumed (915 L for the period of mid-October to Early November 2009).

3.5. Water Efficiency in Australia

Although pumps have been adopted for many years in Australia, the water supply service requirements in Australian dwellings have changed over time and thus are likely to impact pump operation. Since the early 2000s there has been a shift towards increased water efficiency in dwellings. The Water Efficiency and Labelling Scheme (WELS), is a national rating scheme developed to assist consumers to compare the relative water efficiency of water appliances and fittings sold in Australia, and to provide manufacturers with incentives to improve the water efficiency of their products. Since its introduction in 2005 (http://www.waterrating.gov.au/index.html) water using appliances and fittings have been designed for increased water efficiency. Since 1 November 2011, the independent Watermark certification has become a mandatory prerequisite for WELS registration of showers, tap equipment and flow controllers across the country, thus consolidating the promotion of high water efficiency in water using appliances.

As a result, water requirements for household end uses are defined within specific volume and flow limits dictated by design constraints to increase water efficiency. This applies to the flow rates of fittings such as taps, showerheads and irrigation devices (Australian Government 2011). Likewise, household appliances, such as washing machines, toilet cisterns and dishwashers are designed to operate within a specific range of flow and pressure conditions. Table 5 shows the typical design pressure and flow rates for fittings and some common household appliances sold in Australia. The data was obtained by examination of the technical specifications for a range of appliances sold in Australia. For instance, the water inlet valves in a washing machine require a minimum operating pressure ranging from 40 to 100 kPa depending on appliance make and model, whilst a toilet cistern inlet valve is typically designed to function at pressures between 35 to 50 kPa. Flow from a water efficient (four to six star WELS) tap is restricted from 2 L/min to 7 L/min (Australian Government 2011).

As a result, new housing stock will have much lower flow and volume requirements for water supply compared to pre-2006 dwellings, although the actual flow rates are unknown.

Table 5: Design parameters for appliance operation.

Appliance	Minimum Pressure (kPa)	Maximum Pressure (kPa) or flow (L/min)	Reference
Washing machine	40-100[2]	800-1000[2]	Products technical specifications
Dishwasher	30-150[2]	800-1000[2]	Products technical specifications
Toilet cistern	35-50[1] (conventional) 25 (for low pressure valves)	400[1]	Standards Australia (1999)
Tap (WELS 4-6 stars)	n.a.	15-18 L/min (standard) 2-7L/min (WELS)	Australian Government (2011)
Shower head		15-25L/min (standard) 6-7L/min (3stars)	Australian Government (2011)

Note: 1 Standards Australia test conditions for water inlet valve performance assessment. 2 Manufacturer's technical specifications for 7 appliance brands in Australia.

3.6. Characteristics of Household Appliances

The pattern and duration of water supply will influence the energy requirements for pumps. Each individual end use has a characteristic pattern of water supply (Table 6). A washing machine and a dishwasher typically require multiple water supply events during a wash cycle, which causes a pump to start multiple times. Hand washing and toilet cistern filling are single continuous water supply events of short duration. Showering tends to vary between single and multiple events of variable duration (Roberts, 2005).

Cunio and Sproul (2009), Talebpour *et al.* (2011) and SEWL (2010) examined the energy associated with a range of specific rainwater end uses which are shown in Table 7. Once again system set-up, pumps adopted and experimental conditions across the studies varied, making comparison difficult.

Table 6: Water use pattern for domestic water using appliances and fittings.

Appliance	Water Use Pattern	Water Consumption (L)	Source
Washing machine	Multiple events of variable duration	5 - 30 L/kg load (WELS) > 30L/kg load (non-WELS)	Commonwealth of Australia (2010)
Dishwasher	Multiple events for short duration	Not determined	Products technical specifications
Toilet cistern	Single event	Dual flush 9/4.5L, 6/3L and 4.5/3L (WELS) Single flush 10 L(pre-2006)	Standards Australia (1999)
Tap (WELS 4-6 stars)	Single event	Standard 15-18^2 Hand basin: 3.3^1. Kitchen sink: 19.4^1 Laundry through:26^1 Automatic irrigation devices: 9 Hand held trigger: 7-12 Manual hose: >16 (pre-WELS)	Australian Government (2011)
Shower head	Single event	7.6-10 (WELS) 6-20 (pre-2006)	Australian Government (2011)

Note: 1. Typical flow rate during use (Roberts 2005), 2. Design Capacity (Australian Government 2011), 3. Manufacturer's technical specifications for 7 appliance brands in Australia.

Table 7: Analysis of energy associated with specific end uses.

	Specific Energy for End Use (kWh/kL)		
Reference	Cunio and Sproul (2008)	SEWL (2010)	Talebpour *et al.* (2011)
Setting	One rural dwelling with a range of pumps and infrastructure combinations	One urban dwelling with range of pumps and toilet cisterns	One urban dwelling with system not-specified -single event
Toilet Cistern	0.071 to 1.7 depending on pump and infrastructure set-up combination	Full-flush toilet 1.38 (one run) Half flush toilet 1.28 (one run) Sinker valve with Davey HP45-05/Torium switch 1.5 Float arm valve with Davey HP45-05/Torium switch 4.3	Full-flush toilet 1.52 Half flush toilet 1.67
Washing Machine		Front loader with Onga SMH35/Water switch 1.13	1.09
Irrigation		2.27- 4.73 Trigger spray gun with SilverStorm 800W	Long irrigation 1.037 Short irrigation 1.040

3.7. Energy Requirements for Rainwater Pumping

Whilst there is extensive literature on rainwater tanks, there is limited literature on the energy requirements for rainwater tanks. Energy for water supply is typically expressed in kilowatt-hours per kilolitre of water supplied (kWh/kL). As previously explained in section 1, whilst a number of studies have examined the energy associated with rainwater systems from a macro perspective (city-wide and larger) using desktop studies, limited experimental research has been carried on the actual characterisation of such systems. Recent in-situ studies on the energy required for rainwater supply to households in Australia are summarised in Table 8.

Table 8: Recent Australian studies on energy for rainwater supply to individual households.

Reference	Case Study Set-Up	Details	Energy for Rainwater Supply (kWh/kL)
Marsden Jacob Associates (2007)		Desktop study	0.956
Hall *et al.(2011)*		Desktop study	1.6
Apostolidis (2010)		Desktop study	2.0
Lane *et al.* (2010)		Desktop study	2.3
Gardner *et al.* (2006) Beal *et al.* (2008)	4-6 houses in Payne Rd, The Gap, Queensland, Australia	Individual raintank with submersible pumps (0.45kW) at each household and a communal rainwater tank for fire fighting and top-up. End use: all water needs.	2.1 – 3.8
Retamal *et al.* (2009)	8 houses in Sydney and Newcastle, New South Wales, Australia	Each house was fitted with a fitted with a different system including: Venturi jet, variable speed drive pump, fixed speed pump, submersible pump, pressure vessel and mains switch or trickle top switch. End uses varied from house to house.	0.9 – 2.3
Cunio and Sproul (2009)	1 house	Application of various pumps (conventional low pressure and medium pressure) End use: toilet cistern only 2 Scenarios: (i) Pumps with 19mm diameter pipe, (ii) Pumps with 40mm diameter pipe, (iii) Pump and header tank.	0.04 – 1.7
SEWL (2009)	31 houses in Melbourne, Victoria, Australia. Including detailed water use for 11 houses.	Each house was fitted with a different system including: fixed speed pump, submersible pump, and mains switch or trickle top switch. End uses varied from house to house.	0.59 – 11.61 (average 1.98)
SEWL (2010)	1 house (2 storeys) in New South Wales	8 pumps (above ground and submersible), pressure controllers, rain-to-main switches, variable speed control drive, pressure vessel (5-10L). End uses: Toilet cistern, front loader washing machine, shower and trigger spray garden hose.	0.4 – 1.6
Hood *et al.* (2010)	40 houses in Currumbin Ecovillage, Queensland	Mix of 1, 2 and 3 bedroom houses. Pump type usually a fixed speed Davey. Rainwater used for all household uses.	1.4 (median)
Talebpour *et al.* (2011)	5 dwellings in Gold Coast	All dwellings had a Davey pump and Rainbank switch. Rainwater was used for clothes washer, irrigation and toilet.	1.04-1.67 per end use type
Umapathi *et al.* (2012)	20 dwellings in SEQ	Pump system not specified but usually above ground with a switching valve to mains. Rainwater used for toilet, laundry, external.	1.59 (average)

Gardner *et al.* (2006) and Beal *et al.* (2008) studied the energy for rainwater pumping for 4 to 6 high-value properties in Queensland (2.1-3.8 kWh/kL rainwater); Hood *et al.* (2010) examined the energy use in 40 houses in an ecovillage (1.4 kWh/kL) in Queensland; Retamal *et al.* (2009) examined energy consumption for eight houses with various rainwater system configurations in New South Wales (energy use 0.9-2.3 kWh/kL); Hauber-Davidson and Shortt (2011) and SEWL (2009) measured the energy use for 31 houses in Victoria (0.59-11.61 kWh/kL). In a recent study, Umapathi *et al.* (2012) examined the rainwater usage and energy requirements for its delivery and estimated an average energy of supply of 1.59 kWh/kL for 20 households across SEQ.

In summary, the energy for rainwater pumping reported in those studies ranged from 0.59 to 11.6 kWh/kL of rainwater, however the median was less than 3 kWh/kL indicating a large variability in the energy for supply of rainwater to urban dwellings. However, the dwellings monitored in those studies differed in system set-up, number of occupants, dwelling characteristics (e.g. single or double storey) and, most importantly, end uses. All these factors influence the energy requirements for pumping rainwater to individual dwellings: rainwater end uses, pump characteristics, infrastructure losses, water use patterns and system configuration (Retamal *et al.* 2009).

Retamal *et al.* (2009) also remarked, when discussing jet pumps, that many of the pump and distribution technologies available have been initially developed for non-household applications which operate at very different hydraulic regimens from indoor water use. As a result, although such technologies might be energy efficient for their intended application, they might not operate optimally in household settings.

Optimisation of the energy for rainwater systems requires the analysis of the overall rainwater supply system, as multiple factors impact the energy performance of a system as summarised in Figure 6.

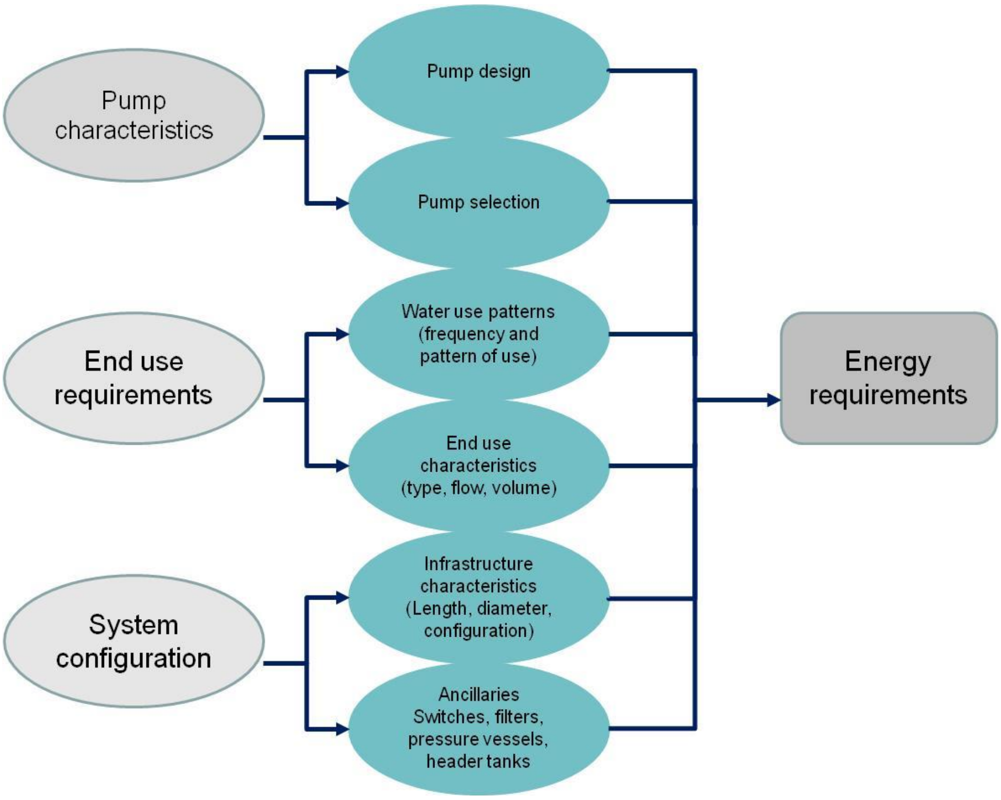


Figure 6: Summary of factors impacting energy consumption of rainwater pumping systems.

In the resurgence of pumps in urban areas, consideration needs to be given to the changed water use requirements and end uses compared to dwellings which are solely dependent on rainwater. The options for a rainwater system configuration include a wide range of pumps types, motor sizes, switches and ancillary devices which can be tailored for a diversity of combinations of end uses, appliance types and characteristics and water use patterns.

The benefits that can be achieved from the incorporation of the various components into a rainwater pumping system are still to be fully understood, given the wide array of combinations that can be achieved for rainwater systems. Are header tanks the ultimate low energy supply system and can they provide suitable level of service with energy savings? What energy reduction can larger capacity pressure vessels achieve? Are there real advantages in increasing piping size?

The next section describes a laboratory based evaluation of rainwater supply systems where a reproducible water demand is replicated for a number of system configurations, and system performance is monitored to understand the energy consumption of rainwater systems.

4. EXPERIMENTAL METHODOLOGY

The experimental evaluation of energy and water usage for rainwater supply was conducted at the CSIRO laboratory, at Highett, Victoria. A purpose built model house was constructed to simulate a single storey dwelling with a rainwater tank. This laboratory set-up allowed the implementation of a range of permutations of pumps, ancillary devices, switches, infrastructure length and configurations.

4.1. Experimental Set-Up

The system set-up adopted for energy evaluation is shown in the diagram in Figure 7. A house frame was constructed for evaluation of energy associated with rainwater supply. Rainwater was supplied from an 850 L tank to a set of common household appliances using a range of pumps. Alternative paths could be used from the tank to the appliances: (i) Direct connection to appliances; (ii) Connection to appliances via a pressure vessel; and (iii) Connection to appliances via a header tank. All water used on the site was recycled back to the rainwater tank to minimise water use. Rig dimensions are detailed in the Appendices. Images of the actual laboratory set-up are shown in Figure 8.

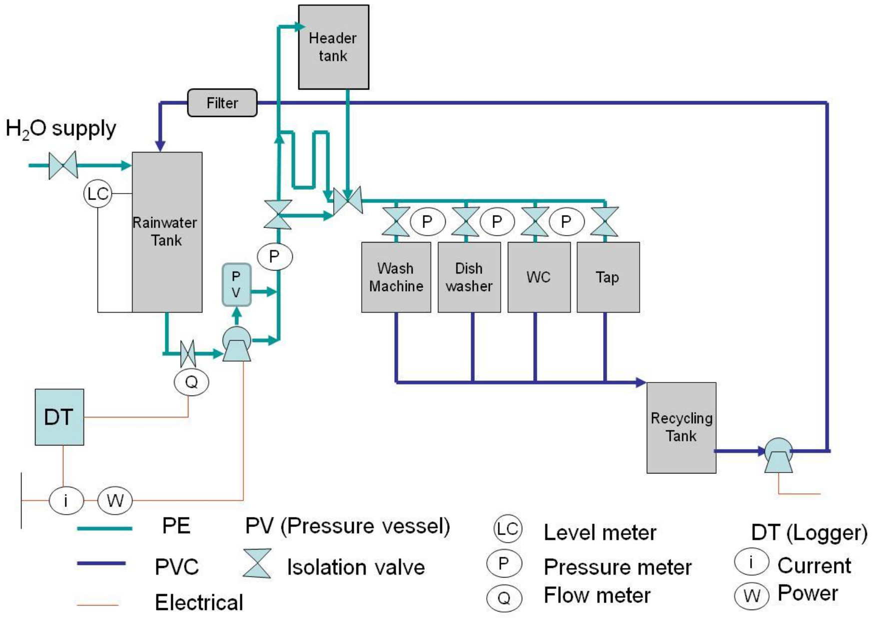


Figure 7: **Diagram of rainwater system used for experimental evaluation.**

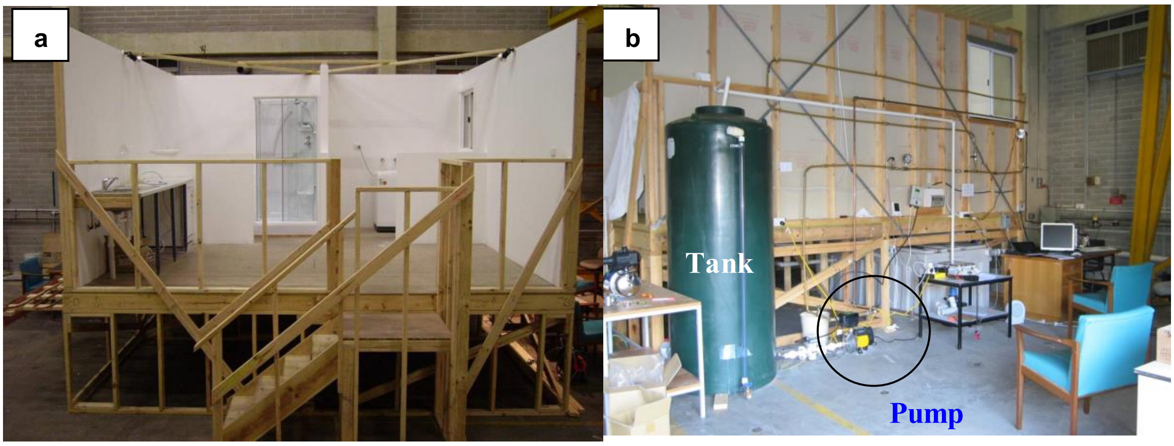


Figure 8: **(a) Household set-up at the CSIRO laboratory; (b) Rainwater supply, pump and pipework at side wall of household.**

The water supply infrastructure was constructed with 19mm polyethylene pipe Sharkbite PN16. Polyethylene pipe is the most common material adopted for new housing water supply in Australia. At the outlet of the pump, the pipe system had a bifurcation that allowed either direct flow from the pump to the appliances or passage through a pressure vessel before connection to the appliances.

Appliances receiving rainwater included washing machines, a dishwasher, a toilet cistern (dual flush) and a tap. Characteristics of the appliances and pipe lengths adopted are provided in Table 11 in section 4.2.3. The system could be supplied with tank water or with mains water. When connected to water mains the baseline pressure was 650 kPa.

Monitoring equipment details are outlined in Table 9. Pressure and flow within the water system and the energy consumed by the pump were monitored in real time at intervals of 0.2s and logged every 1s. An electromagnetic flow meter located between the outlet of the rainwater tank and the inlet of the pump was used to measure the flow rate and the volume of water delivered to the household. A Campbell Scientific data logger was used to record the energy consumption of the pump and the pressure in the pipeline. Energy consumption was measured using energy and voltage transducers. Pressure transducers were used to measure the pressure in the system after the pump outlet, and at the interface between the supply system and the pipe inlet to each appliance.

Table 9: Monitoring equipment.

Parameter	Brand	Accuracy
Flow	ABB Magnetic flowmeter	± 0.008mA ± 0.16% of reading/20°C
Pressure	ABB 2699T pressure transducers Gem 2200 Pressure transducers	±0.15 % FSD ±0.25 % FSD
Power and current	AWT190 AC power transducer LEM AC current transducer	Class 0.2 (AS1384-1973) ± 0.5%
Datalogging	Campbell CR100 datalogger Datataker 500	Minimum recording interval 0.2s

4.2. Equipment

4.2.1. Rainwater Tank

The rainwater tank supplied to the model house was an 850 L polypropylene tank equipped with a level indicator.

4.2.2. Pumps

Various external pumps of various power capacities were tested and their characteristics are shown in Table 10. The pumps include three external fixed pumps with various motor output capacities (0.2 kW, 0.55 kW and 0.75 kW) and a submersible pump (0.65 kW). They were designated as pumps A, B, C and D in the study.

Pumps A, C and D were purchased with pre-installed pressure switches. Pump B was purchased with an automatic rainwater to mains switch, and was also tested with a pressure switch of the same manufacturer.

Table 10: **Rainwater pump characteristics.**

Pump	Manufacturer	Description	Control Device	Motor Output	Flow (L/min)	Settings (kPa)	Recommended Applications
A	Davey	Single stage jet assisted centrifugal pump	Pressure switch	0.2kW (output) 31m 6m (lift) 6m (suction)	25 @140kPa	140 (cut-in) 280 (cut-out)	Pressurising drinking water from rainwater tanks Small weekenders, cottages
B	Universal	Multistage centrifugal pump	Automatic switch from rainwater tank to mains supply Pressure switch	0.77kW (input) 0.55kW (output) 33m 7m(lift) 7m (suction)	80	450 (max)	Domestic water supply, irrigation, water transfer
C	Davey	Jet pump	Pressure switch	0.75kW 45m	48	Not specified	Water supply
D	Davey	Submersible pump	Pressure switch	0.94kW (input) 0.60kW (output) 32m 32m	130	Not specified	Water supply

Note: Input power is the power required to operate a pump, Output power is the mechanical power of the water at the pump outlet.

4.2.3. Appliances

Household appliances supplied with rainwater included a top loading washing machine, a front loading washing machine, a dishwasher, a dual flush toilet cistern and a tap (Figure 9). Their photos and characteristics are shown in Figure 9 and Table 11 respectively

Figure 9: **Appliances used in the evaluation.**

Table 11: Details of appliances used for rainwater investigation.

Appliance	Model	Details	Pipe Length from Pump Outlet (m)
Washing Machine Top Loader	LG WT H55TH Turbo drum	Capacity 5.5 kg Water use 113 L/wash WELS 4 stars Energy rating678 kWh/365 uses (warm) 81 kWh/365 uses (cold)	9.6
Washing Machine Front Loader	LG WD11020D	Capacity 7 kg Water use 45 L/wash WELS 4.5 stars Energy rating 4 (280 kWh pa) P (100-800 kPa)	9.6
Dishwasher	Conia CDW 1211	Water use: 16 L/wash WELS 2.5 stars	14.7
Toilet	Not applicable	Dual cistern 6 L/Full flush 3 L/Half flush WELS 2 stars	9.3
Tap	Not applicable	Up to 35 L/min	10.6

4.3. System Configuration

The rainwater system configurations examined are outlined in Table 12. These include combinations of pump types, switches, with and without pressure vessels of various sizes, header tanks and pipe infrastructure of variable length and diameter. The systems adopted were:

- Rainwater supplied by a fixed speed external pump (0.2, 0.55 or 0.75 kW) with direct connection to end uses using standard infrastructure (19mm diameter and maximum length 17m). This is the most common configuration observed in dwellings. Configuration 1 is with pressure switches and configuration 2 is with an automatic rainwater to mains switch. The operation of these switches was previously explained in section 3.3.1. Configuration 2 was examined only with pump B.
- Rainwater supplied by a fixed speed submersible pump (capacity 0.65 kW) controlled by pressure switch and direct connection to end uses (configuration 3) using standard infrastructure (19mm diameter and maximum length 17m).
- Rainwater supplied by a fixed speed external pump (0.2, 0.55 or 0.75 kW) via pressure vessels of various sizes to the end uses (configuration 4) using standard infrastructure (19mm diameter).
- Rainwater supplied by a fixed speed external pump (0.2, 0.55 or 0.75 kW) to a header tank. The pipe diameter from the pump to the header tank was (a) 19mm or (b) 25mm diameter. The header tank supplies water by gravity to the end uses (configurations 5 and 6).

Table 12: System configurations examined.

Number	Name	Components				
		Pump Type	Switch	Pressure Vessel	Header Tank	Infrastructure
1	External pump	External (0.2, 0.55, 0.75kW)	Pressure switch			DN 18mm Length 17m
2	External pump + mains switching valve	External (0.55kW)	Automatic mains switch			DN 18mm Length 17m
3	Submersible pump	Submersible (0.65kW)	Pressure switch			DN 18mm Length 17m
4	Pressure vessel	External (0.2, 0.55, 0.75kW)	Pressure switch	8-80L		DN 18mm Length 17m
5	Header tank	External (0.2, 0.55,0.75kW)	Both		300L	DN 18mm
6	Header tank + larger pipe	External (0.2, 0.55,0.75kW)	Both		300L	DN 25mm

4.4. Methodology for End Use Evaluation

Appliances were operated individually one at a time or simultaneously in combinations of two, three and four at a time. Power consumption by the pump, water flow rate and pressure in the system were recorded at 0.2 second intervals in real time for each appliance run.

End use activities analysed include:

- Operation at various flows dictated by tap, including hand washing;
- Toilet cistern filling after half and full flush;
- Dishwasher operation at various settings; and
- Washing machine operation at various settings.

Each test was performed multiple times (n = 5-10). Data was analysed using Matlab® and Excel® to identify pump operation and used to estimate mean energy usage patterns and the characteristics of the system. The total energy required for each run was determined by integration of the energy monitoring data. Analysis of pump start-up, operation and over-run phases (see section 5.1 and Figure 13 for a description of each phase) during pump operation was also performed for individual appliance runs.

For analysis of friction losses, pressures at the start of the system and at connection to each appliance were measured at 1 second intervals for each run, and compared with theoretical values for flow losses.

The relationship between specific energy and flow rate was determined by controlling the flow rate at the laundry tub tap and measuring the energy requirements for water supply for each pump operating at constant flow for intervals of one to two minutes.

4.5. Methodology for Pressure Vessel Evaluation

Four pressure vessels of nominal capacities of 8, 18, 40 and 80 L were examined. Their characteristics are shown in Table 13 and Figure 10.

Each pressure vessel's operation was characterised by: pump operation, flow rate, pressure, volume of water provided by the pump to fill the pressure vessel. Each individual pressure vessel was characterised for its holding capacity, i.e. the maximum volume of water that the vessel can hold, and its release capacity, i.e. the volume of water provided by the vessel prior to pump activation.

The optimal internal pressure for each header tank was also examined by measuring the volume of water released at various pre-set values.

Table 13: Pressure vessel characteristics.

Brand	Nominal Capacity (L)	Factory Set Pressure (kPa)	Recommended Maximum Operating Pressure (kPa)
Lowara	8	175	1000
Lowara	18	137	1000
Pressurewave	40	190	1000
Onga Aqua Pack plus APP80	80	137	690

Figure 10: **Pressure vessels examined: 8L, 18L, 40L and 80L nominal capacity.**

4.6. Methodology for Header Tank Evaluation

A header tank was constructed using a 300 litre poly water tank with a float control valve for the rainwater inlet from the pump. The header tank was installed at a height of 2.7m from the floor of the dwelling, as shown in Figure 11. This height was equivalent to the height of the ceiling beams in the roof of a single storey dwelling. The minimum ceiling height for habitable rooms is 2.4m (BCA 2011). The tank chosen could fit into the ceiling vault of a single storey dwelling and provided an effective volume of 257 L, sufficient to supply all the appliances requirements in a household. Two different diameter (19mm and 25mm) polyethylene pipes were adopted for the supply line from the pump to the header tank.

The pump operation during the filling of the header tank was monitored for flow rate and energy use. The header tank supplied water by gravity to a toilet cistern and a laundry tap. Pipe infrastructure from the header tank to appliances followed the ceiling contours. Level of service conditions were monitored by verification of the time required for filling the toilet cistern and the flow to the laundry tap.

The toilet cistern fill time under gravity was also tested after substitution of the original inlet flow valve (requiring > 50kPa) with a special low pressure inlet flow valve (operating pressure 15kPa).

Figure 11: 300L header tank used in the analysis. It was located 2.7m above house floor level.

4.7. Methodology for Infrastructure Loss Evaluation

The energy losses attributed to friction from travel through the pipe network were estimated for each appliance run. The standard pipe configuration had a total length of 17m from the tank to the end uses. This value was selected after estimation of the potential infrastructure length range of 2 to 44.8m for rainwater supply in new dwellings (Appendix B).

4.8. Methodology for Estimation of Energy Requirements for Rainwater Supply to a Household

To gain an understanding of the energy used for pumping rainwater to a dwelling over time, the energy consumption to supply rainwater to a household was estimated assuming a range of end-uses, frequencies and the use of pump configurations. Assumptions adopted were:

- Dwelling with 4 inhabitants;
- Rainwater supplied with pump B or C;

- Weekly end use patterns were obtained from average appliance use frequencies from Athuralya *et al.* (2008):
    - Toilet cistern fill 2.7 times per person per day;
    - Washing machine 5.4 times per week;
    - Irrigation: 20 L/min for 20min at 2 times per week;
    - Laundry tap: 20 L/min for 1min once per day;
    - Tap basin: 9.4l/min for 0.25s at 3.5 times per day per person; and
    - Shower: 9.6L/min for 4 minutes per person per day.

For simplification purposes, it was assumed that each appliance was operated as a stand-alone (no simultaneous appliance operation), which does not always apply in an actual dwelling. Athuralya and colleagues have also shown that a distribution applies to the frequency at which different appliances are used (Athuralya *et al* 2008). Thus, our calculations produce a more conservative energy estimate (i.e. the pump is assumed to operate more often).

5. RESULTS AND DISCUSSION

5.1. Pump Operation

Pump operation during rainwater supply was initially characterised in Retamal *et al.* (2009). The pump is activated as a tap or valve is opened, causing a drop in pressure in the system. The typical operation cycle for a fixed speed pump is comprised of three stages, illustrated in Figure 12:

(a) Start-up: triggered by a drop in pressure associated with an end-use. This is characterised by a spike in power associated with the initial start-up of the pump. Energy is drawn to overcome the inertia in the system causing a brief peak in power consumption and flow increases. The spike in power was observed to last less than 0.5 seconds in all runs examined.

(b) Operation or constant flow: the pump provides water at a steady state. Fflow rate, pressure and power consumption are constant during this stage.

(c) Over-run: when the flow ceases, the pump continues running to re-pressurise the line to stand-by pressure (set by the pump's manufacturer).

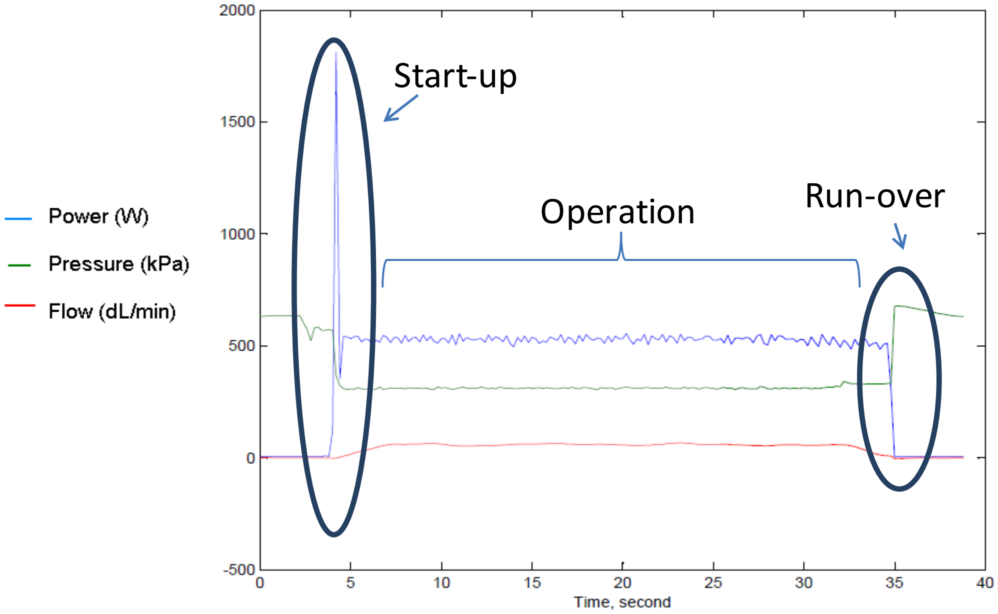


Figure 12: Typical pump operating profile.

The energy used for the start-up, operation and over-run stages by a pump depends on the design characteristics of each individual pump and the end use conditions, including how many times the pump starts, the duration of each run and the flow and pressure service requirements. For shorter events, the contribution of the start-up and run-over stages will be larger than for longer events when the operation phase is dominant. This is shown for the filling of a washing machine and a dishwasher in Figure 13, and will be further explained as we examine the pattern of water supply and pump operation for specific end uses in the following sections.

Figure 13 shows that the relative contribution of the start-up and over-run stages to the total energy consumed during the wash is much smaller for the washing machine than for the dishwasher. This is because a top loader washing machine uses on average 113 L/wash and a dishwasher 16 L/wash. Hence, the pump operates for much longer in the flow stage to deliver the larger volume of water required by the washing machine.

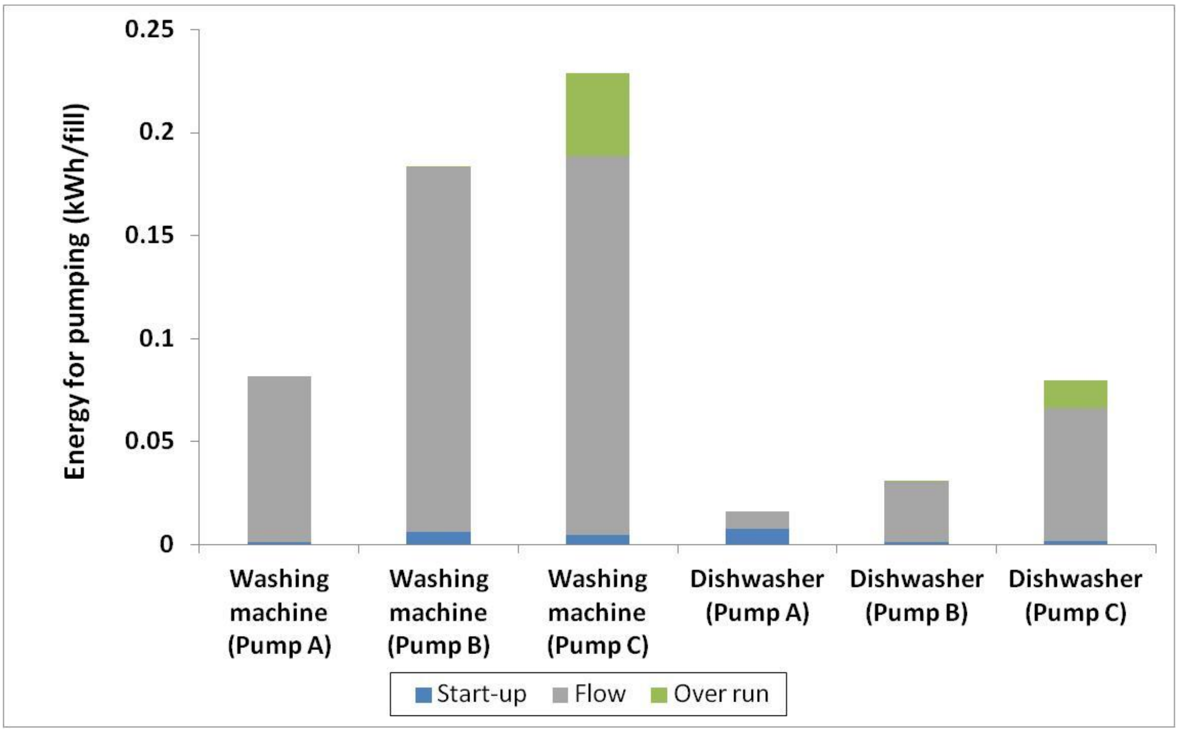


Figure 13: **Energy distribution for filling a top loader washing machine and a dishwasher.**

5.2. Energy of Rainwater Delivery

The energy associated with rainwater supply was examined for five pump systems directly connected to the end uses:

(a) External pump A (motor capacity 0.2 kW) with pressure switch;

(b) External pump B (motor capacity 0.55 kW) with pressure switch;

(c) External pump B (motor capacity 0.55 kW) with automatic mains switch;

(d) External pump C (motor capacity 0.75 kW) with pressure switch;

(e) Submersible pump D (motor capacity 0.60 kW) with pressure switch.

The relationship between the specific energy of water supply in kWh/kL is shown in Figure 14 for the five pump systems. Each pump system displayed a distinct energy vs. flow curve, with the larger capacity pumps C (0.75 kW) and D (0.60 kW) having a higher energy requirements than the smaller capacity pumps: A (0.20 kW) and B (0.55 kW).

Figure 14 shows that the lowest energy for water delivery occurs at flow rates larger than 22 L/min for each of the five pump systems examined. Thus, energy for pumping can be minimised by operating the pump at high flow rates within this optimal energy efficiency range. On other hand, as flow rate is reduced, the difference in energy requirements for the different pumps increases, clearly differentiating the energy performance of the different capacity pumps.

That is, under similar supply conditions, the larger capacity pumps C and D will have higher specific energy requirements than the smaller capacity pumps, particularly for flows of less than 22 L/min.

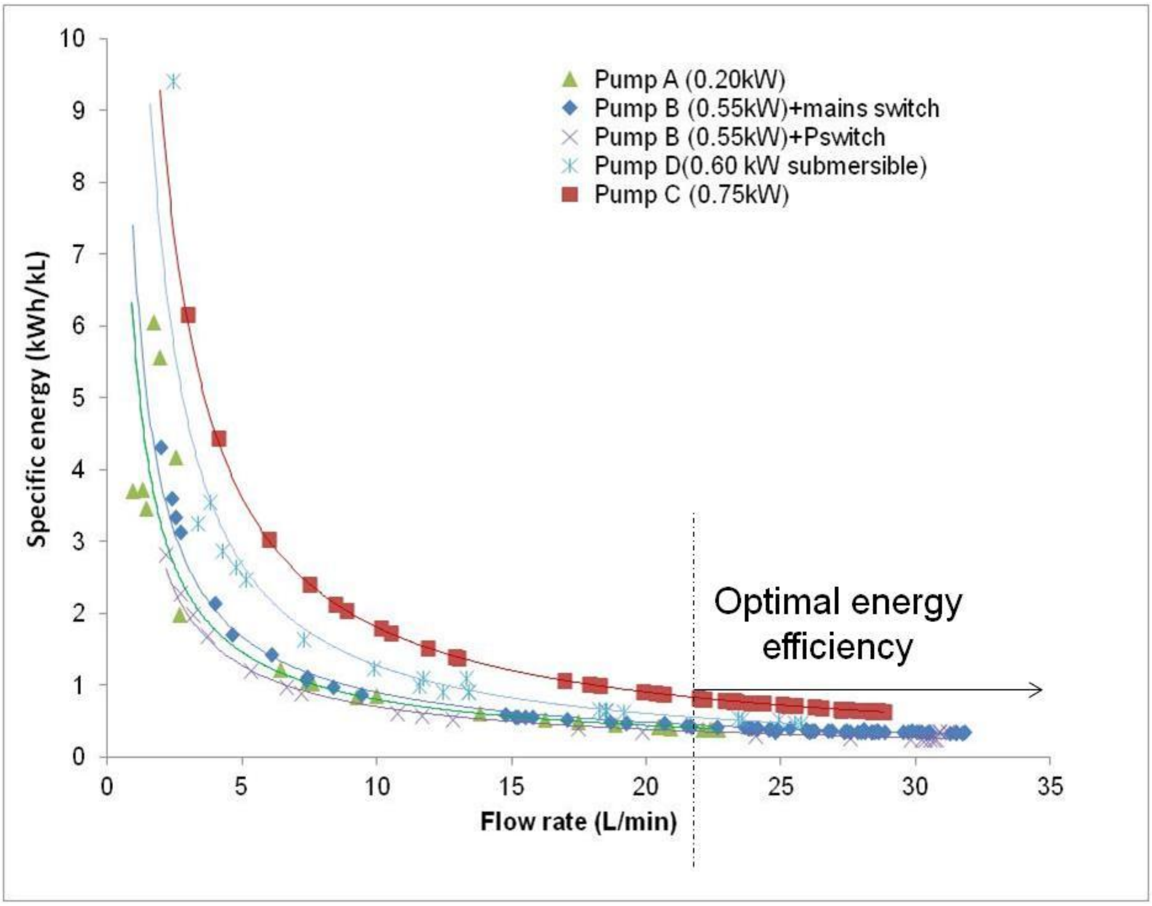


Figure 14: **Relationship between specific energy and flow rate for rainwater supply in the system.**

5.3. Pump Operation for Specific End Uses

The number of times a pump starts, the duration of its operation, and the flow and volume of water supplied will vary with the water use pattern for each individual appliance and with the pump settings.

Therefore, rainwater supply to a range of specific household end uses was examined. End uses examined included tap use, filling a toilet cistern, filling a washing machine and filling a dishwasher. The typical pattern of water supply during operation of the individual appliances examined is shown in Figure 15. However, these can also vary depending on individual appliance brands, models and programs selected.

5.3.1. Top and Front Loading Washing Machine

The duration of the washing machine cycles, the volumes of water delivered and the pattern of delivery for top and front loaders differ as shown in Figure 15 (a) and (b).

The top loader was equipped with an automatic sensor that adjusted the water volume to the weight of the laundry placed in the machine. A laundry load of 5.5 kg was adopted in the trials, and used 125 ± 30 L of water per wash. Its wash cycle was characterised by two to three major water supply episodes of 40 ± 18 L, and four to five small water top-up episodes when water was added to the washing machine tub. A wash cycle lasted on average 75 minutes under the normal program, with the rainwater pump operating on average for 21 ± 4 min.

The front loader used 2/3 less water, 43 ± 2 L per wash. The wash cycle was characterised by three to four water supply episodes of 11 ± 0.5 L each and up to five small injections of water. A wash cycle lasted on average between 45 to 60 minutes, with the rainwater pump operating on average for 5 ± 2 min.

5.3.2. Dishwasher

Water was supplied to the dishwasher in multiple events of short duration (Figure 15 (c)). Consequently, the pump started and stopped multiple times. The dishwasher can operate in rapid or normal settings and used 10 ± 0.9 L and 14 ± 0.9 L for those respective settings. Water was delivered in four to five supply episodes of 3 ± 0.5 L, with additional short sprays at various stages.

The normal wash cycle lasted on average 120 min, with the rainwater pump operating for a total of 3 to 5 min during the appliance run. The rapid wash cycle lasted between 33 to 53 min, with the pump operating for between 2.6 to 3.4 min in total, and providing on average 3.5 ± 0.5 L/min of water.

5.3.3. Toilet Cistern

The toilet cistern fills through a lever than opens up at a minimum pressure of 50 kPa pressure and closes at 400 kPa. Water supply to the toilet cistern was a single continuous event that provided 3 or 6 L of water for a half or a full flush, respectively (Figure 15 (d)). The rainwater pump operation lasted on average for 33 ± 1.5 seconds and 63 ± 2 seconds for each of the two respective settings, at a flow ranging between 4 to 6.4 L/min, depending on the pump size.

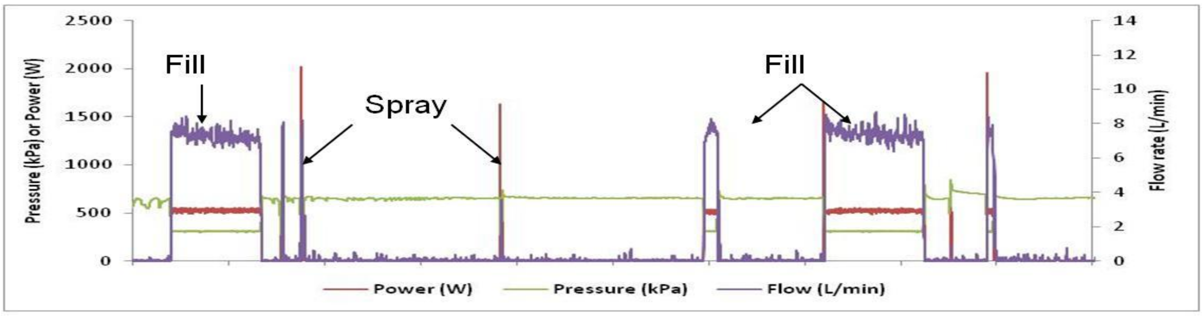
5.3.4. Tap

Pre-WELS taps can supply water at flows larger than 30 L/min. However, standard taps are designed for operation at flow rates ranging from 2 to 18 L/min (WELS 2011).

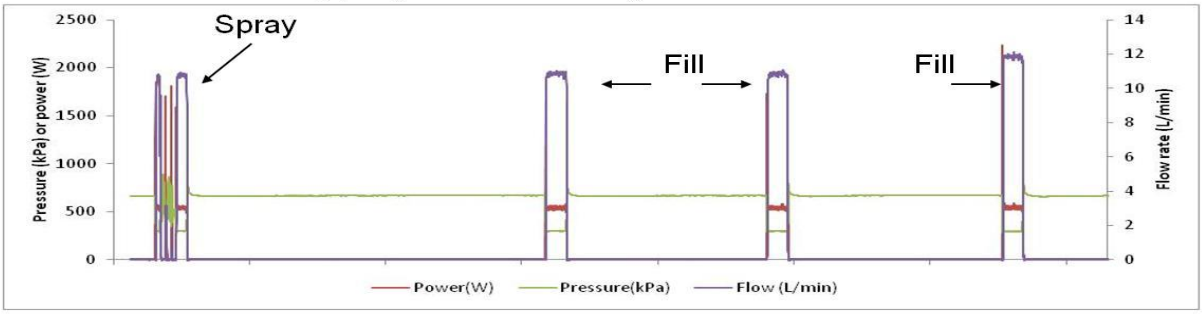
Outdoor garden irrigation exemplifies the highest flows in a house, with typical values of less than 10 L/min to more than 25 L/min reported in the literature (Athuralya *et al.* 2012, Roberts 2005). However, the use of irrigation hose triggers restricts flows to a maximum of 7 L/min (SEWL 2010).

Irrigation patterns are difficult to quantify as they depend on garden size and vegetation type, owner preferences, climate, season of the year and the irrigation devices adopted (e.g. manual hose, drip irrigation, watering can, sprinkler system) (Beal *et al.* 2010). Beal *et al.* (2010) examined water use in SEQ during 2010 and verified that houses used between 6.8 to 14.4 L/hh/d on average for irrigation. However, that study did not specify the duration or frequency of irrigation events. Surveys of irrigation practices in Victoria during the summer of 2012 established an average irrigation flow rate of 10 L/min for 20 minutes duration, with 64% of dwellings irrigating for less than 15 minutes per day (Athuralya *et al.* 2012).

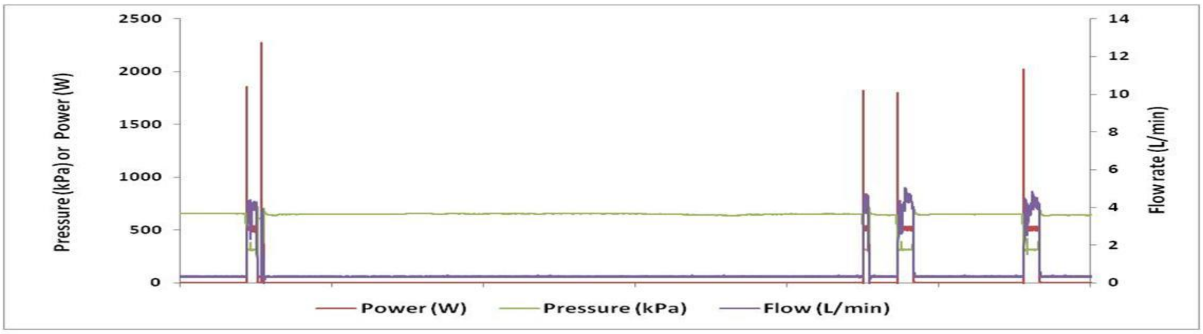
Figure 15 (e) shows the operation of a pump for rainwater supply to the laundry tub tap in the lab operating at 30 L/min until the tap is closed. On the opposite end of the tap water use scale, indoor tap uses, such as hand washing, are typically short events, which consume 2-3 L of water per episode and require low flows of less than 6 L/min (Roberts 2005).



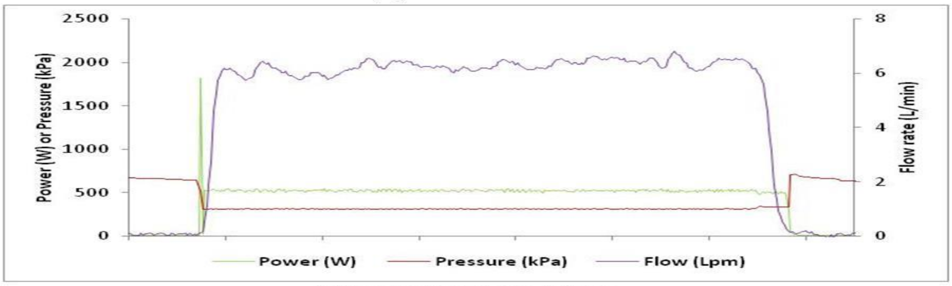
(a) Top Loader washing machine



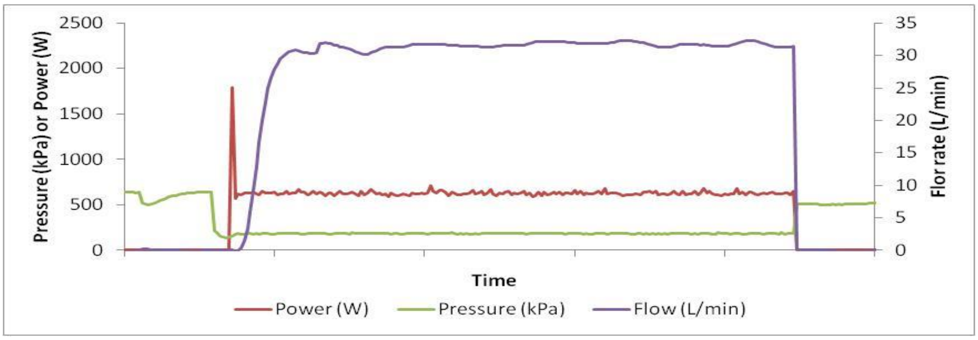
(b) Front Loader washing machine



(c) Dishwasher



(d) Toilet cistern filling



(e) Laundry tub tap

Figure 15: Rainwater supply to washing machines, dishwasher, toilet cistern and tap using pump B. The scale on the x-axis is different for each graph.

5.4. Energy Requirements for Individual End Uses

The pump operation during rainwater supply to each major end use was examined using pumps A (0.2kW), B (0.55kW), C (0.75kW) and D (0.60kW). The operation of the front loader washing machine was not verified with Pump D, as the front loader was not available at the time of the pump's installation.

Figure 16 compares the specific energy for the various pumps when supplying a range of end uses: toilet cistern, dishwasher, washing machines, header tank and irrigation at 20 L/min. Figure 17 shows the overall energy expended for the overall operating cycle of each appliance. The washing machine, toilet cistern and dishwasher operate in cycles of pre-determined duration. Hence, the total energy requirements and the specific energy needs are positively correlated, and can be compared when using pumps of various capacities under reproducible conditions.

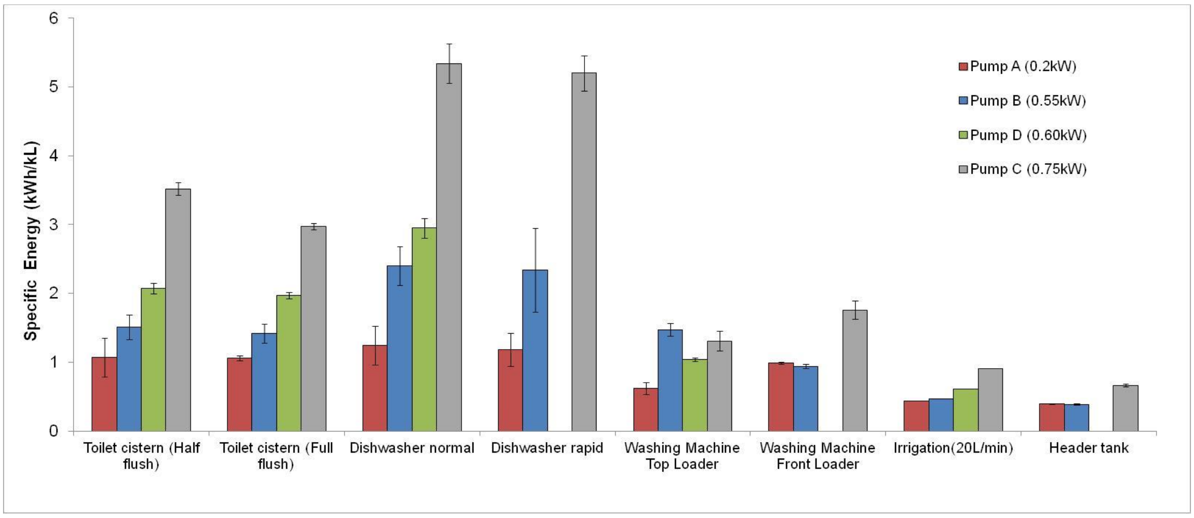


Figure 16: Variation in specific energy requirements for operation of household water end uses using pumps of different motor capacities. Note: Energy for irrigation was determined from specific energy vs flow curve for each pump. Error bars show the 90% confidence limit range.

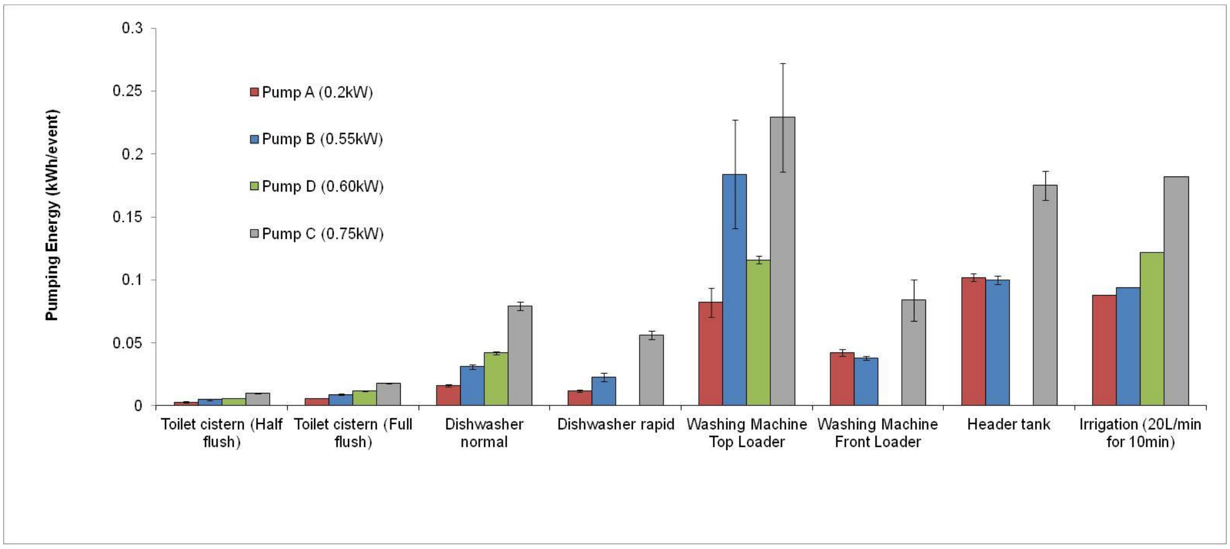


Figure 17: Variation in pumping energy requirements per event for operation of household water end uses using pumps of different motor capacities. Error bars show the 90% confidence limit range.

The dishwasher and the toilet cistern had larger specific energy requirements for rainwater delivery than the other end uses (Figure 16). However, high specific energy (kwh/kL) does not necessarily equate to high energy consumption (kwh/day) as this depends also on the volume of rainwater supplied and pump operating time. Figure 17 shows that it was the supply of rainwater to the top loader washing machine that consumed the most energy among all appliances. The washing machine was also the appliance that used the largest volume of water (>140 L/wash) amongst the indoor end uses examined (excluding the header tank which will be discussed in a separate section).

Overall, when comparing pumps of different motor capacities, the lower capacity pumps displayed lower energy requirements, as seen in Figure 17. The specific energy for pumps B and D was approximately 50% lower than pump C for most end uses, and up to 30% lower for pump A when compared to pump B depending on the end use. The only exception was for the top loader washing machine, where pumps B and D displayed similar specific energy requirements. Note that Pump D was the submersible pump, whilst the other three were external pumps.

Figure 18 shows the corresponding average pumping flow rate during pump operation. For rainwater supply, the relationship between flow rate and specific pumping energy has previously been shown in Figure 14. A detailed analysis for each end use will be conducted in the next few sections.

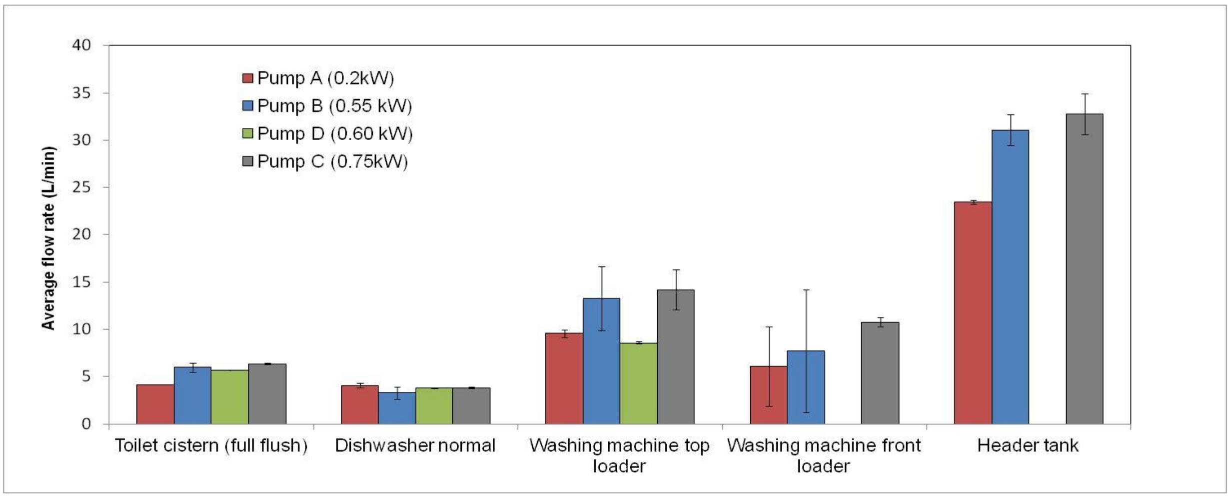


Figure 18: Average flow rates of rainwater delivery to appliances using pumps of various motor capacities. Error bars show the 90% confidence limit range.

5.4.1. Energy Requirements for Water Supply to a Tap for Hand Washing

To evaluate the impact of short duration supply events on pumping energy, four volunteers were asked to wash their hands using rainwater supplied with pumps B (0.55kW) and C (0.75kW), the most common size pumps observed in actual installations.

Hand washing was a single continuous event of short duration. It lasted on average 19.9 ±1.55 seconds (12 replicates), consumed 1.8 L of water, and used 1.43±0.18 kWh/kL and 6.59 ± 1.75 kWh/kL for pumps B (0.55kW) and C (0.75 kW), respectively.

The total energy consumed was 0.002 ± 0.0002 kWh/event for pump B, of which 95% was for the operation stage; and 0.006±0.0005 for pump C, of which 53% was for the operation stage and 43% for the over-run as shown in Figure 19. The start-up energy for both cases was less than 5% of the total energy used.

Overall, the level of service provided by the pumps was similar, but pump C used 200% more energy for hand washing compared to pump B. This was attributed to the pressure settings for the pump and the individual pump design.

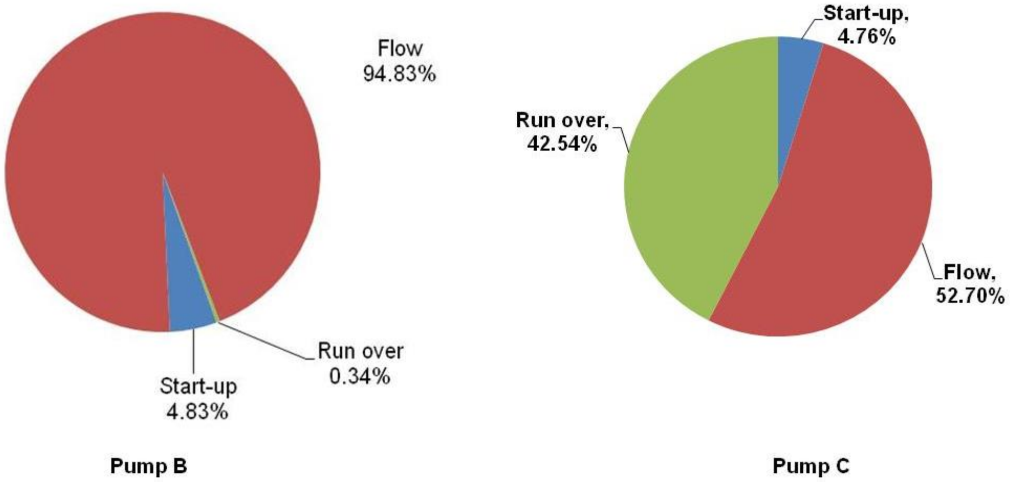


Figure 19: **Energy distribution during hand washing using pump B (0.55 kW) and C (0.75 kW).**

5.4.2. Toilet Cistern

For the toilet, the energy use increased as the pump's motor capacity increased. The four pumps consumed, 6.4± 0.1 x 10^{-3}, 8.8 ± 0.3 x 10^{-3}, 11.8 ± 0.2 x 10^{-3} and 18.2 ± 0.2 x 10^{-3} kWh for pumps A, B, D and C respectively, after a full flush (Figure 17).

Likewise, the specific energy increased with pump motor capacity, it was 1.06 ± 0.02 kWh/kL, 1.42 ± 0.08 kWh/kL, 1.93 ± 0.03 kWh/kL and 2.97 ± 0.03 kWh/kL for pumps A, B, D and C respectively as shown in Figure 16. The difference in specific energy between a full and a half flush was negligible for most pumps, except for pump C. Rainwater was supplied at flow rates ranging from 4.2 to 6 L/min (Figure 18).

The energy distribution during the operating cycle differed for the external pumps A, B and C (shown in Figure 20), which highlights the impact of pump capacity on energy use.

Pump A operated with a series of stop-starts and consumed 43% and 57% of the energy in the start-up and supply flow phases, respectively, whilst the over-run energy was negligible. The impact of the frequent cycling of pump A on its lifetime was not evaluated. For pump B, 98% of the energy was consumed in the supply flow phase, whilst pump C used majority of the energy in the flow phase, and expended 25% to 15% of the total energy in the over-run stages when filling a cistern by half or in its entirety.

In conclusion, for filling a toilet cistern, the smaller pump A was the most energy efficient. It provided suitable levels of service level, requiring an additional 19 seconds to fill the toilet cistern, but used only 35% of the energy compared to the pump C, which was the fastest.

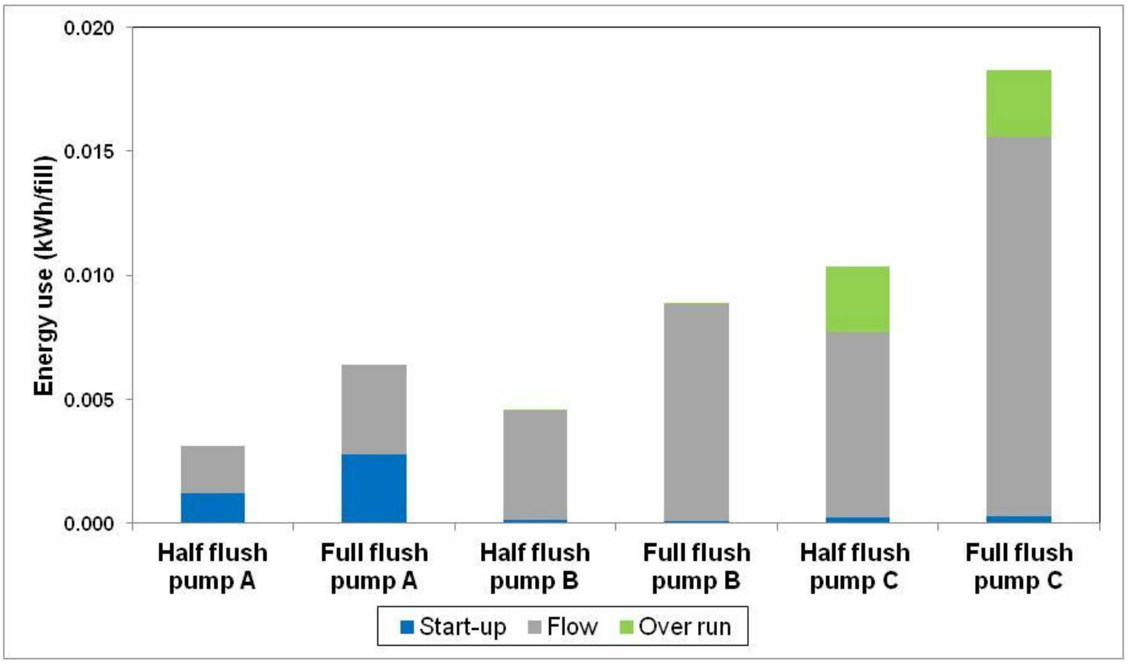


Figure 20: **The effect of pump capacity on energy consumption during toilet cistern filling.**

5.4.3. Dishwasher

For pumps A, B, C and D, the total energy for pumping ranged from 0.02 ± 0.001 to 0.08 ± 0.002 kWh/cycle for the normal wash (Figure 17). Pump A used the least energy and Pump C the most. Likewise, the specific energy for supply to the dishwasher for the pumps was lower for the smaller capacity pumps. It ranged from 1.24 ± 0.17 kWh/kL for pump A to 5.34 ± 0.28 kWh/kL for pump C (Figure 16).

The energy distribution during pump activation differed among the pumps. For pump A, the energy was partitioning between the start-up and flow phases, corresponded to 46.5% and 53.4% of the total energy use, respectively. For pump B, the energy intensity for individual phases varied with phase duration and the amount of water provided, but the majority of the energy (96%) was used for the flow phase, 3% was required for start-up and less than 0.2% for the over-run. Pump C consumed 2.1% at start-up, 16.4% in the over-run phase and the remainder in the flow phase (normal wash).

Similar to the toilet, there was little variation in the average flow rates generated by the pumps for supply to the dishwasher. The mean flow was 3.74 ± 0.32 L/min and ranged from 3.3 ± 0.05 to 4.05 ± 0.14 L/min across the four pumps (Figure 18).

5.4.4. Top Loader Washing Machine

A wash event consumed between 0.08 ± 0.23 and 0.27 ± 0.026 kWh of pumping energy depending on the pump capacity adopted (Figure 17). The rate of water delivery varied from 8.6 ± 0.1 to 14.2 ± 1.3 L/min, with a difference in flow rate of 59% between the slowest (pump D) and the fastest (pump C) (Figure 18). Operating times for the pumps ranged from 4.9 ± 0.1 to 15.9 ± 0.22 min per supply event. The shortest operating time was for the largest pump C.

The water supply and the energy distribution to the top loader washing machine was characterised by a number of phases including:

- Filling with water (1);
- First rinse (2);
- Occasional water top ups during the cycle (3, 4, 5 and 7); and
- Final rinse (6).

For an individual wash cycle, the largest proportion of energy was used in the fill (1), first rinse (2) and final rinse (6) which corresponded to 25%, 19% and 47% of the total energy of the wash, as shown in Figure 21.

The specific energy for pumping water to the washing machine (Figure 16) ranged from 0.62 ± 0.05 to 1.47± 0.06 kWh/kL. The highest values were 1.47 ± 0.06 kWh/kL for pump B and 1.31 ± 0.9 kWh/kL for pump C. Pump A again had the lowest specific energy requirement at 0.62 ± 0.053 kWh/kL.

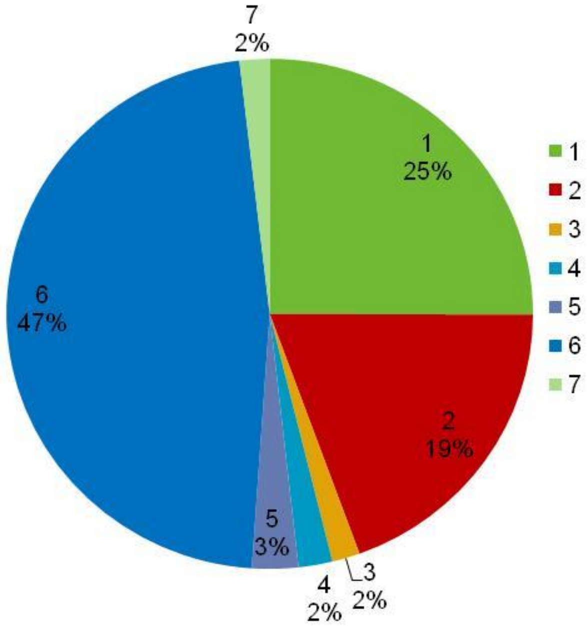


Figure 21: Energy distribution during the operation of a top loader washing machine (using pump B). Each stage 1 to 7 represents an event during the washing cycle when the pump is activated to supply water to the washing machine.

5.4.5. Front Loader Washing Machine

The specific energy intensity for a wash was examined for pumps A (0.2kW), B (0.55kW) and C (0.75kW) and ranged from 0.94 ± 0.01 to 1.76 ± 0.08 kWh/kL depending on the pump selected (Figure 16), with average flow rates of water delivery between 6.1 to 10.8 L/min (Figure 18).

Again, the smaller pumps delivered the lowest specific energy of water supply, which were 0.99 ± 0.01 and 0.94 ± 0.03 kWh/kL for pumps A and B respectively (Figure 16).

During a wash, the pump delivers 43 ± 2 L of water in three episodes of 10-11 L, and two to three injections of one to five litres of water, resulting in the energy distribution shown in Figure 22, which differs significantly from the pumping energy distribution during the wash cycle of a top loader.

Although front loaders had a higher specific energy for water supply than top loaders, the total energy per wash was lower due to the lower volume of water required and hence the shorter interval of pump operation (Figure 17). The difference in energy consumption for the two types of washing machine types can be seen for pumps A, B and C in Figure 17, where pumping water to the top loader for the smallest pump (A) and the largest pump (C) required 94% and 270% more energy compared to the front loader.

Research on appliance uptake trends in Victoria from 2003 to 2012 shows an increase in uptake of front loader over top loader washing machines over time (Roberts 2005, Athruralya *et al.* 2008, Athruralya *et al.* 2012). In 2011, 48% of dwellings surveyed owned a front loader compared to only 30% in 2008 (Athruralya *et al.* 2012).

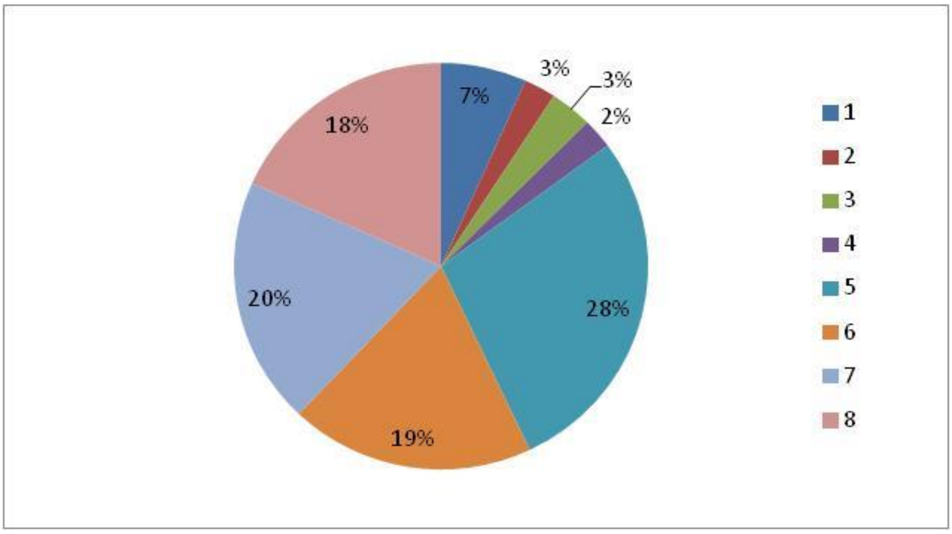


Figure 22: **Energy distribution during the operation of a front loader wash machine operation (using pump B). Each stage 1 to 8 represents an event during the washing cycle when the pump is activated to supply water to the washing machine.**

5.5. Simultaneous Appliance Operation

Simultaneous operation of multiple appliances increases the demand for rainwater and hence the flow required from the pump. As a result, the pump operates at a higher energy efficiency. This is illustrated in Figure 23, which shows that a lower specific energy is required for the simultaneous operation of multiple appliances (two, three and four) compared to individual ones. The probability of having multiple appliances operating simultaneously is likely to increase in households with multiple occupants.

However, controlling the timing and flow requirements of end uses would be a difficult task as most of the end uses occur independently at various times in the day; and each appliance has a distinct water use pattern (volume, duration and timing) which will not necessarily coincide with other appliances' timing to increase flow.

Likewise, the energy reduction that can be achieved during the simultaneous supply of rainwater to multiple appliances will vary with the type of appliances in the dwelling, the sequence and timing of their operation, as illustrated in Table 14 for the different energy requirements for the various permutations. Therefore, estimating the total energy savings would be a difficult task. Additional examples of simultaneous appliance operation can be found in Appendix D.

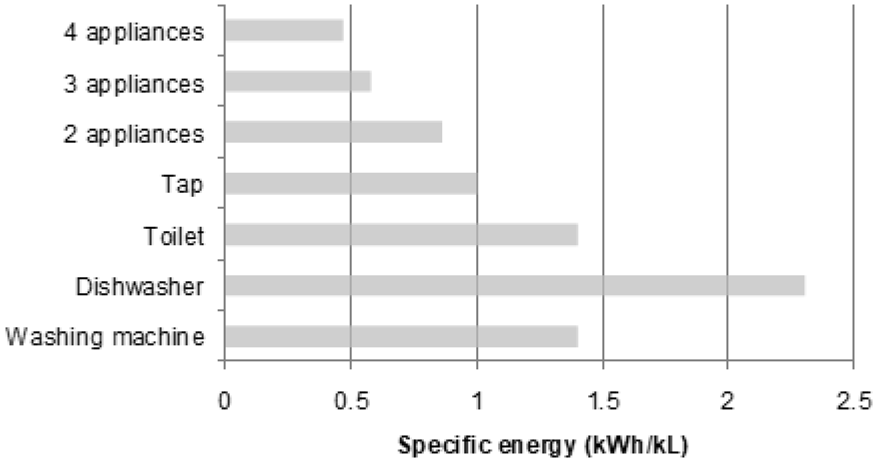


Figure 23: **Example of simultaneous operation of multiple appliances using pump B (0.55kW). The specific energy values in the graph are the averages from all the permutations shown in Table 14.**

Table 14: Specific energy requirements for the simultaneous operation of appliances using pump B.

Number of Appliances Used	Permutation of Appliances / Specific Energy (kWh/kL) Washing machine (WM), Dishwasher (DW), Toilet cistern (TO), Tap@ 10L/min (T)						Average Specific Energy (kWh/kL)
1	WM 1.4	DW 2.3	TO 1.4	T 1			1.5
2	WM + DW 0.86	WM + TO 0.77	DW + TO 1.01	T + WM 0.78	T + DW 0.81	T + TO 0.94	0.86
3	T+DW+TO 0.62	WM+DW+T 0.6	T+WM+TO 0.52		T+WM+DW 0.57		0.58
4	T+WM+DW+TO 0.47						0.47

5.6. Service Provision

Previously in section 3.5, it was shown that the appliances sold in Australia are designed to operate under specific pressure settings. The pressure or differential flow settings that control a pump start-up are preset at the factory by the manufacturer. Hence, it is important that the service pressure delivered by any pump matches or exceeds the minimum operating pressure required for an appliance.

Figure 24 shows the average pressure produced during operation of pumps A (0.20kW), B (0.55kW), C (0.75kW) and D (0.60kW) and compares them to the minimum pressure required for operation of the appliances tested. All pumps were able to provide the minimum pressure required for the appliances' operation. Pumps B, C and D generated pressures greater than 290 kPa, whilst the smallest capacity pump A supplied water in the pressure range of 180 to 203 kPa.

The flow rates of rainwater supply measured for the pumps were previously shown in Figure 18 and ranged within:

(a) For filling the toilet cistern: 4.2 to 6.3 L/min;

(b) For dishwasher: 3.3 to 4.0L/min; and

(c) For washing machine: 8.6 to 14.2 L/min for the top loader and 6.1 to 10.8 L/min for the front loader.

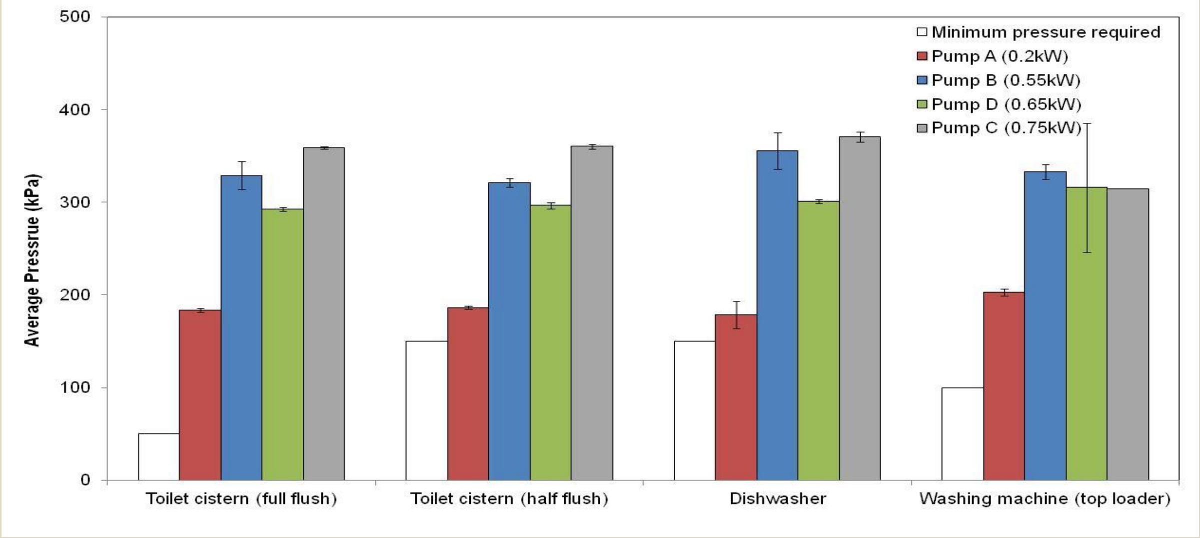


Figure 24: Average service pressure of water for different end uses and pump capacities compared to the minimum pressure required to operate the appliance.

Pressure and flow rate typically increase with pump size, however service flows are restricted by appliance's inlet valve design, as previously explained in section 3.5. Therefore, although the largest capacity pump C, generated pressures 55% to 107% higher than pump A, the variation in the service flow rates by the two pumps was much smaller, ranging between -6% to 77% for pump C compared to pump A depending on the appliance (Figure 18). This similarity in flow applies particularly to appliances that are designed to operate at low flows, such as the toilet and the dishwasher. In such instances, larger size pump will not necessarily deliver a better service.

In Table 15 the pumping rates measured were compared to the service conditions measured in earlier studies (Roberts 2005, Athuralya *et al.* 2008, 2012,) and to the flow rate ranges recommended in HB230 (Standards Australia 2008).

Roberts (2005) and Athuralya *et al.* (2008, 2012) surveyed the water service flows of various appliances in occupied dwellings in Victoria over the last eight years. Taps for hand basins, kitchen sinks and the laundry tub ran at average flow rates of 4.9 L/min, 15 L/min and 20 L/min respectively in 2008 (Athuraliya *et al.* 2008). However, the 2012 study (Athuralya *et al.* 2012) shows that flow rates for hand basin and kitchen sink taps have decreased since that time, and are much closer to the values recommended in the HB230 standard, whilst laundry tub averages have changed little.

Overall, the flow rates recorded in our study were comparable to the flow rates recommended in HB230 for the hand basin, toilet and washing machines, but were lower than those reported in HB230 for the dishwasher (Table 15).

Table 15: Typical service conditions for end uses reported in Australia.

Study	**Average Flow Rate (L/min)**					
	This study	Roberts (2005)	Athuralya *et al* (2007)	Athuralya *et al* (2012)	HB230[1] Recommended	HB230[1] Pmin (kPa)
Hand Basin	4.3 -6.3	4.9	8	5.4 ± 2.7	6-9	50
Kitchen Sink	n.d.	19	15	6.5 ± 2.5	7-9	50
Laundry Tub	n.d	25.7	20.2	19.6 ± 9.9	7-9	50
Shower	n.d	6.1	6.8	5.9	6-9	200
Dishwasher	3.3 - 4	n.d.	n.d.	n.d.	12	50
Washing Machine	6.1-14.2	n.d.	n.d.	n.d.	12	100
Toilet	4.2 - 6.3	n.d.	n.d.	n.d.	6	50

[1] Standards Australia and New Zealand 2008. N.d. not determined.

5.7. Relationship between Energy and Level of Service

A summary of the energy and service requirements for pumps connected to individual appliances is presented in Figure 25. Figure 25 shows the specific energy required for water supply to a tap at various flow rates using pumps A, B, C and D (0.2 kW, 0.55 kW, 0.75 kW and 0.60 kW, respectively) and the range of flow rates observed during rainwater supply to the various appliances tested (DW: dishwasher, TO: toilet, WMT/F: washing machine top and front loader; and HT: Header tank) in this study.

The experimental results indicate that the differences in the overall energy efficiency between the pumps tested are not dependent on pump size alone, but also predicated on service requirements.

The rainwater end uses in new urban dwellings have low flow rates (< 15 L/min) and, hence, are within the high energy intensity range of pump operation. As previously described in section 5.2, the optimal pump energy efficiency is achieved for flow rates of more than 22 L/min for all pumps. However, the only appliance that could be filled at that flow rate was the header tank that we installed. Note that the header tank service range in Figure 25 shows two flow brackets; one for pump A (average flow 23.5±0.1 L/min) and the other for pumps B and C (> 30 L/min).

Consider now the two most common rainwater end uses in a dwelling; filling a toilet cistern and filling a washing machine. In Figure 25, the specific energy for supply to the toilet cistern will be higher than for supply to the washing machine because of the flow rates required for each appliance.

When comparing the four pumps A, B, C and D delivering the low end use requirements, a higher specific energy intensity was required for the larger capacity pump C for delivery of a similar flow (Figure 25). On the other hand, the two smaller pumps (A and B), only displayed marginal differences in energy efficiency despite of a difference in power of 64% between A and B. A limitation observed for pump A, however, was that the maximum flow rate it could achieve was only 24 L/min, whilst pump B, C and D were able to provide flow rates of more than 30 L/min.

Pump C had a different manufacturer than pumps A, B and D. Earlier research by the Water Conservation Group P/L, which compared eight pumps of various brands and sizes, verified that manufacturer set-up and design were two major factors impacting the overall energy efficiency of pumps (SEWL 2010). That same study also showed that two pumps of the same motor capacity but from different manufacturers produced distinct specific energy curves, hence motor size is not the only factor that needs to be considered when comparing pump energy efficiency. Instead, examination of the energy and flow curve for each pump would be required to also account for the effect of brand.

In summary, for the pumps used in this study, as the rainwater flow rate increased, the specific energy requirements decreased. Thus, to reduce the energy requirements for rainwater pumping, consideration needs to be given to the end use type and the associated service requirements for appliances adopted in households.

For the pumps examined in Figure 25, the adoption of the smaller capacity pump A is likely to provide the greatest reduction in the pumping energy required for water delivery, particularly for low flow applications such as filling a toilet cistern.

The operation of pump B with a pressure and an automatic rainwater to mains switch is also shown in Figure 25, however the variation in energy performance was within the expected standard deviation and hence not statistically significant.

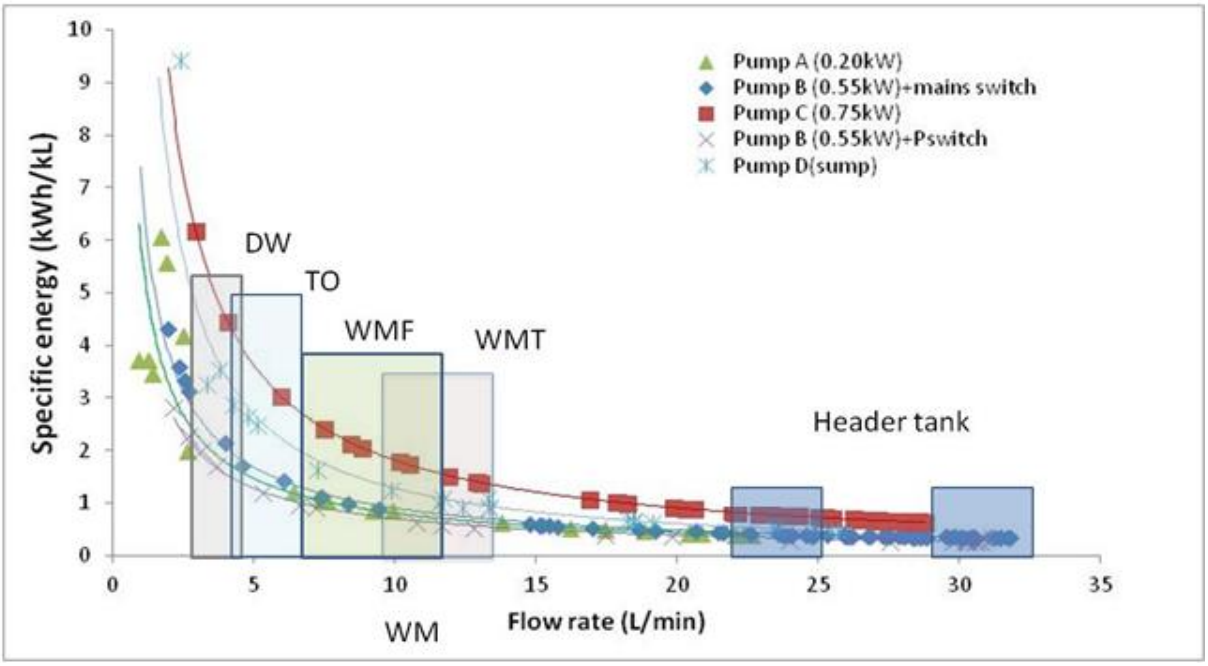


Figure 25: Relationship between specific energy and flow required for rainwater uses in a dwelling. Legend: DW (dishwasher), TO (toilet), WMF (washing machine front loader), WMT (washing machine top loader) and header tank.

5.8. Pressure Losses in Infrastructure

When designing a rainwater supply system, in addition to the minimum level of service pressure requirements for individual appliances, it is also necessary to account for pressure losses in the pipeline infrastructure. Friction losses from infrastructure are governed by infrastructure characteristics (material, pipe diameter, system configuration, bends and length of the pipework) and the flow rate of water delivery. Friction losses in the pipes comprise major losses, with minor losses occurring due to junctions, bends and valves.

The relationship between friction losses and water flow rate for a straight length of 19mm diameter polyethylene pipe, as adopted in the lab and common in the construction of new dwellings, is shown in Figure 26.

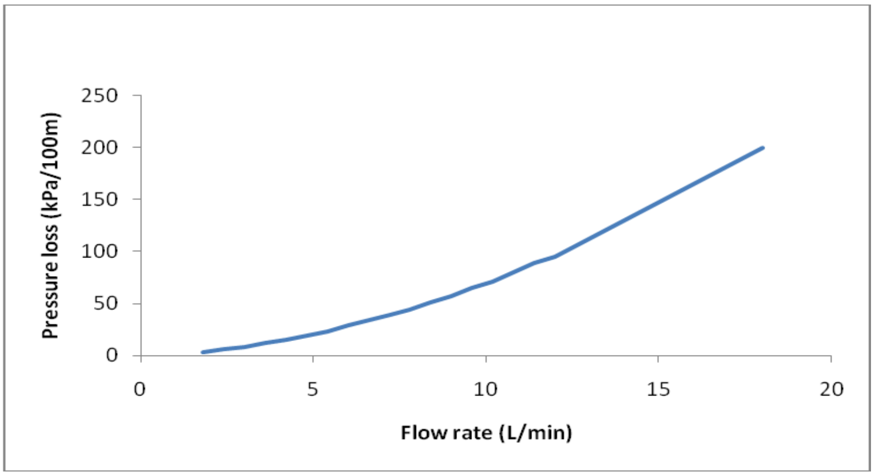


Figure 26: Relationship between flow rate and friction loss for the model house distribution infrastructure.

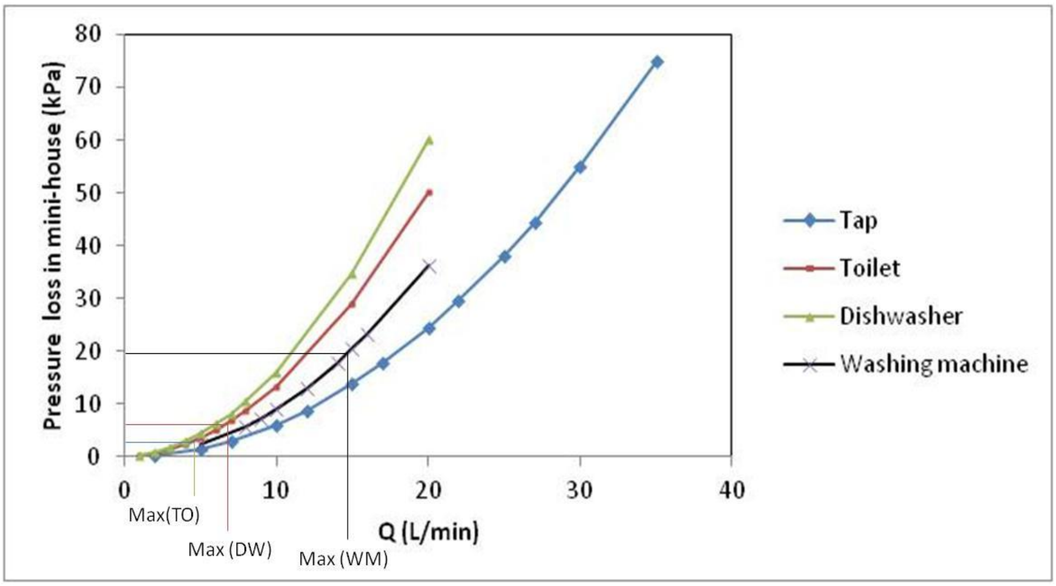


Figure 27: Pressure loss as a function of flow rate for the rainwater system examined in the laboratory. The maximum flow rates for rainwater supply to the various appliances are marked. Legend: Max (TO): maximum flow rate for toilet, Max(DW): maximum flow rate for dishwasher, Max(WM): maximum flow rate for washing machine. Losses for the tap depend on the flow rate adopted.

The length of pipework in actual dwellings will depend on the location of the rainwater tank and the relative location of the appliances serviced by rainwater. The water supply velocity in the pipes will be determined by the end use and the pump trigger settings. Therefore, in flow controlled appliances, such as such as toilet cisterns, washing machines, dishwashers and taps with flow restrictors, the maximum pressure loss can be estimated from the required operating flows for individual appliances and the infrastructure configuration of an individual dwelling.

There was good agreement between theoretical estimates and measured friction losses verified for the system adopted in this study. Comparison of the theoretical (Figure 27) and measured friction losses differed by less than 2% (±2 kPa) of friction head, except for the dishwasher outlet, where the head loss measured was 4%, whilst the estimated head loss was 2%.

The friction losses from the outlet of the pump to the various end use locations ranged from 1% to 6% (at 14 L/min) of the total head, depending on flow rate and location, when using pump A (Figure 27). For instance, the washing machine, which has the highest flow rate of all indoor end uses, incurred a loss of 20 kPa (or 6%) in total head when the pressure at the pump outlet was 314±4 kPa.

In summary, the losses attributed to infrastructure friction for the operating conditions of the various appliances measured in the laboratory resulted in losses of less than 6% of the initial pressure supplied. If the infrastructure length is increased, the friction losses are also expected to increase as shown in Figure 27. Whilst the friction losses were only a small portion of the total head, estimating the friction losses in any system will assist in the evaluation of the required supply pressure for end use and the capacity of the pump. In addition, minimising the length of pipe between the pump and the end uses will assist in minimising friction losses.

5.9. Ancillary Devices

The most common configuration adopted for rainwater supply to dwellings in Australia is direct connection from the pump to the end uses in a dwelling, with or without a mains water switch. However, a number of ancillary devices can be incorporated in the design of rainwater supply systems. In the following sections we will examine the most common ancillary devices: pressure vessels, and header tanks.

5.9.1. Pressure Vessels

A pressure vessel is a rigid tank that contains an internal elastic diaphragm or bladder which is partially filled with air (Figure 28). It is typically placed after the pump and serves as a receptacle for water storage. When the pressure vessel is filled with water, the water expands the bladder and compresses the air in the vessel. When water is released from the vessel, the air expands and the pressure reduces until a pre-set pressure is reached, which then activates the pump to refill the vessel as shown in Figure 29. Rainwater from the pump to the pressure vessel is initially supplied at a maximum flow rate, which decreases as the vessel is filled (Figure 29).

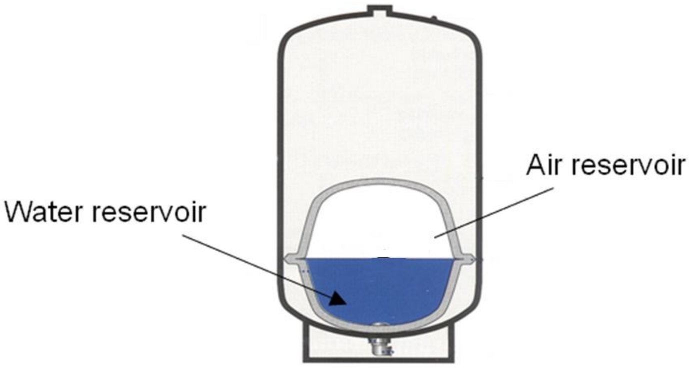


Figure 28: Pressure vessel bladder.

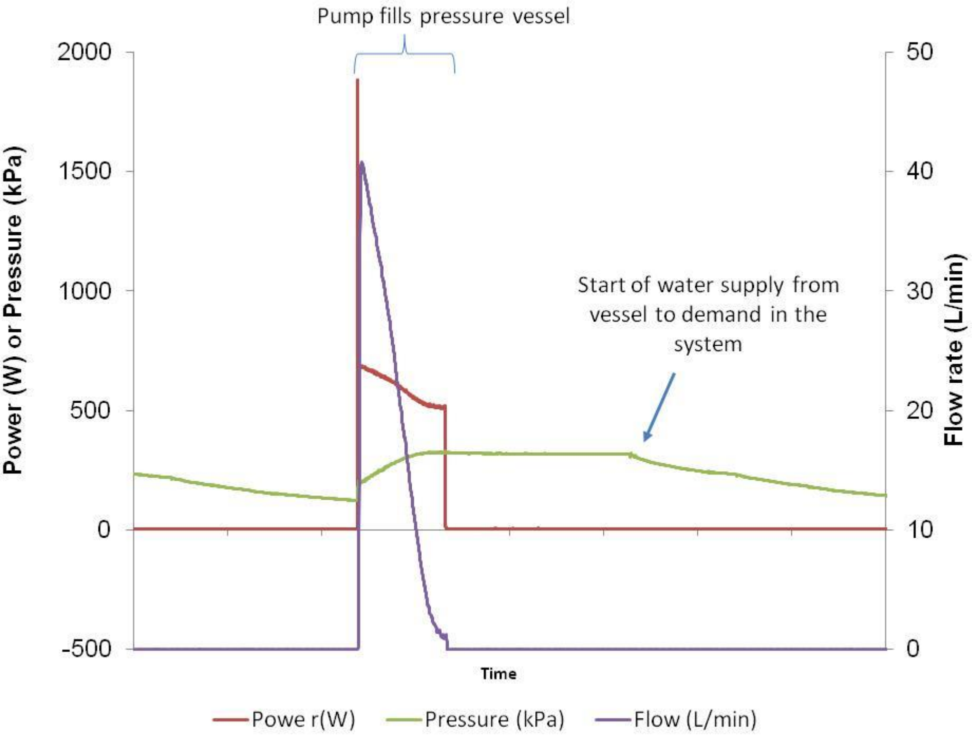


Figure 29: Time trend in flow rate, pressure and energy use to fill an 80 L pressure vessel using pump B.

Effective Volume

Pressure vessels come in a range of sizes (nominal volumes of 5 L to over 1000 L). Small volume pressure vessels of five to eight litres are sometimes installed with pumps to reduce the number of pump start-ups caused by small leaks experienced in the water supply of a dwelling. The larger sizes are usually adopted for industrial applications.

The volume of water delivered by a pressure vessel (effective volume) is usually less than the nominal volume of the vessel. An empty pressure vessel has a pre-charge pressure in its bladder. The optimal pre-charge pressure for the pressure vessels is typically 138 kPa (20 psi), at such pressure the effective volume of water is optimal.

The effective volume is a function of the nominal volume of the vessel and the pump trigger pressure settings. Figure 30 shows the volume of water delivered by pressure vessels of sizes ranging from 8 to 80 L when coupled to two different pumps, A (0.2kW), and C (0.75kW).

The effective water volume released by these pressure vessels was respectively 16 ± 7% and 37 ± 4% of the nominal volume of the vessel when coupled to Pumps A and C respectively. Hence, a larger volume of water was provided when pump C was used.

The effective volume impacts the frequency and duration of pump operation. For example, an 8 L pressure vessel releases less than 2 L with either pump A or C. This has little impact on the number of pumps starts as the minimum volume for water supply for an application such as toilet flushing is 3 L for a half flush or 6 L for a full cistern. On the other hand, using a 40 L pressure vessel, which releases 13 L of water, a toilet cistern can be filled at least two times before the pump is activated. This explains why small pressure vessels (5-8 L) caused no significant reduction in pumping energy as previously observed in Hauber-Davidson and Shortt (2011).

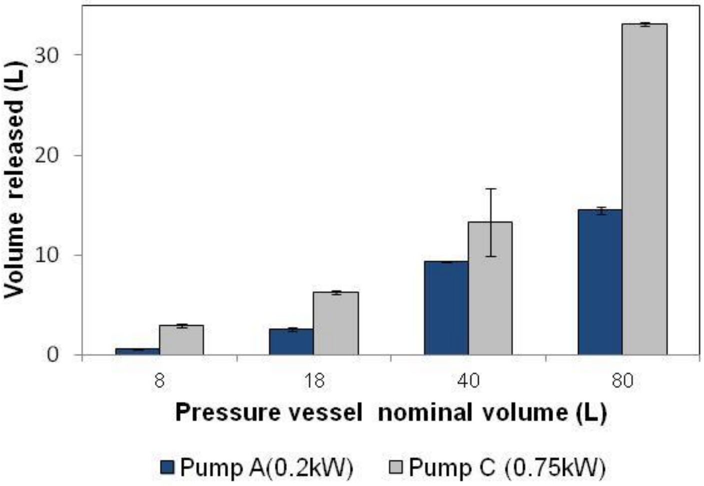


Figure 30: **Volume of water released by pressure vessels of various sizes before pump activation.**

In summary, a pressure vessel has two major effects:

- It reduces the number of pump starts if the volume required for an end use is equivalent to or lower than the water volume contained in the vessel; and
- The flow rate at which the pressure vessel is filled differs from that at which an appliance is filled, which is particularly advantageous for low flow end uses.

To maximise the benefits from adoption of a pressure vessel it is necessary to consider the size of the vessel and the volume of water required for the end uses.

Typically pressure vessels are used with pumps activated by pressure switches, In this study, the addition of a pressure vessel to Pump B (0.55kW) coupled with an automatic mains switch was also trialled. However, such arrangement caused a malfunction of the switch. The switch preferentially used mains water to fill the pressure vessel, by-passing the rainwater tank even when rainwater was available in the tank. By replacing the automatic switch with a pressure switch, the pump and pressure vessel system was able to operate effectively.

Energy Savings

As the pump operates less frequently and at higher energy efficiency with a pressure vessel, the associated energy demand was reduced. Once again, the energy savings achieved from a pressure vessel will depend on pump capacity, the effective volume of water, and the amount of water that needs to be supplied.

The washing machine uses a larger volume of water than the effective volume of the pressure vessels tested. Figure 31 and Figure 32 show respectively the total energy per wash and the specific energy for rainwater supply to the top loader washing machine using pumps A (0.2kW), B (0.55kW) and C (0.75kW) with and without an 80 L pressure vessel.

The addition of the pressure vessel reduced the total pumping energy during the wash, particularly for the larger capacity pumps, as less active duty was required due to the larger effective volume (Figure 31). This is because the washing machine requires a fixed volume of water, and the operating time for each pump to replenish the pressure vessel and provide the balance of water required decreased as motor size increases. For pump A, the energy consumption associated with the wash had no significant change, but for pump B and C it was reduced by 79% and 96% respectively, reducing the energy consumption to a range equivalent to pump A, the least energy intensive option.

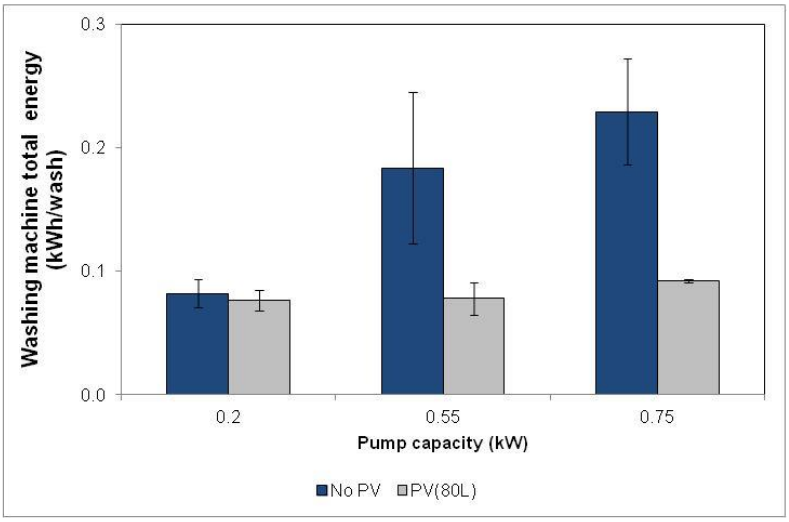


Figure 31: Energy for rainwater supply to a top loading washing machine with and without an 80 litre pressure vessel.

The associated specific energy for the three pumps with the 80 L vessel was thus reduced to 0.63± 0.01, 0.74± 0.09 and 0.82± 0.01 kWh/kL for pumps A, B and C (Figure 32).

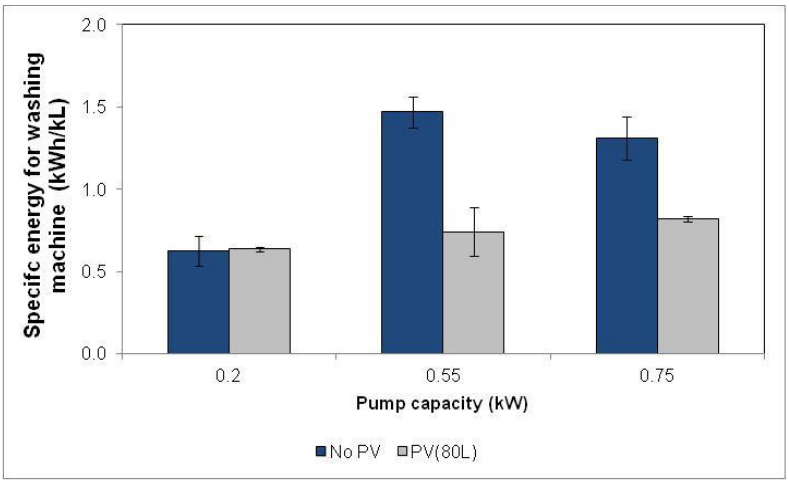


Figure 32: Specific energy for rainwater supply to a top loader washing machine with and without an 80 litre pressure vessel.

5.9.2. Header Tanks

Pumping rainwater to a header tank for supply by gravity is expected to reduce the energy of water supply, as fewer start-ups would be required, and the pump fills the header tank at high flow rates.

However, given the service requirements for operation of water using appliances and the current design standards for modern dwellings, verification is required of the level of service that a header tank can provide.

The energy savings that can be achieved by a header tank were examined for a tank with an effective volume of 257 L positioned at a height of 2.7m above the house flooring. The tank dimensions were selected so that it could be fitted in the ceiling vault of a single storey dwelling and its volume satisfied the daily water requirements of a one person household (Figure 33). The average water consumption per person across SEQ ranges from 110 to 170 L/p/d (Beal and Stewart, 2011) and the water demand for the major rainwater applications (washing machine, toilet and irrigation) has been reported to range from 137 to 233 L/hh/d in 2010 (Beal *et al.* 2010).

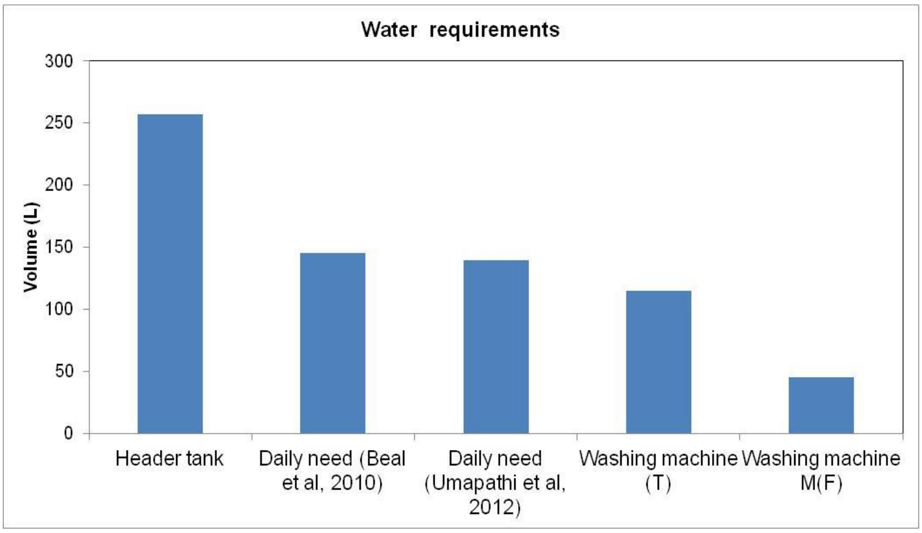


Figure 33: **Comparison of per capita daily water requirements for SEQ, water requirements for top and front loader washing machine water and header tank volume installed in the model house.**

Figure 34 compares the pumping energy for provision of rainwater to the header tank with the energy required for provision of an equivalent volume of water directly to individual appliances (3 dishwasher events, toilet flushes (16 half / 10 full) and one top loader washing machine cycle). The resulting energy savings ranged from 58% to 79% compared to direct supply to individual appliances, which required between 0.24 to 0.86 kWh for the different pump sizes.

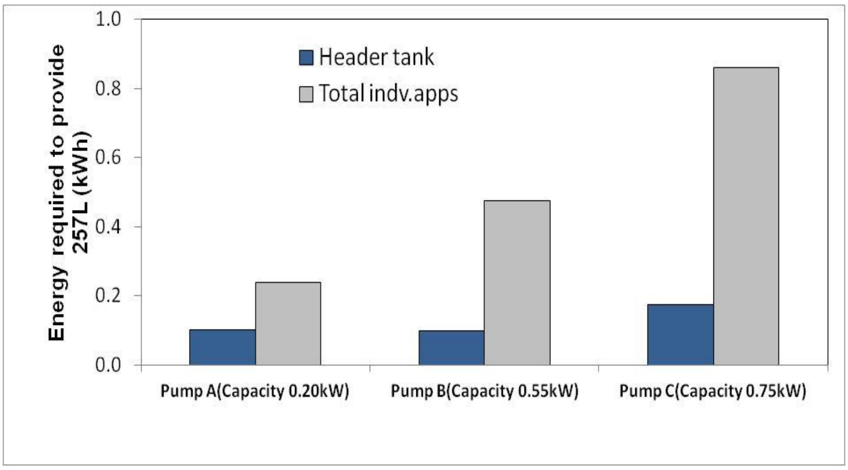


Figure 34: **Energy required for water supply via a header tank compared to direct supply from pump to individual appliances that consume an equivalent volume of water.**

Filling a header tank required the least specific energy among the appliances tested (Figure 17). This is because the pump operates at high flow rates. The average flow rates were 23.5 ± 0.1, 31.09 ± 0.15 and 32.74 ± 0.16 L/min for pumps A, B and C respectively. The resulting specific energy ranged from 0.39 to 0.66 kWh/kL, depending on the pump adopted. Increasing the diameter of supply pipes to the header tank from 18mm to 25mm diameter had no impact on the specific energy (Figure 35).

However, the service pressure provided by gravity was only 20 kPa, which was below the minimum pressure requirements for operation of household appliances in Australia (31-100 kPa), as shown in Figure 36. By changing the toilet cistern valve to a low pressure valve and seal (minimum operating pressure 15 kPa) we were able to fill the toilet cistern in less than four minutes, whilst mains pressure filled the cistern in one minute. Based on these estimates, the header tank needs to be placed at a height greater than 5m to achieve the 50 kPa minimum pressure. In comparison, the smallest pump A (0.2 kWh) operates at 180 kPa when filling the toilet cistern.

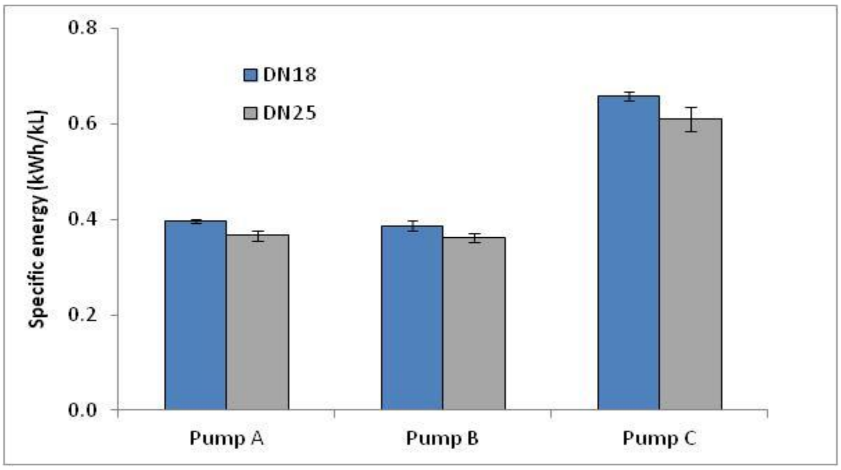


Figure 35: **Specific energy for filling the header tank using pipe infrastructure of two sizes: DN 18 (18mm diameter) and DN25 (25mm diameter).**

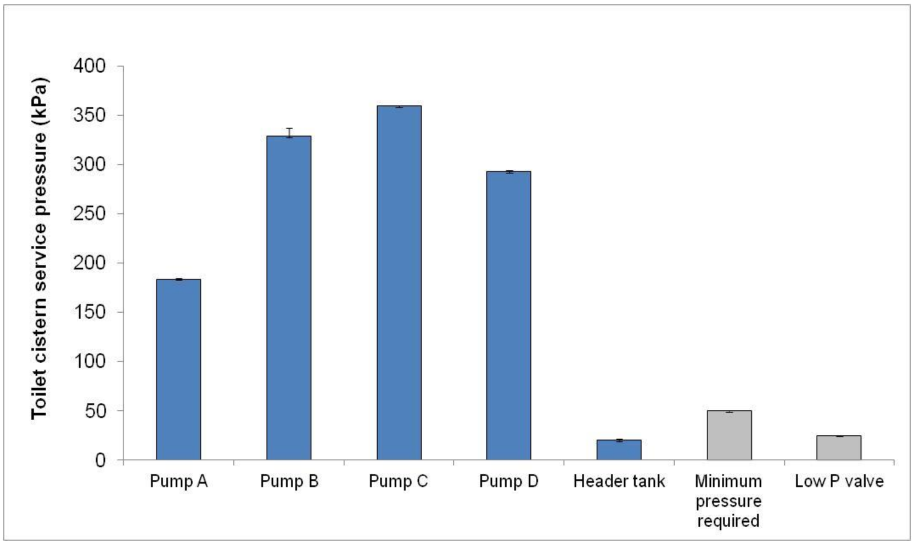


Figure 36: **Pressure of rainwater delivered to toilet cistern with various pump and supply systems. Minimum pressure to operate the valve is also shown.**

In conclusion, a header tank is able to substantially reduce the overall energy requirements for water delivery by pumps, independent of pump size. However, given that the solenoids and valves of appliances are designed to operate under high pressure, gravity supply from the header tank would require the placement of the header tank above the current ceiling height of a single storey dwelling. Alternatively, re-design of the water inlet valves for common appliances such as washing machines could be discussed with appliance manufacturers.

5.9.3. Variable Speed Drive Controllers for Pumps

Variable speed drive (VSD) control units were not within the scope of our experimental analysis. Variable speed drive control units maintain the pressure in a system by adjusting the pump's power consumption. As a result, pumps are able to use less power at low flow applications and increase the power consumption for high flow applications. Pumps with VSD currently sold in the market are designed to operate from 18 to 130 L/min. The smallest pump of that type in the market is able to provide from 18-65 L/min at 450 kPa head. However, they are not a common pump and are made to order costing $6,300. In comparison, a fixed speed pump costs less than $1,000.

6. ENERGY CONSUMPTION AT HOUSEHOLDS

This section examines the selection of rainwater end uses in a dwelling. Energy consumption increases with the number of occupants in a household, as the frequency of appliance use, such as washing machines and toilets, and amount of rainwater consumed increases.

A desktop assessment was conducted for the energy consumption expected for a dwelling. The assessment assumed rainwater supply for a range of end uses including toilet, laundry (washing machine) and garden irrigation at the average frequency of appliance use as described in the 2007 Melbourne survey of household water use (Athuralya *et al.* 2008) described in section 4.8. The energy estimates will be conservative as they assume that appliances are used one at a time, supplied by pump B.

Table 16 shows the ratio of the energy and water requirements for various rainwater end uses relative to the energy and water supplied for a toilet cistern only. It aims to show how the total energy consumption for rainwater pumping increases for a dwelling as rainwater is adopted for more end uses, by comparing the supply of rainwater to individual and multiple end uses in a dwelling, including low water volume applications, such as the dishwasher, and high flow applications, such as irrigation of the garden.

For instance, compared to the energy requirements for supply to the toilet cistern alone, pumping rainwater for irrigation twice a week consumes 19% less energy, whilst a washing machine requires 22% more energy. On the other hand, such supply patterns increase rainwater use by 80% and 30% respectively. Increasing the number of end uses to include irrigation, toilet flushing and laundry, requires 93% more energy and 3.4 times more rainwater compared to toilet cistern filling alone.

Table 16: Energy requirement for end uses compared to energy for daily toilet cistern filling (pump B).

End Uses	Ratio Energy Use/Energy Toilet	Ratio Water Supply/Water Supply to Toilet
Toilet cistern	1.00	1.0
Dishwasher	0.65	0.2
Irrigation	0.81	1.8
Washing machine	1.22	1.3
Toilet cistern + irrigation	1.16	2.8
Shower	1.32	3.4
Shower + Tap (hand wash)	1.45	3.8
Wash machine + irrigation	1.38	3.3
Toilet + laundry + irrigation	1.93	4.4
Toilet + laundry + irrigation + shower	2.60	7.8
Toilet + laundry + irrigation + shower +dishwasher +tap	2.82	8.5

The corresponding associated specific energy is then estimated using the total energy and rainwater supplied. Therefore, households that use their pumps less frequently, or for supply of low flow end uses such as for toilet supply, tend to operate the pump in its high specific energy range. For example in Figure 37, the specific energy associated with a dwelling that supplies all end uses with rainwater is estimated as 1.13 kWh/kL, whilst a dwelling of equivalent characteristics that uses rainwater for toilet flushing only has a specific energy of 3.29 kWh/kL. Under such a scenario, a dwelling that adopts rainwater supply for irrigation, toilet and washing machine would have a specific energy of 1.45 kWh/kL using pump B or 2.24 kWh/kL if the larger pump C was used instead. Hence, the overall energy consumption in kWh, will not necessarily be higher when the specific energy is higher for a dwelling. Therefore, caution is required when comparing overall energy consumption and pump efficiency for water delivery.

Multiple end uses and various pump sizes are some of the reasons for the large variance observed in the energy consumption and specific energy for rainwater systems in situ in the literature (SEWL 2009, Retamal *et al.* 2009). However, more recent studies (Table 8) are showing average in-situ measurements around 1.4-1.6 kWh/kL for dwellings in SEQ (Umapathi *et al.* 2012).

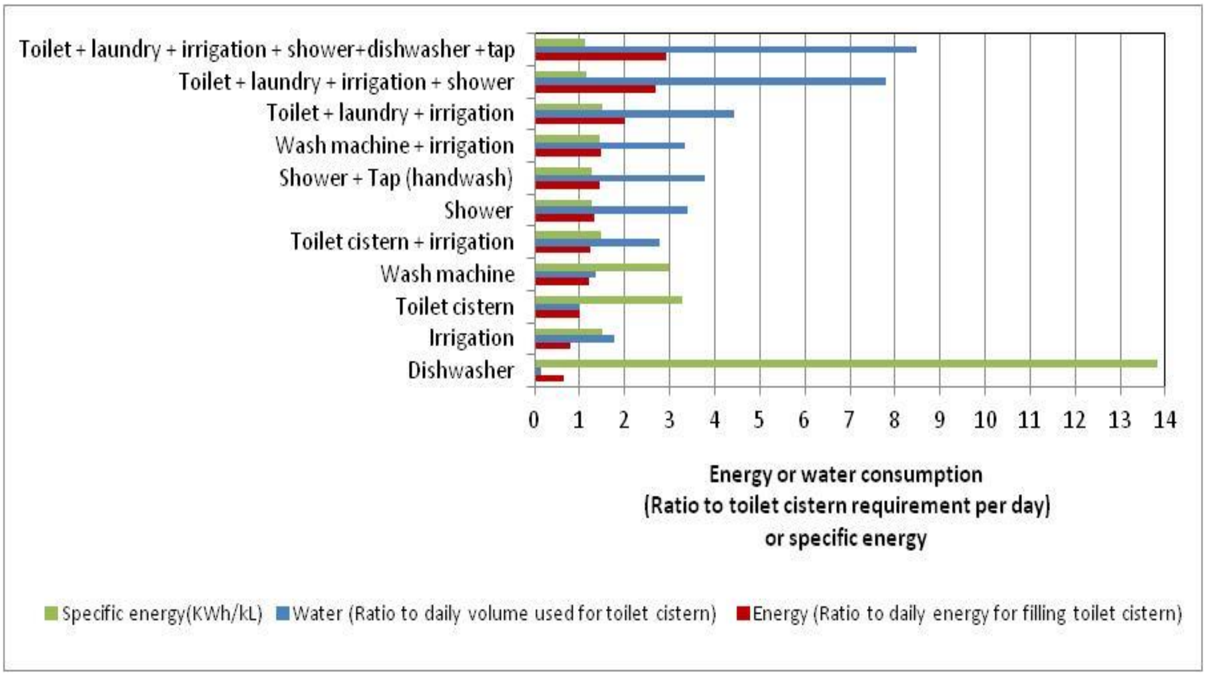


Figure 37: Comparison of specific energy, energy and water needs for dwelling with four occupants' household supplied by direct rainwater connection using pump B.

6.1. Stand-By Energy

SEWL (2010) examined the role of stand-by energy and other non-active energy uses on the overall pump energy consumption, and reported that the contribution from automatic switches could represent 20 to 40% of the total energy consumed by a rainwater system.

The stand-by energy of a pump is a characteristic of the specific design of each pump and switch system. However, the active energy component, which is determined by the pump operating time and hence by the frequency and type of end uses in a dwelling, is typically a more significant energy component than the stand-by energy.

This study estimated the stand-by and active energy for households of up to five people assuming that rainwater is supplied to a toilet cistern, washing machine and garden irrigation with appliance usage as outlined in section 3.7 with two different pumps, B (0.55kW) and C (0.75kW). The estimates are shown in Figure 38.

In Figure 38, pump C has a lower stand-by energy than pump B (Figure 38). For pump B (0.55 kW), the stand-by energy (in kWh/d) contributed between 26% to 47% of the total pump energy consumption, with the relative contribution of stand-by decreasing as household size increases (1 to 5 people) (Figure 38). For pump C (0.75 kW), stand-by contributed 16% to 33% of the total energy, and was again inversely proportional to household size.

In both cases, the pump operating time was less than 3% of the total hours in a day, therefore the stand-by energy component changed very little despite household size. Hence, consideration of energy requirements for individual stand-by requirements for pump and switch design are worthy of attention to reduce energy requirements for pump operation, particularly for low occupancy dwellings. However, it is the active energy of pumping that is responsible for the major energy burden associated with rainwater supply (Figure 38).

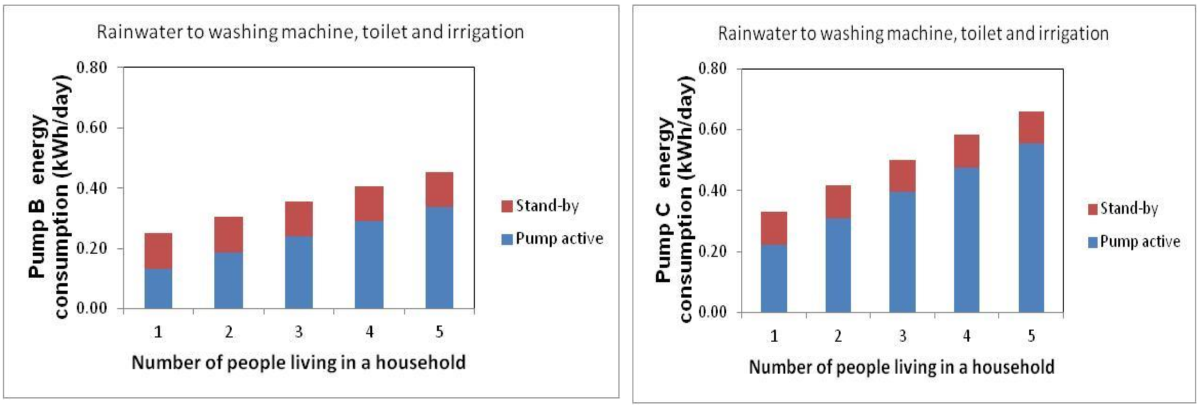


Figure 38: **Estimated daily energy consumption for stand-by use and pump active use to supply rainwater to households of various sizes using (left) pump B (0.55kW) and (right) pump C (0.75kW).**

The distribution between energy for pump stand-by and activity changes as more end uses are included (Figure 39). This is attributed mostly to the increase in energy consumption for pump operation, because the stand-by energy varies by less than 10% (~0.12 KWh/d ± 10%) despite of the larger number of end uses.

This is reinforced in Figure 39, which shows the estimated impact of changing the type and number of rainwater end use combinations in a household of four people with pump B. For any given household occupancy, the energy will be determined mostly by the end uses in the dwelling, with stand-by energy becoming less significant as rainwater end use is increased (Figure 39). Further estimates on the breakdown between active and stand-by energy under different end use scenarios are shown in Appendix E.

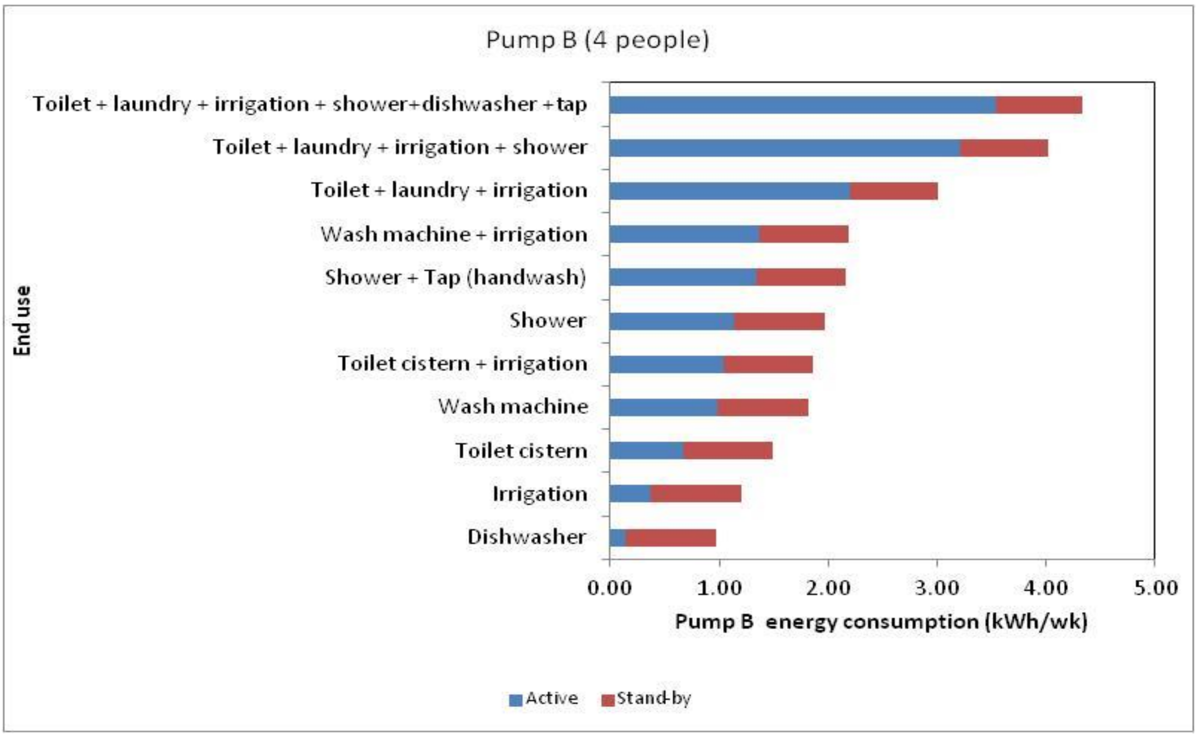


Figure 39: **Active and stand-by energy consumption under various end use patterns for a household of four people using pump B (0.55kW).**

6.2. Rainwater System Costs

The life cycle costing of individual tanks systems has been previously reported in Marsden Jacob Associates (2011), Stewart (2011) and Gurung *et al.* (2012). According to these studies summarised in Table 17, the major cost components are the capital investment for purchase of the rainwater harvesting system and its installation, which represent over 71% of the total costs (Marsden Jacob Associates 2007, Stewart 2011, Gurung *et al.* 2012). Operating costs, and in particular electricity costs, were deemed minor, e.g. 2% of total operating costs in Gurung *et al.* (2012).

To illustrate the significance of electricity costs associated with pumping from a rainwater tank to the householder, the daily energy consumption and the equivalent cost in electricity supply for pump B at the current rate of 22.76 c/kWh (Gurung *et al.* 2012) were estimated. The pumping cost would add \$1.59 to \$2.59 per month to the electricity bill for a dwelling with an occupancy of one to four inhabitants.

Table 17: Breakdown of costs associated with individual residential rainwater systems.

Components	**Breakdown of Total Cost for Rainwater Harvesting (%)**		
Tank cost (%)	30	80- 82	53 16 (replacement of pumps and tanks at end of life)
Water pump cost (%)	35		
Installation and plumbing cost (%)	25		
Operation and maintenance cost (%)	10	8	29 2 (electricity)
Lifetime assessed	50 years	25 years	50 years
Reference	Marsden Jacob Associates (2007)	Stewart (2011)	Gurung *et al.* (2012)

A dwelling with four people that uses rainwater for toilet, irrigation and washing machine was estimated to use 66, 148 and 213 kWh/yr for the respective pumps A, B and C (Table 18). Hence, adopting pumps A and C instead of B could change the yearly energy consumption and greenhouse gas emissions by -0.56% and + 43%, respectively.

In addition, the time of active pumping of a system will be determined by the water end use and configuration of the system. Thus, leaks in the system or different end use patterns will vary the energy requirements for a dwelling.

Table 18: Energy and greenhouse gas estimates for a dwelling of 4 people with rainwater supply to toilet, washing machine and irrigation. Based on the water usage assumption described in Athuralya *et al.* (2008).

Pump	Energy (kWh/hh/yr)	GHG (kgCO2/hh/yr)
A	66.1	69.0
B	148.2	155.1
C	212.8	222.6

Note: Based on the greenhouse emission rate of 1.046 $KgCO_2/kWh$ (Talebpour *et al.* 2011)

Pressure vessels were shown to reduce the active pumping time and the increase the energy efficiency of water delivery. Adoption of pressure vessels also allows reduction in energy consumption, but represents an additional capital cost component. Table 19 shows the costs of components for a standard rainwater system as reported by Gurung *et al.* (2012). The cost for pressure vessels was obtained from Australian retailers and range from \$290 for a 40 L vessel to \$1,410 for a 300 L vessel. In addition, they require installation by a plumber (\$80/hr).

The average upfront cost for a typical rainwater tank system with direct connection from the pump to the various end uses in a dwelling is reported to be $3,638 (Gurung *et al.* 2012). Addition of a pressure vessel to the system would increase the upfront cost by 10.1% for a 40 L vessel and up to 20% for a 100 L pressure vessel.

Table 19: Individual components costs (Adapted from Gurung *et al.* 2012).

Component	**Average Cost ($)**
Tank (5kL)	1,529[a]
Pressure vessel 100L	656[b]
Plumbing	842[a]
Concrete pad	700[a]
Installation	567[a] 80[b] (pressure vessel installation)
Maintenance	130[a] (annual) / 162[a] (tri-annual)
Operation (electricity)	$0.2276/kWh
Total upfront cost	$3,638 (standard) or $4,374 (with 100 L pressure vessel)

Note: [a]Gurung *et al.* (2012), [b]This study.

7. DISCUSSION ON ENERGY OPTIMISATION OF RAINWATER SYSTEMS

Under the current climatic and urban conditions, there is a need to reduce the energy footprint of urban water supply and energy optimisation is now essential.

In the design of rainwater harvesting systems, energy has not been a major concern to date, partly because of the way in which rainwater has been traditionally used in Australia. It is typically adopted for supply to dwellings isolated from the water grid, and hence provides all water needs in the dwelling. In such instances, rainwater is often the only source of water, and high pressure and flow applications are required to deliver an acceptable level of service. However, as rainwater evolved to become a supplementary source of water in urban areas, co-existing with other water sources, the range of allowable end uses for rainwater has been restricted to toilet flushing, laundry cold water taps, outdoor taps and in some states supply to hot water systems, with the first three uses the most widely promoted. In addition, as Australian society has moved towards increased water efficiency and water conservation since the mid-2000s, there have been significant changes in the design of water using appliances and fittings aimed at the reduction of the water usage and flow rates during operation (as discussed in section 3.6).

On the other hand, the pumps for domestic rainwater use are still designed to operate at their best energy efficiency at flow rates greater than 20 L/min. When operating for supply to toilet cisterns (4-6 L/min), washing machines (6–14 L/min) and flow restricted taps (< 15 L/min) they operate in their high energy intensity range. For those end uses, selection of a pump that can deliver the required service conditions with the lowest energy requirements would assist in reducing the energy footprint. Although it is possible to compare the energy requirements of pumps by examining the specific energy curve to service flow provision, such curves are not provided by the pump manufactures at point of sale. The lack of information available for comparison of existing pump systems is a major challenge to the optimisation of the system.

Pressure vessels are another item that can assist in reducing the energy usage. Their major advantage is supplying low volume and low flow rate end uses such as filling a toilet cistern, thereby reducing the active pumping time. However, their effectiveness is dependent on pump capacity and pressure trigger settings, and also on the volume requirements of specific end uses in a dwelling. The data in section 5.9.1 shows that adoption of a pressure vessel for a small pump, such as pump A, offers limited energy advantage, as the capacity of the pump to fill the pressure vessel is limited. However, pressure vessels were observed to substantially reduce the energy requirements for larger pumps. Again, almost no information is available to the public on the performance of pump and pressure vessels combinations.

The sizing of the pressure vessel also requires consideration. The larger the pressure vessel is with respect to the end use volume requirements, the least often the pump needs to start. However pressure vessel prices increase with its size.

In addition, it has been verified that the automatic rainwater to mains switch can malfunction when coupled to a pressure vessel. Consultation with pump and switch manufacturers is required to develop an alternative system configuration that allows the adoption of pressure vessels in systems with the automatic “rainwater to mains” supply switch. The modification of such a switch should encourage the installation of pressure vessels.

Other factors that need to be considered in the rainwater system design include the infrastructure losses, which in our standard laboratory set-up were negligible (<6%), but these can vary for individual dwellings.

The results showed that much of the variability observed for rainwater pumping will be dictated by the range of end uses, the frequency and duration of pump operation, and the pump characteristics including motor capacity. Whilst it is possible to select system elements, ancillaries and system configurations to optimise the pumping energy, these need to be matched on a case by case basis.

8. IMPLICATIONS FOR POLICY

Rainwater tank policy has, to date, focused on the uptake and implementation of rainwater tanks in urban areas for the security of water supply. Energy has received very little consideration in system design, despite the potential implications to greenhouse emissions. The experimental results indicate that optimisation of rainwater systems can be conducted to mitigate emissions.

Issues for consideration:

- Mismatch of end uses and pump design

  The emphasis on water efficiency for water using appliances and fittings has impacted on their operating design and requirements. There is currently a mismatch between the pumps' best energy efficient operating range and requirements for the recommended rainwater end uses, such as toilet cisterns and washing machines, which have restrictors to control the water flow rate into the appliance. It is possible to reduce the energy required for pumping by either: (i) adopting small kW pumps that fulfil level of service requirements, whilst having low energy consumption; or (ii) by increasing the rate of rainwater supply. To achieve (i), it would be necessary to create a benchmark that allows comparison of the energy performance of different pumps models and service conditions. The feasibility of this option would require collaboration and buy-in from pump manufacturers. To achieve (ii), it is possible to adopt pressure vessels in a system, or alternatively consult with appliances manufacturers about design modifications to the water inlet valve of appliances. For either option, further discussion and investigation would be required.

- System design improvements

  Rainwater systems need to be considered as a "system" and not as components in isolation. The data has shown that energy optimisation can be achieved in different ways and it is also impacted by the various factors in a system (pumps type and design, number and type of appliances, infrastructure, dwelling occupancy, etc).

- Access to information, consumer education and manufacturer

  Limited information and unfamiliarity with rainwater system operation in urban areas are likely to be a key contributors to the mismatch of sub-systems. Providing access to information on the system set-up and tools or applications that can assist householders and plumbers to understand and improve the design of their systems (e.g. estimate losses in the system, end use requirements and match pumps to their individual needs) would improve overall design. This will also require discussion with appliance manufacturers to get a better understanding of the water end use needs and to ensure greater compatibility with pressure vessels and consider low pressure solenoids to operate with header tanks. Discussions are also needed with pump manufacturers on pump characterisation and design improvements, including information available for comparison of existing pump systems. Consultation is also suggested with the plumbing industry on the set-up and installation of systems.

- Promoting best practices in energy conservation

  In addition to water delivery, consideration could also be given to the promotion of best practices in energy efficiency, such as the inclusion of pumps in the energy rating scheme to benchmark energy efficiency. This would promote consumer awareness towards energy efficiency and would also serve as an incentive to encourage product development towards energy efficiency and greater sustainability.

9. CONCLUSIONS

The research highlights that there is a large variation in the energy usage associated with rainwater supply for urban dwellings. Design of the rainwater pumping system with proper selection of ancillary components has potential to reduce the energy usage in rainwater pumping systems. To achieve optimal energy use for rainwater supply, it is necessary to first understand the operational aspects and limitations of the various system components. The research shows that:

- Pumps are most economic when performing in their best efficiency range, at which energy requirements are minimised. For pumps adopted in urban dwellings, the best efficiency range occurs at high flow applications (>22 L/min). In contrast, the majority of household water end uses requires low water flow (<14 L/min), causing the pump to operate in the low energy efficiency range.
- System energy efficiency varies with pump capacity, type and make. Correct pump sizing and informed selection of system components could reduce specific energy values to less than 1.5 kWh/kL, which is much lower than the energy footprint of alternative water sources such as desalination and recycled water. To achieve energy efficiency, rainwater system design needs to assess the configuration of the system adopted for rainwater supply and the water end use requirements (operating pressure and flow) for the appliances, and other rainwater end use in individual dwellings.
- The efficacy of header tanks and pressure vessels to reduce energy and deliver suitable service has been examined. Header tanks providing water by gravity supply have the potential to produce a marked energy reduction in the pumping of rainwater. However, their application are hampered by the minimum operating pressure requirements of common domestic appliances, which are designed for pressurised systems, and by the current single story dwelling heights. Under the current house design, insufficient pressure would be generated by placement of a header tank in the roof cavity of a single storey dwelling for operation of common appliances such as a toilet cistern and a washing machine. However, adoption of header tanks and gravity feed systems could be revisited upon discussion with manufacturers on the redesign of appliances with water inlet valves for low pressure/flow supply.
- Pressure vessels, if properly sized, have the potential to reduce the energy consumption and maintain suitable pressure and flow for appliances. A pressure vessel can help reduce low-flow, low-volume, high-energy intensity water requirements, while maintaining system pressure. In selecting a pressure vessel, it is necessary to match the volume of water released to the end use water requirements. Pump pressure settings will also impact the released volume, and could be further explored in discussion with manufacturers. One caveat, observed during examination of pressure vessels, was the need to devise a system configuration that allows the use of an automatic rainwater to mains switching system when a pressure vessel is adopted, given that the automatic switch would by-pass the rainwater supply in the pressure vessel set-up examined in the laboratory. It is recommended that compatibility of various switches with pressure vessels is verified with manufacturers.

Overall, increasing the access to information on how system components operate and water requirements of various appliances in urban dwellings is the most effective tool to improve design for energy efficiency. The research can also encourage pump and other accessories manufacturers to come up with energy efficient products for rainwater supply systems.

APPENDIX A: Standards and Guidelines

Table 20: Standards relevant to rainwater tank and components.

Category	***Standard***	**Major Requirements**
Product minimum quality	*AS/NZS 4766:2006 Polyethylene storage tanks for water and chemicals*	Thermal stability: Polyethylene base resin used in compounds for tanks shall contain anti-oxidants, either singly or in combination, such that, when determined in accordance with Appendix B, the percentage melt index change shall be not more than 20% of the base resin value Carbon black for UV stability: When determined in accordance with ISO 6964, polyethylene compounds containing carbonblack to provide UV stability shall contain 2.25 ±0.25% by mass of carbon black. UV resistance: When tested in accordance with ASTM D2565, the polyethylene compound for tanks, fusion-bonded fittings and welding rods shall contain UV stabilizers such that the natural(non-pigmented) compound will retain 50% tensile elongation after 8000 h of exposure in a Xenon-Arc weatherometer. Tanks certified to AS/NZS4766:2006 need to be identified with manufacturer's name, tank capacity, date of manufacture, serial number and standard number. Installation: see manufacturer's recommendations.
Product minimum quality	*ATS5200.466 2004 : Technical Specification for plumbing and drainage products - Rainwater tank connection devices*	Performance requirements: • Products in contact with water • Hydraulic test strength • Water tightness • Endurance test The device shall be installed and commissioned in accordance with the manufacturer's instructions. With a pressure of between 500 and 800 kPa applied to the mains supply inlet and at the manufacturer's maximum flow rate, the device shall be operated in its normal manner through rainwater/mains supply/rainwater for 50 000 cycles. During this period there shall be no leakage, visible or functional failure of any component of the operating mechanism and the operational characteristics of the device shall not evidence any change, i.e., discharge pressure mains/rainwater.
Product minimum quality	*ATS 5200.467-2004* : Technical Specification for plumbing and drainage products - Rainwater tank connection valve	Performance requirements: • Products in contact with water • Pressure resistance • Endurance test (500-800kPa 2000 cycles) • Installation instructions shall be provided. Maintenance instructions: "The manufacturer shall provide maintenance instructions, which shall include the following: (a) Any regular maintenance requirements including routine service to be undertaken and frequency of service, i.e., cleaning of filters, routine operation of switching mechanism. (b) Spare parts information (c) Troubleshooting guide. (d) Contact details for after-sales service." Operating instructions Consumer instructions shall be provided in a form suitable for display at the location of installation, e.g., affixed to the rainwater tank.
Product minimum quality	AS 3735-2001 Concrete structures for retaining liquids	It does not apply to concrete tanks of less than 25kL.
Design and installation	HB- *230-2008* : Rainwater Tank Design and Installation Handbook	Applications: (a) Laundry washing machine connection. (b) Toilet flushing. (c) Outdoor use. (d) Pool/pond/spa top-up. (e) Garden irrigation. (f) Hot water use. (g) Fire fighting. (h) Cooling towers. (i) Drinking water uses. Pressure requirements: AS/NZS 3500.1 maximum static pressure at any outlet (other than fire service) max 500kPa, min50kPa at the minimum flow rate required at least disadvantaged outlet. Minimum pressures for appliances. Check list for ordinary maintenance over time provided. Estimates of water use per appliance.

APPENDIX B: Estimation of Pipe Length

The length of pipe from a rainwater tank to the end use in a dwelling depends on the location of the tank, the location of end uses in a house and the configuration and space available in a property. As no data could be found on the actual length of pipework from rainwater tanks to the end uses in dwellings, we resorted to the estimation of the length range. According to data from the ABS (2008), new houses built in New South Wales, Victoria and Queensland have increasingly larger floor areas.

In Queensland the average floor house for new houses in 2006-07 was 239 m^2 and for other dwellings (units and apartments) was 153 m^2.

Adopting the mean floor area as a reference we examined a sample of 30 floor plans of entry level price houses sold in SEQ by large developers. The floor mean floor area of the sample was 215.6 $\pm$ 50.1 m^2, with floor areas ranging from 111 to 340.7m^2. Majority of the dwellings, 83.3% had two toilets, and the remainder had one only. We assumed that a rainwater tank was located either at the back or the side of the house in proximity to either the laundry or the closest toilet. Afterwards the pipe work from the tank to the toilet and the laundry was assumed to run along the pipe walls to minimise the number of bends and the length of the overall pipework for each dwelling. The mean length of rainwater pipe estimated was 22.9$\pm$9.6 m, within the range of 2 to 44.8m.

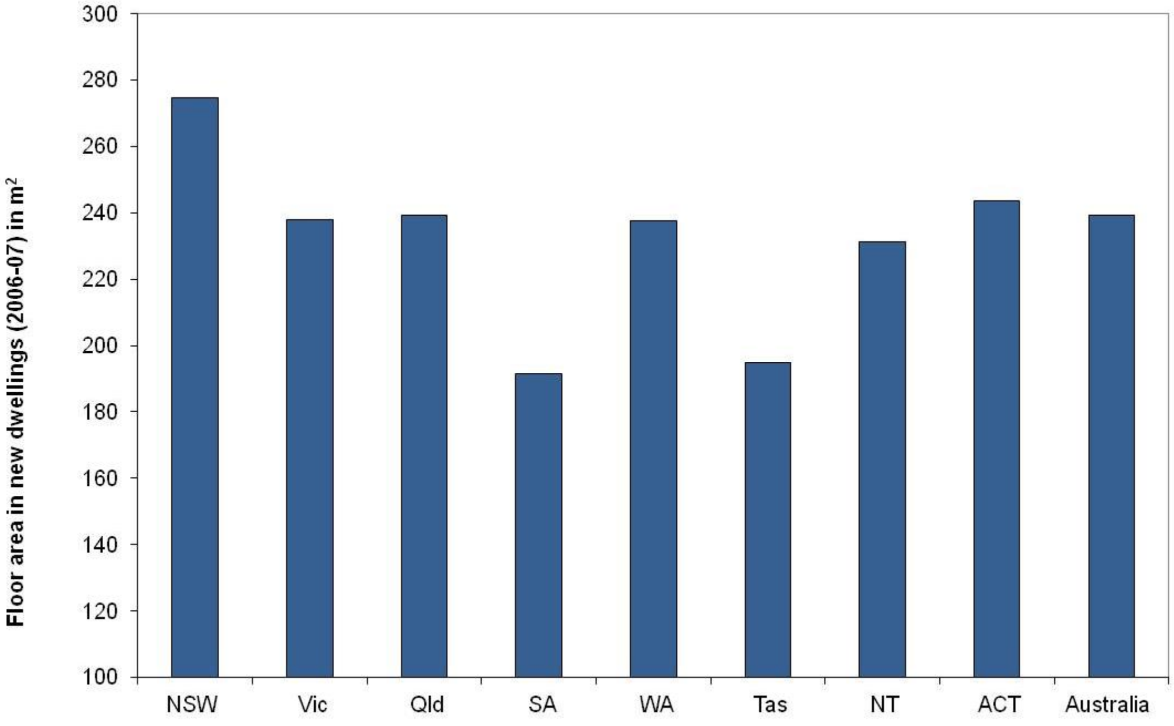


Figure 40: **Average floor area in new houses across Australia in 2007 (Adapted from ABS 2008).**

APPENDIX C: Laboratory Floor Plan

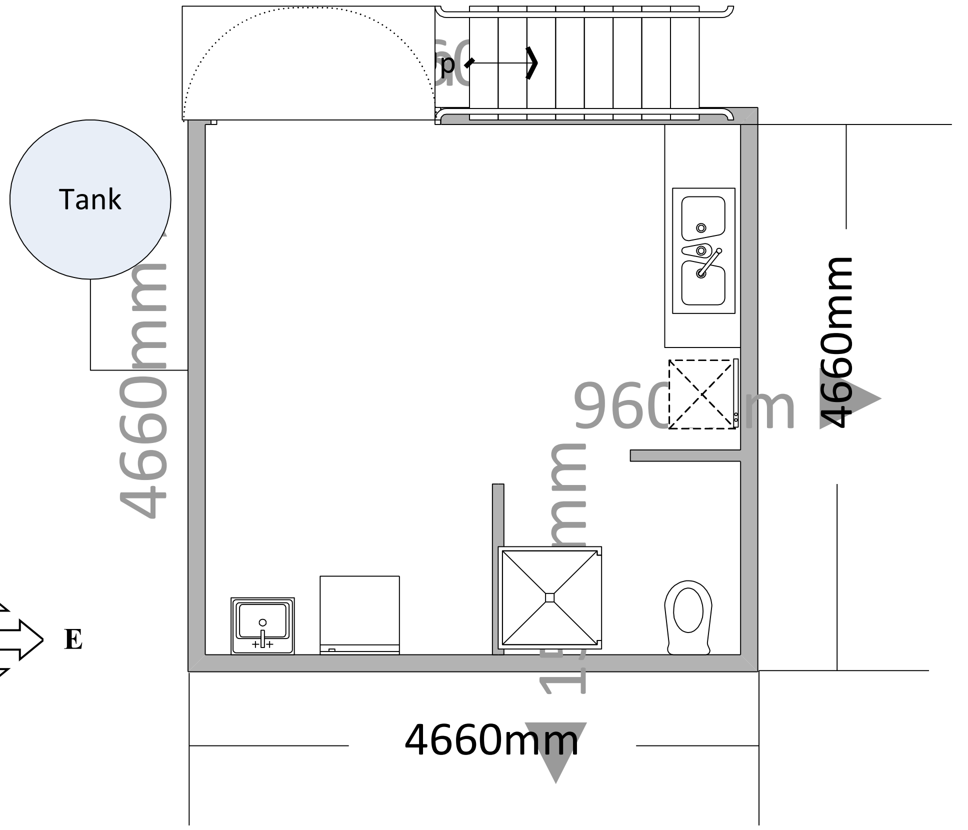


Figure 41: **Top view of test set-up for rainwater supply.**

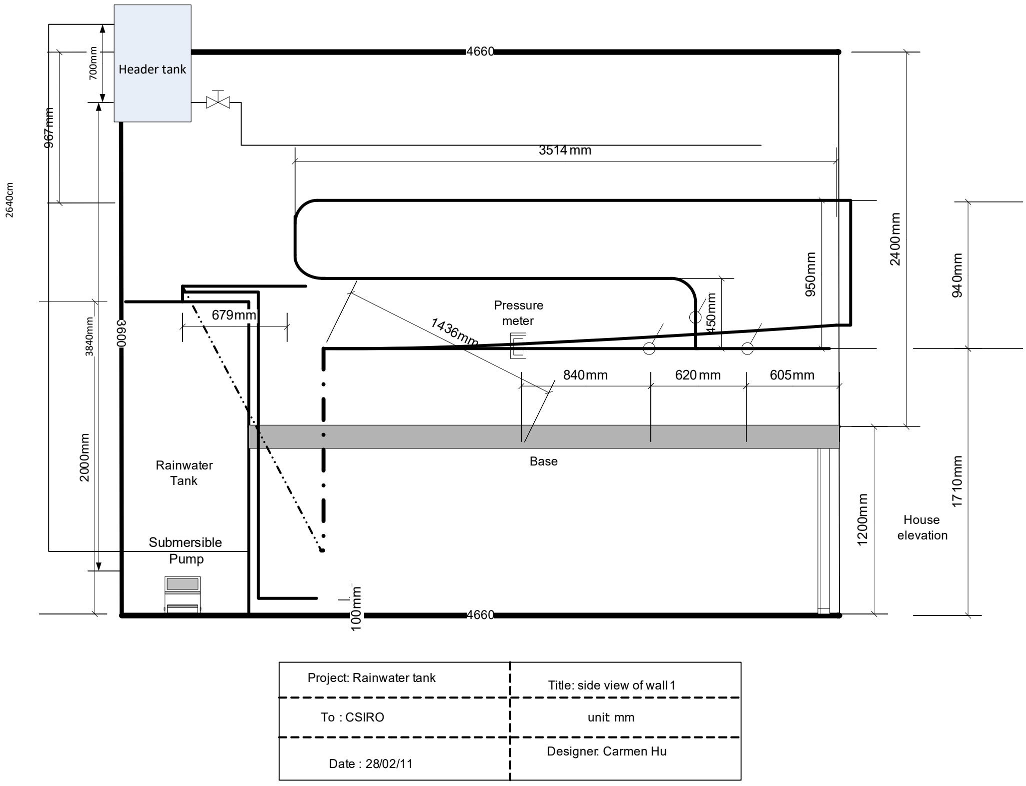


Figure 42: **Diagram of west wall of rainwater tank laboratory.**

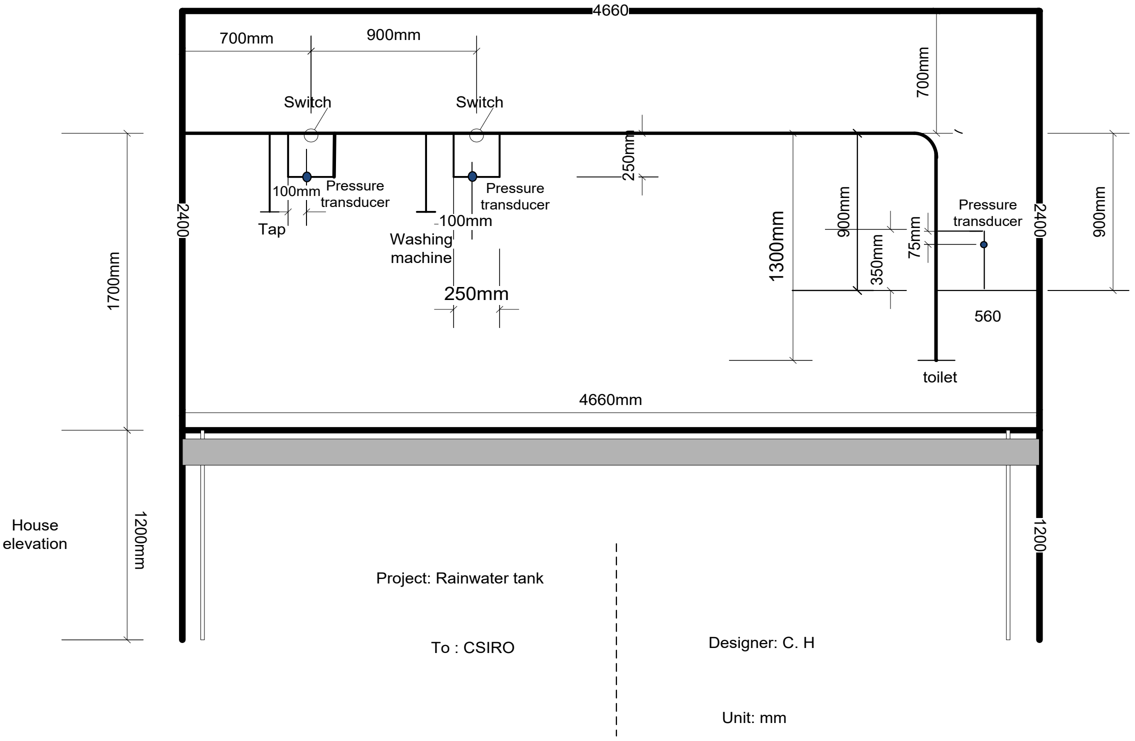


Figure 43: Diagram of south wall of rainwater tank laboratory.

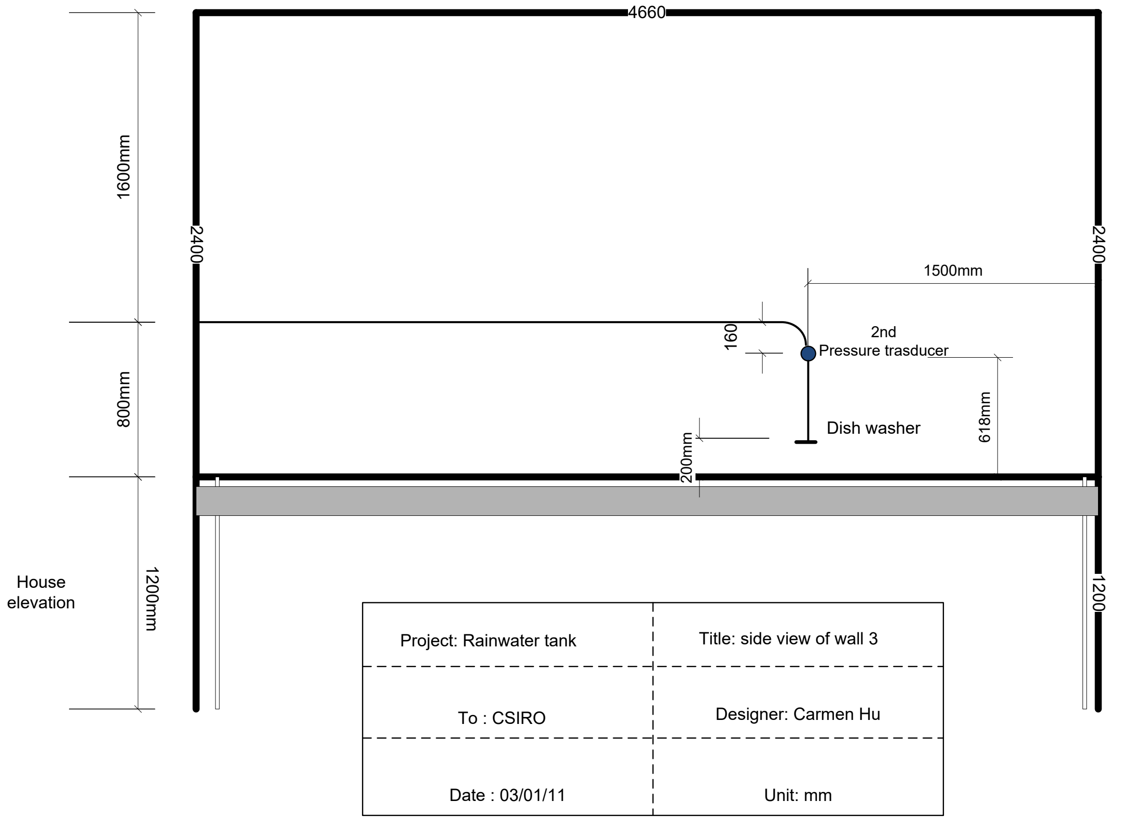


Figure 44: Diagram of east wall of rainwater tank laboratory.

APPENDIX D: Simultaneous Operation of Appliances and Associated Energy Needs

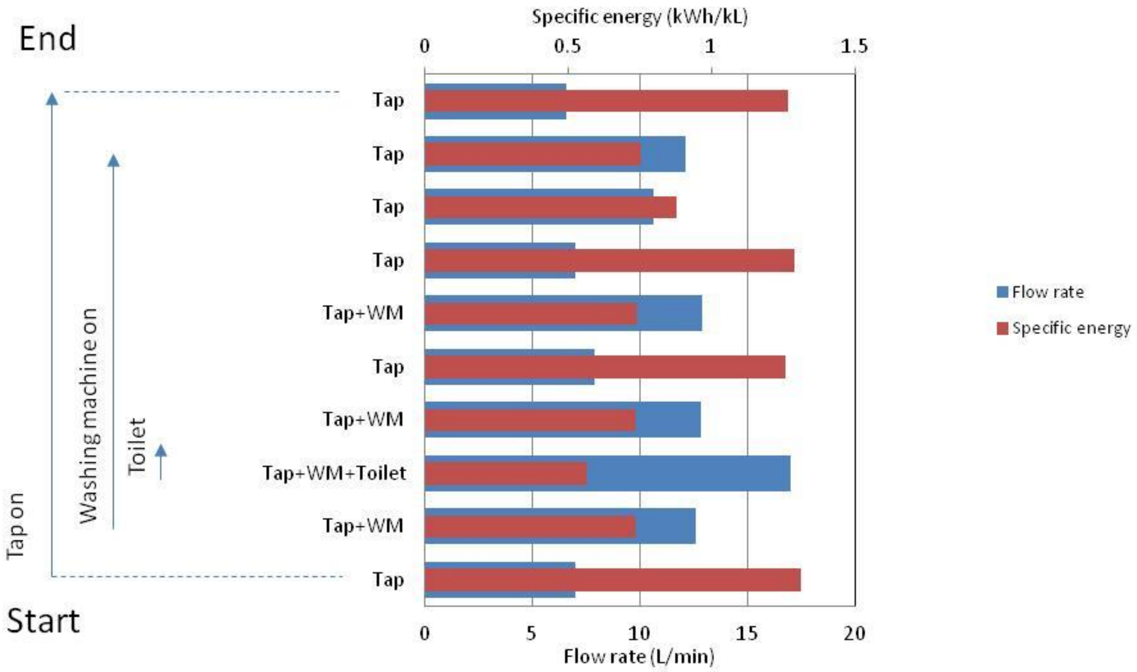


Figure 45: Rainwater supply using pump B during simultaneous appliance operation. The tap was opened first at 6L/min, then the washing machine was activated and the toilet was flushed. Because the washing machine cycle has various water supply events, the flow of water supplied and the specific energy vary during the run.

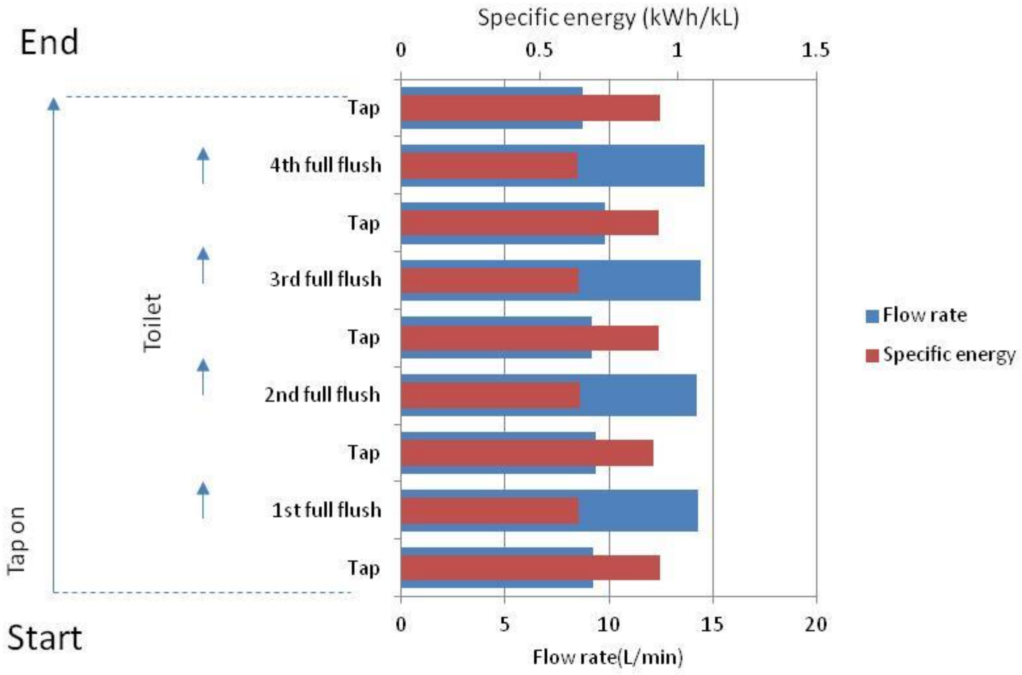
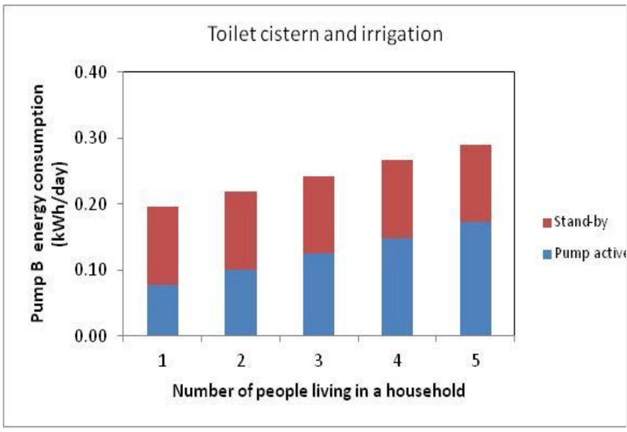
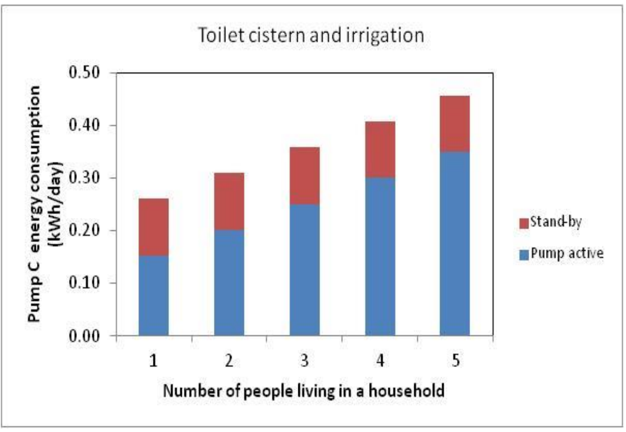
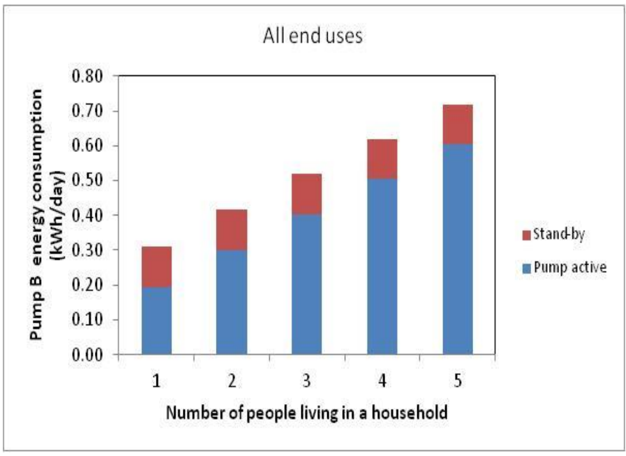


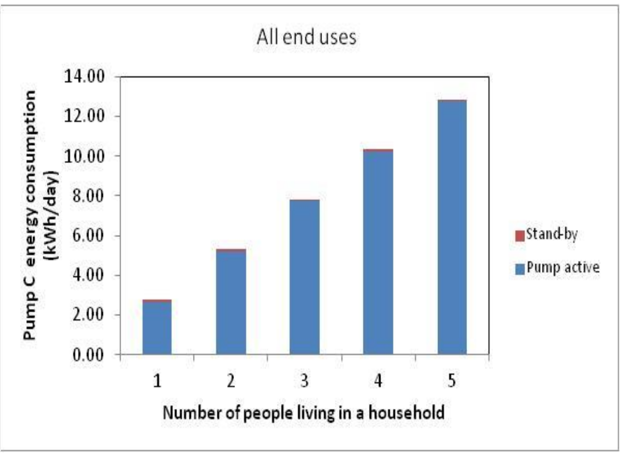
Figure 46: Rainwater supply using pump B during simultaneous appliance operation. The tap is opened at 8L/min, then while the tap is on the toilet is flushed on four occasions, increasing the flow rate and reducing the specific energy.

APPENDIX E: Stand-By Energy Evaluation Under Alternative End Use Scenarios









APPENDIX F: Publications

Tjandraatmadja, G., Pollard, C., Sharma, A. and Gardner, T (2011) Dissecting rainwater energy use in urban households, in Begbie, DK and Wakem, S.L. (eds) (2011) Science forum and Stakeholder engagement: building linkages, collaboration and science quality, Urban Water Security Research Alliance, 14-15 September, Brisbane, Queensland. Accessed Jan 2013: http://www.urbanwateralliance.org.au/publications/forum-2nd-2011/science-forum-2011-program-abstracts.pdf

Summary: Rainwater tanks are a viable alternative to reduce the demand of mains water and increase the resilience of cities to drought. However, previous studies have found that the energy footprint of rainwater systems can be much higher than the energy footprint for traditional water distribution and is also subject to high variability across various systems in use. This study investigated the operation of pumps used for rainwater supply in a controlled residential environment (a model house) to understand the factors affecting the energy footprint for rainwater supply in urban areas. Pumps commonly installed in urban households operate more efficiently for high flow applications (>15 L/min). However, the majority of household water end uses requires low water flow (<10 L/min), causing the pump to operate in the low energy efficiency range. Energy efficiency varies for each pump. Correct pump sizing and informed selection of system components could improve energy efficiency significantly to <1.5 kWh/kL, lower than or close to the energy footprint of other alternative water sources such as desalination and recycled water.

Tjandraatmadja, G., Pollard, C., Sharma, A. and Gardner, E.A (2012). Rainwater system design for urban residential households – the role of header tanks and pressure vessels in improving energy efficiency, in Begbie, DK, Wakem, S.L., Kenway, S.K. (eds) (2012) Science forum and Stakeholder engagement:building linkages, collaboration and science quality, Urban Water Security Research Alliance, 18-19 June, Brisbane, Queensland. Accessed Jan 2013: http://www.urbanwateralliance.org.au/publications/forum2012/UWSRA%20Science%20Forum%20-%2019-20%20June%202012.pdf

Summary: Pumps are most energy effective when performing in their best efficiency range, at which energy requirements are minimised. However, in urban dwellings typical end uses for rainwater can have flow and volume requirements which cause the pump to operate at a high specific energy for rainwater delivery. In an attempt to reduce the overall energy for rainwater delivery a number of rainwater system configurations have been proposed. We examined some of the most common components (pump sizing, header tanks, pressure vessels and infrastructure pipe size) to determine their potential to increase the energy efficiency of rainwater pumping systems for a single storey dwelling. Whilst all measures can improve energy efficiency, dwelling characteristics and appliance design can limit the effectiveness of some system components, such as gravity fed header tanks. Greater access to information on how system components operate and service requirements in urban dwellings is the most effective tool to improve design to achieve increased energy efficiency.

Tjandraatmadja, G., Pollard, C., Sharma, A. and Gardner, T (2012). How supply system design can reduce the energy footprint of rainwater supply in urban areas in Australia, Proceedings of the 3rd IWA-Rain Water Harvesting Management Conference and Exhibition, 20-24 May 2012, Goseong, Korea, IWA RWHM.

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. 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. Therefore 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 footprint for rainwater supply in urban dwellings. Results show the impact of end uses, pump size and switches on the effectiveness of pressure vessels in reducing the energy footprint for rainwater supply.

Tjandraatmadja, G., Pollard, C., Sharma, A. and Gardner, T (in press). How supply system design can reduce the energy footprint of rainwater supply in urban areas in Australia, Water Science and Technology: Water Supply (in press), IWA Publishing.

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.

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