

Investigation and Monitoring of Twenty Homes to Understand Mains Water Savings from Mandated Rainwater Tanks in South East Queensland

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Cover Photograph: Mandated Rainwater Tank System

Description: Household mandated rainwater tank system
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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>.



Chris Davis

Chair, Urban Water Security Research Alliance

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EXECUTIVE SUMMARY

The aim of this study was to quantify the mains water savings that could be achieved in detached residential dwellings with internally plumbed rainwater tanks in South East Queensland (SEQ). Twenty Class I dwellings were monitored for their water and energy consumption associated with the use of their rainwater tanks. All the chosen dwellings were constructed after 2007 and were therefore expected to meet the requirements of the Queensland Development Code (QDC) MP 4.2 – Water Savings Target that requires detached dwellings to achieve a mains water savings of 70 kilolitres per household per year (kL/hh/yr). An accepted method to achieve these savings is to install a rainwater tank of 5 kilolitres (kL) capacity or greater, connected to 100 m² roof area, and internally plumbed to the toilets, washing machine cold water tap, and at least one external tap.

The primary focus of this study was to validate the mains water savings due to the implementation of mandated household rainwater tanks. The 20 selected dwellings were distributed across four densely populated Local Government areas in SEQ: Pine Rivers and Caboolture (now part of the Moreton Bay Regional Council), Gold Coast (Gold Coast City Council) and Redlands (Redland City Council). This study also reports on the continual monitoring of water flows at various points in the households as well as monitoring of their respective energy consumption patterns. The report presents a discussion on the volumetric reliability of rainwater through water balance analysis, diurnal pattern analysis and the energy consumption over a 12-month period from April 2011 to April 2012.

A previous desktop analysis by Beal *et al.* (2012) found that the average savings in potable (i.e. mains) water in internally plumbed rainwater tank (IPT) households across three SEQ regions (Pine Rivers, Redland and Gold Coast) was around 50 kL/hh/yr for the year 2008. Their study used a pair-wise statistical analysis of water billing data to compare 1,183 randomly paired households of similar physical properties, with and without rainwater tanks in the three SEQ regions.

The Beal *et al.* (2012) study was followed by a more comprehensive benchmark analysis by Chong *et al.* (2012) that drew on the methodology used by Sydney Water to assess water savings from the BASIX (Building Sustainability Index) water and energy saving legislation in NSW (NSW Department of Planning, 2008). Here the water use from 691 detached dwellings of known demographic characteristics with internally plumbed rainwater tanks (IPTs), distributed over four local authority regions in SEQ, was compared with the community average mains water consumption for the same regions (Chong *et al.*, 2012). Water consumption data was obtained for Moreton Bay Regional Council (comprising the targeted Pine Rivers and Caboolture areas), Redland City Council and Gold Coast City Council. Their study found the average mains water savings per IPT household was 58.8 kL/hh/yr and 58.2 kL/hh/yr for the years 2009 and 2010 respectively, with a significant reduction in mains water consumption for all 4 regions, and with the largest savings for the Gold Coast and Redland regions.

The study documented in this report was conducted to validate mains water savings through internally plumbed rainwater tanks as reported in the literature, and to gain a detailed understanding of water usage patterns across the studied households on a real time basis through monitoring of 20 IPT households. The aim of the study was to analyse rainwater tank yields in response to various drivers such as climatic conditions, household occupancy, and various end uses of rainwater supply. During the initial stages of the study, householders were contacted from the database of 691 homes that had previously participated in the Chong *et al.* (2012) benchmark analysis, until a set of 20 householders, distributed over the four regions, consented to voluntarily participate in the study. On-site household audits were conducted for the 20 selected households and smart meters and remote telemetry data loggers were used to monitor the water and energy consumption patterns associated with the rainwater supply systems at each household. The smart water meters installed in the rainwater tank systems were capable of recording data at 0.5 L/pulse whilst the mains water meters provided 5 L/pulse outputs. The pulsed outputs from the water and energy meters were recorded at one minute intervals to loggers installed on-site, and the data was retrieved wirelessly.

The recorded data was analysed to determine the mains water savings, volumetric reliability of rainwater supply, internal and external (garden tap) water demand from rainwater tank, mains water supply backup for rainwater supply system, total mains water used, total household water consumption and energy consumption of the rainwater system. The 20 households were analysed both individually and as a cluster to understand their diurnal water demand patterns.

The analysis showed that the average reduction in mains water was 40 kL/hh/yr over the 12-month monitoring period, during which time the average total household water consumption was 151 kL/hh/yr. The average volumetric reliability, defined as the ratio of rainwater usage to total household water demand, was 31%. In addition, the diurnal pattern analysis for the cluster of 20 homes showed that the average household water demand was characterised by two water demand peaks occurring in the morning and evening. From diurnal pattern analysis conducted over a 4-month period, it was found that 28% of the total peak hour water demand was supplied through rainwater alone. The median peak water demand was estimated to be 26 L/minute.

The average energy usage for rainwater supply in the 20 homes was estimated to be 71.2 kWh/year, with an average specific energy of 1.52 kWh/kL. The median specific energy for homes with mechanical trickle top-up systems (1.59 kWh/kL) was slightly higher than those with electronic switching devices (1.46 kWh/kL).

Although the sample size (houses for monitoring) used in this study is small from a statistical standpoint, the study has been useful in examining the various factors that either directly or indirectly influence the mains water savings in household with internally plumbed rainwater tanks in South East Queensland. Monitoring and validation are required to determine the effectiveness of alternative water systems implemented under strategic urban water planning to address the increasing load on potable water resources, and to implement sustainable water demand management initiatives. This study constitutes an important piece of research, providing critical input into strategic urban water planning for sustainable water resource management.

1. INTRODUCTION

1.1. Background

The aim of this research was to investigate mains water savings achieved through mandated internally plumbed rainwater tanks in detached dwellings. Mandated rainwater tanks have been installed in all new detached residential dwellings in South East Queensland (SEQ) to meet the requirements of the Queensland Development Code (QDC MP 4.2), effective January 2007, to reduce reliance on council supplied potable mains water. The code mandates that all detached households are required to meet a mains water savings target of 70 kilolitres per year (kL/yr). One of the acceptable measures to meet this target is the installation of a 5 kL rainwater tank connected to 100 m² of roof area which, in turn, is plumbed to household appliances such as the washing machine cold water tap, toilets and at least one external tap. The internal fixtures connected to the rainwater tank also require a back-up to the mains water supply either through a mechanical trickle top-up or an electronic switching valve system to ensure a continuous supply of water (Department of Infrastructure and Planning (DIP), 2008). Twenty households located in four local government areas in South East Queensland: Pine Rivers, Caboolture, Redlands and Gold Coast in SEQ were selected for rainwater use monitoring.

The focus of this research is on households located in regions across South East Queensland, which have been previously been examined by several research groups (i.e. Beal *et al.*, 2012; Chong *et al.*, 2011a) for reasons of high population density and rapid growth in new greenfield urban residential developments. Beal *et al.* (2012) conducted a pair-wise statistical analysis where 1183 households with plumbed rainwater tanks were randomly paired with households without rainwater tanks, but of similar biophysical characteristics, to estimate mains water savings by comparing their water billing data for 2008. In a similar study in the same geographic areas, Chong *et al.* (2011b) performed a benchmark analysis of 691 households with plumbed rainwater tanks using their mains water billing records and comparing them with the regional average residential water demand for the same period (years 2009 and 2010). The study by Beal *et al.* (2012) found an average mains water saving of 50.5 kL/hh/yr across three local government areas (LGAs): Pine Rivers, Gold Coast and Redlands for the year 2008. Chong *et al.* (2011b) included Caboolture into their study of Pine Rivers, Gold Coast and Redlands, and determined a mains water savings in 2009 and 2010 of 58 kL/hh/yr across the four LGAs.

However, both desktop studies indicated that the installation of a 5 kL raintank connected to 100m² roof catchment area may not be sufficient to collect sufficient rainwater to meet the mains water saving target of 70 kL/hh/yr. Imteaz *et al.* (2011) also conducted spreadsheet based water balance modelling to investigate the reliability of rainwater tanks in Melbourne and found that for a roof area of 150 m², it was almost impossible to achieve 100% reliability (for a 2 person household). Moreover, the supply gain from increasing tank size became insignificant for tanks over 5 kL.

Several other analytical methods and modelling tools have been reported in the past to predict rainwater harvesting potential from rainwater tank systems for combinations of various end uses, connected roof catchment, and tank size (Coombes and Kuczera, 2003; Fewkes, 2000; Khastagir and Jayasuriya, 2010). However, results obtained from these modelling analyses were generally not validated by experimental results to support their estimates. Hence, in order to determine the efficacy of household plumbed rainwater tanks, monitoring and validation are required to understand the effect of water planning strategies to address the demand on fresh water resources. The study described in this report aimed to quantify the magnitude of mains water savings achieved from plumbed household rainwater tanks and to validate mains water savings estimated by water balance analysis.

Apart from the monitoring and analysis of water consumption in households, the study also covered the energy perspective of operating plumbed household rainwater tank systems. Earlier studies monitoring the energy consumption of small estate rainwater supply systems in Australia were

conducted by Gardner *et al.* (2006) and Beal *et al.* (2010). The energy intensity of these estate-scale small water supply systems was found to be higher than centralised water supply systems, with an average value of 2.6 kWh/kL (Gardner *et al.*, 2006). Another study conducted by Retamal *et al.* (2009) found that the energy intensities in rainwater tank households using rainwater for toilet flushing, laundry and outdoor water use ranged between 0.9-2.3 kWh/kL. The differences in the intensities were found to be attributed to differences in pump sizes, presence of other system components, specific end uses and water use efficiency of the appliances. Nonetheless, Retamal *et al.* (2009) showed that the energy intensities in small scale decentralised systems were much smaller than that of large scale desalination plants.

The mains and rainwater consumption of a set of 20 dwellings were monitored to estimate actual water usage and volumetric reliability of rainwater tank systems. The 20 chosen homes were situated in the same regions previously studied in the work by Beal *et al.* (2012) and Chong *et al.* (2011a), which were: Pine Rivers, Caboolture, Gold Coast and Redlands. The real time monitoring data of the households commenced in April 2011 and continued for a period of one year, ending in April 2012. The water supply (mains water and rainwater) and demand arising from internal and external water use in these homes were monitored, and the performance of each home in achieving water savings were analysed together with the corresponding energy consumption, which was also measured in each household.

1.2. Research Leading to this Study

In order to assess the full potential of plumbed rainwater tanks to achieve the QDC 4.2 water savings target, and to resolve inconsistencies in some of the previous analyses, an extensive research project was undertaken in two distinct study phases prior to the current study. *Phase 1* (Chong *et al.*, 2011a) of the previous research was an analysis of the baseline characteristics of plumbed rainwater tank users in South East Queensland, undertaken through a telephone survey. In *Phase 1* of the study, telephone Computer Aided Telephone Interviews (CATI) surveys conducted for 1,134 new households (built after 2007) were used to confirm occupancy data and date occupied. Participants from Caboolture, Pine Rivers, Redland and Gold Coast subsequently gave consent to access their mains water billing records for *Phase 2* (Chong *et al.*, 2012) study. *Phase 2* of the research involved a benchmark analysis of water savings by plumbed rainwater tank users using water billing records of households with mandated tanks in comparison with the average mains water use across the same regions. Results obtained from *Phase 1 and Phase 2* showed that households constructed under the QDC MP 4.2 did not meet the 70 kL/hh/yr mains water saving target. This led to an extension of the research project with real-time monitoring studies of the rainwater systems to gain a better understanding of the reliability of mandated rainwater tanks.

1.3. Purpose of Study

As the implementation of plumbed rainwater tanks is still relatively in its infancy, an in-depth understanding of the effectiveness of rainwater tanks through actual monitoring or process validation of their contribution towards mains water savings is important for water professionals and policy makers. Hence, this study aimed to provide an improved insight into the real world performance of plumbed rainwater tanks in SEQ.

The regions targeted for the study include Caboolture and Pine Rivers (now in Moreton Bay Regional Council), Redland City Council and Gold Coast City Council, which have all been the focus of previous analyses by Beal *et al.* (2012) and Chong *et al.* (2011a). Recently, Chong *et al.* (2012) have shown water savings at IPT households in Pine Rivers and Caboolture to range from 24 – 39 kL/hh/yr and 37.3 – 40.9 kL/hh/yr respectively between years 2009 – 2010. In contrast, IPT households in the Gold Coast and Redlands were shown to have mains water savings range from 81 – 88.5 kL/hh/yr and 71 – 84 kL/hh/yr respectively between years 2009 and 2010 for the same study. A potential reason for lower mains water savings could be lower water demand in IPT households in Pine Rivers and

Caboolture regions due to drought imposed obligatory water restrictions that were not uniformly applied to all of SEQ. (Beal *et al.*, 2012). Previous studies conducted in these regions to assess mains water savings from rainwater tanks were mostly based on estimations and modelling. Hence, validation of these estimated results was considered essential by implementing actual monitoring and assessment of these systems. This study aimed at determining the actual allocation of rainwater resource for various end uses within the households. The reliability of rainwater supply and the mains water required to back up the rainwater tank systems were also determined, along with the total water demand within the household. In order to assess the energy required to run the rainwater tank system, the pumping energy requirements were also monitored. Hourly and minute peak water demands in the households were plotted for individual homes as well as for the cluster of 20 homes. The plotted peak water demand curves were used to determine peak demands. This information will help designers in understanding the flow patterns in IPT households.

2. METHODOLOGY

2.1. Selection of Households and Sample Distribution

The real-time monitoring of 20 detached dwellings with plumbed rainwater tank systems was undertaken in the LGAs of Caboolture, Gold Coast, Pine Rivers and Redlands in SEQ. These areas have been in focus during recent years owing to their high growth rate and population density, resulting in growing water demands. The newly built (post 2007) houses in these regions have rainwater tanks systems installed that are plumbed to toilet(s), laundry cold water tap and external tap for garden supply. Twelve homes were chosen from the Pine Rivers and Caboolture regions combined due to lower mains water savings in IPT households highlighted in previous desktop studies. The remaining eight households were equally distributed amongst Redlands and Gold Coast areas (Figure 1). A prerequisite for the selection of households was to have approximately equal numbers of households using the trickle top-up system for mains water backup and those using the automatic switching device type of system (Table 1). The average occupancy across the 20 homes was 3.1 people, with individual occupancy data shown in Table 1.



Figure 1: Map showing the location of the 20 monitored homes in SEQ.

From the database of 691 households used for mains water saving analysis (Chong *et al.*, 2011b; 2012), households were contacted until a set of 20 households willing to participate in the study were accumulated. The database was also used to extract details on household occupancy numbers to enable the research to determine per capita water use in the households.

Table 1: Sample size of selected households based on region, household occupancy and types of top-up system employed in the RWT systems.

Region	Number of Households	Average Household Occupancy	Households with Trickle Top Up Systems	Households with Switching Device Systems
Pine Rivers	9	3.1	4	5
Caboolture	3	2.3	2	1
Redlands	4	2.8	3	1
Gold Coast	4	4.0	0	4

2.2. Rainfall Patterns and Accurate Extraction of Weather Data using Location Coordinates

SEQ is situated in the sub-tropical part of Australia. Rain falls throughout the year, however the wet season typically last for about six months, mainly during summer (between December and March). The dry season occurs during the autumn and winter months, between May and September. The average local rainfall during the monitoring period ranged from 1,374 mm to 1,861 mm across the locations of the 20 homes. This data was obtained from the SILO patch point database hosted by the Queensland Climate Change Centre of Excellence (QCCCE, 2012) (Table 2). Figure 2 shows the seasonal rainfall distributions across SEQ over the 12-month monitoring period. The distribution of households situated in regions with slightly different levels of precipitation enabled the examination of the effects of rainfall on the magnitude of mains water savings achieved from having an internally plumbed rainwater tank.

Table 2: Average rainfall in studied regions based on SILO data

Region	Rainfall (12-month monitoring period) (mm)
Pine Rivers	1,453
Caboolture	1,602
Gold Coast	1,692
Redlands	1,757

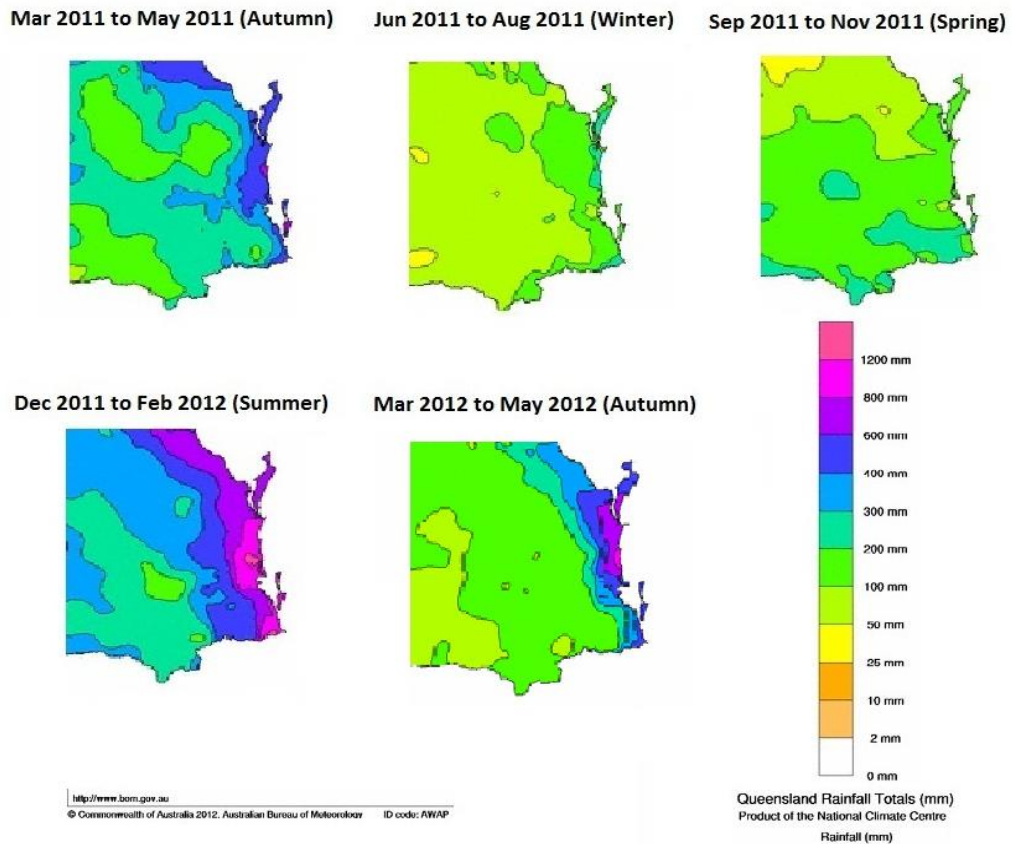


Figure 2: South East Queensland rainfall for monitored months (distribution based on gridded data), Bureau of Metrology (BOM, 2012).

The 20 homes were monitored for individual mains and rainwater consumption and the corresponding rainfall intensities for each home were also individually obtained using the SILO data drill based on their location co-ordinates. As the 20 homes are distributed over 13 different weather stations in SEQ, it was necessary to obtain rainfall and weather data specific to the location of each home to achieve a better understanding of their respective water usage patterns (Table 3). The rainfall for a particular LGA was calculated as an average of rainfall measured at the nearest weather stations to each of the participating homes as opposed to using a published rainfall value for the entire LGA.

Table 3: Rainfall at the 20 homes being analysed for the study (QCCCE, 2012).

Property ID	LGA	Nearest Weather Station Number	Rainfall (mm) over 12 month Monitoring Period
1	Pine Rivers	040986	1373.7
2	Redlands	040265	1482.6
3	Pine Rivers	040960	1423.1
4	Pine Rivers	040986	1488.4
5	Redlands	040984	1861.2
6	Pine Rivers	040986	1488.4
7	Pine Rivers	040986	1448.8
8	Pine Rivers	040971	1448.8
9	Gold Coast	040196	1671.4
10	Redlands	040984	1861.2
11	Pine Rivers	040633	1468.4
12	Caboolture	040929	1545.6
13	Caboolture	040929	1559.5
14	Caboolture	040774	1700.9
15	Redlands	040269	1822.9
16	Gold Coast	040884	1790.3
17	Gold Coast	040166	1771
18	Gold Coast	040160	1536.6
19	Pine Rivers	040633	1468.4
20	Pine Rivers	040633	1468.4

2.3. Household Inspections and Audits

After selection, an on-site inspection and audit of the 20 households was conducted to collect site parameters of each household rainwater tank system relevant to the study. The information collected was based on parameters imperative to the operational efficacy of rainwater tank systems such as:

- rainwater tank sizes, shape and dimensions;
- pumping type and pump specifications;
- additional devices incorporated in the rainwater tank systems (i.e. pressure vessels, alternative switching devices for mains water backup, etc.);
- end-use connections requiring water supply from rainwater tanks (toilets, laundry taps and external garden taps); and
- connected roof catchment used to collect rainwater

Most audit parameters, such as dimensions of the tanks, were either directly collected from the manufacturer labels or through manual measurement. The types of pumps installed were determined using manufacturers' specifications or by directly contacting the manufacturers to collect data which was not readily available on pump labels and to confirm missing details. The pump systems were also

examined to determine the presence/absence of pressure vessels. The information about the backup supply mechanism was also collected. These systems are either an automatic switching device or trickle top-up, described in more detail in Section 2.4.2. End-use connections, such as to toilet cistern, laundry tap/cold water supply to the washing machine, and outdoor/external garden taps that rely upon rainwater tank systems as the primary water source were also recorded. Finally, the roof area of each home was determined using aerial photos obtained from Nearthmaps® and the corresponding connected roof catchment areas were determined through on site examination of the location of the connected downpipes to the rainwater tank.

2.4. Smart Metering Approach for Water Demand Profiling, End Use Analysis and Energy Demand Profiling

Following the household audit, smart water flow meters with fine pulse resolution were installed at relevant points in the household rainwater tank supply network, as well as the mains water supply, to allow subsequent analysis of the water balance, demand profiling and end-use analysis. Smart energy meters were also installed to monitor the energy requirements for pumping water from rainwater tanks for the various end uses. Data was monitored for a total of 12 months (April 2011 – April 2012).

The monitored water flow points in each of the 20 homes included (Figure 3): (1) total mains water flow into the households; (2) mains water flow for topping-up the household rainwater tanks; (3) total water flow out of the household rainwater tank; and (4) water flow for external garden irrigation. All smart water flow meters had a pulse conversion rate of 0.5 L/pulse except for mains water meters which were pre-configured at 5 L/pulse. Similarly energy meters have been installed at each home to record energy consumption by the rainwater pumps. The data captured by the smart meters were stored in wirelessly enabled data loggers installed at each household, from which the data was retrieved on a monthly basis. Further descriptions of the relevant water flow monitoring points for each household are provided below.

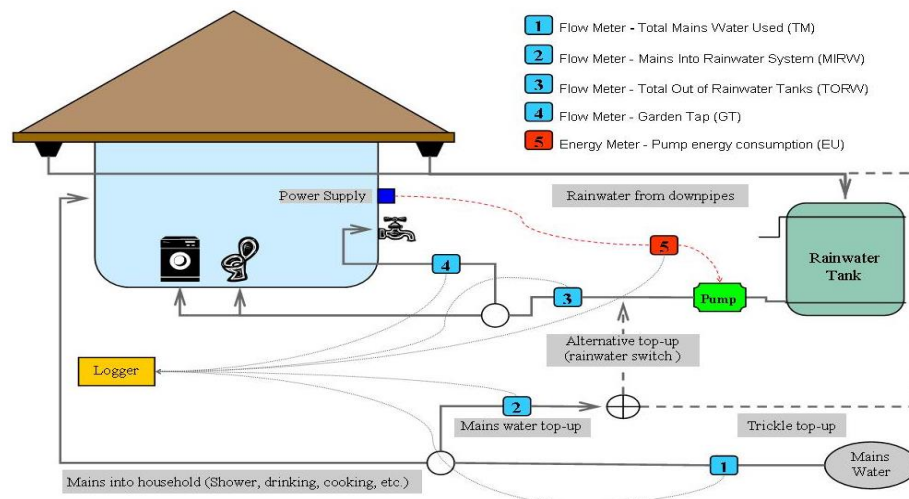


Figure 3: Schematic diagram of metering system setup at each of the 20 households with plumbed rainwater tank systems.

2.4.1. Total Mains

The total mains (measured at flow meter 1 in Figure 3) is the total volume of mains water utilised in the household supplied from the council mains water line. The variations in monthly and daily potable water consumption patterns and characteristics are also analysed using this data. TM is the only source of (potable) water supply to internal household fixtures such as showers, cooking/drinking, internal taps and others end connections in dwellings with plumbed rainwater tanks. However, the flushing of

toilets, laundry tap connection (washing machine cold water tap) and external garden taps, all have rainwater as the primary water source. The potable mains water acts as the backup water source when rainwater is not available.

2.4.2. Mains Water Top-Up into Rainwater Tank System

Mains water top-up into rainwater tank system (MWTU) is the quantity of water supplied from mains water supply in the absence of rainwater to meet the demand of end uses connected with rainwater tank. All the studied households incorporated a MWTU system. In general, there are two main types of top-up systems present in household rainwater tank systems. Of the 20 homes, the back-up water supply to rainwater tanks in 9 homes is regulated by a “*trickle top-up*” mechanism (Figure 4) while 11 work on a “*rainwater switch*” mechanism (Figure 5). Rainwater tank systems working on *trickle top-up* mechanisms are regulated by a valve, which is activated by a float, which in turn either allows or stops the flow of mains water into the tank; in this case, the valve opens when the water level in the tank falls below a fixed threshold value. However, in a *rainwater switch* system, mains water bypasses the tank system and delivers directly to the connected end-uses until there is sufficient rainwater available in the tank again; the potable mains water does not enter the rainwater tank. The switching valve is activated by an electronic float switch inside the tank.

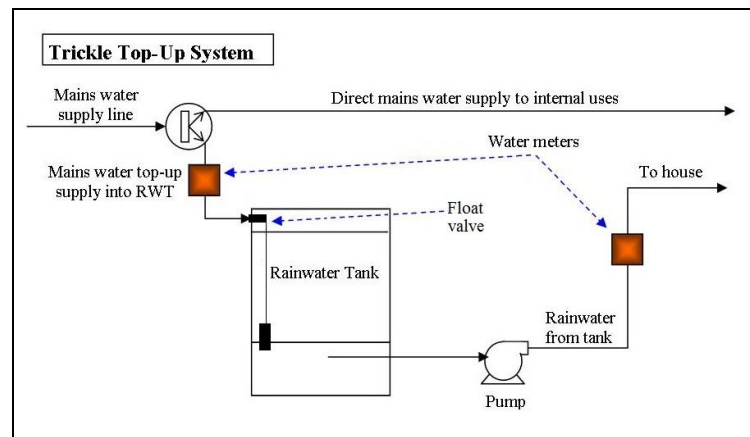


Figure 4: Illustrative diagram of a rainwater tank system working on a ‘Trickle top-up’ mechanism.

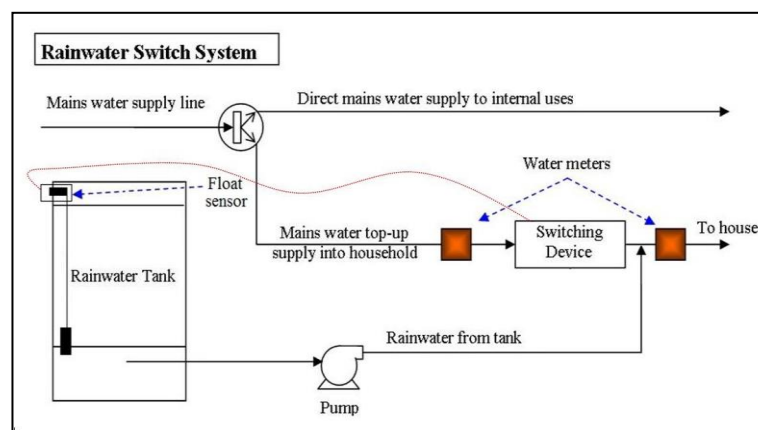


Figure 5: Illustrative diagram of a rainwater tank system working on a ‘Rainwater Switch’ system.

2.4.3. Total Rainwater Supply from the Rainwater Tank System

The total rainwater supply from the rainwater tank system (TORW) is the water quantity supplied from rainwater tank system incorporating rainwater and mains water top-up. Based upon the type of top-up systems employed, there was a minor variation in the installation of smart water flow meters measuring the water being supplied from the household rainwater tanks to the connected end-uses. In systems using *trickle top-up* mechanism, the water leaving the rainwater tank would contain either roof harvested rainwater or mains water (top-up) or a mixture of both. Hence, for these systems, the water exiting the rainwater tank was measured immediately after the rainwater pump. For the *rainwater switch* systems, the water exiting the rainwater tank consisted solely of rainwater. Hence, in order to measure the total water exiting the system (including the mains water top-up), measurements were taken after the water had passed through the automatic switching device. Hence, in systems with rainwater switches, the TORW stream was measured after the rainwater or mains water top-up had passed the switching device (Figure 5). Thus it is important to note that, in both systems, TORW includes rainwater and mains water top-up due to the arrangement of flow meters employed.

2.4.4. Water Supply to Garden Tap (External Water Usage)

The external garden tap (GT) stream is the water supply from rainwater tank to external garden taps installed for outdoor gardening or any other allowable purposes. All the garden taps were supplied with water from the plumbed rainwater tank system. In order to determine external end-use water demand, the water supply to the garden taps was monitored as shown in Figure 3.

2.4.5. Energy (Electricity) Usage in Rainwater Tank System

In order to supply water from the rainwater tank system to the various end uses, a water pump is employed. The electricity used by the pumps was monitored in order to determine the energy consumption/efficiency of each system and to examine the factors influencing the energy efficiency such as the type of top-up, water demand peaks, types of end uses, and pump size etc. The energy meters installed generated one pulse per watt-hour with data recorded in one-minute time steps.

2.5. Data Collection, Validation and Preparation

Data loggers were installed on each site to store information collected by the on-site smart meters. Logged data was retrieved remotely using wireless telemetry system on a fortnightly basis, initially for two months, and thereafter at monthly intervals.

The raw data retrieved from the loggers was converted from pulses to litres (for flow meters) or watts-hours (for energy meters). The water flows and energy data (per minute) obtained for each home was reviewed for discrepancies and validated in terms of data presence, consistency, range and format, both manually and using the 'macros' function on Microsoft Excel® to ensure ambiguous data was excluded from the analysis.

The validation of monitoring data was followed by an extensive data preparation process for each household, wherein the data was sorted and arranged in suitable formats using Macros^(c) functions enabling efficient analysis of the large and comprehensive array of data sets. Both daily and monthly summaries of the four monitored water flow parameters as well as the energy usage were made. In the next step of the analysis, calculation of a series of parameters required to study reliabilities and individual water and energy usage patterns of the rainwater systems in each home was carried out. The flow diagram of the data collection, validation, preparation and analysis is shown in Figure 6.

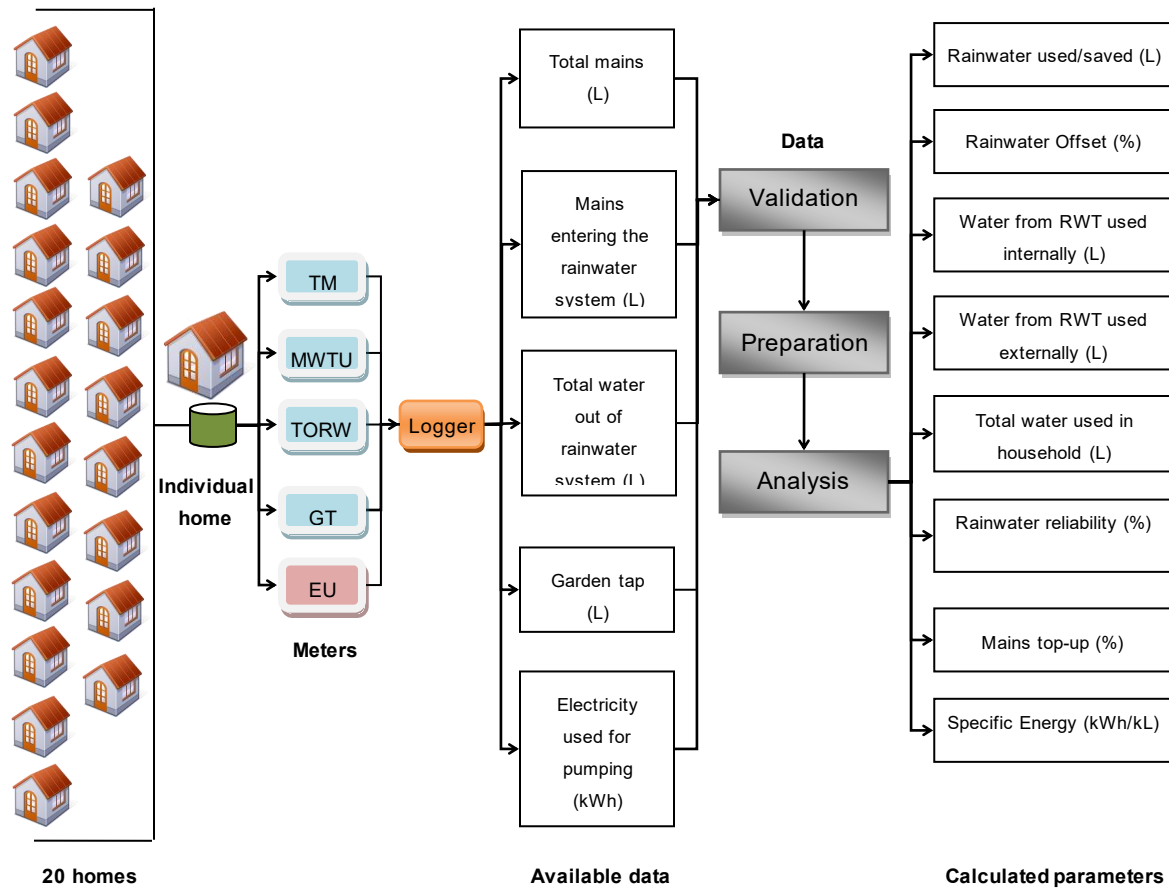


Figure 6: Schematic diagram showing steps involved in data collection, validation and analysis.

2.6. Data Analysis

Data was analysed for rainwater use (i.e. saving of mains water), mains water top-up, total household water consumption, volumetric reliability of RWTs, percentage of top-ups into the RWT systems, water supplied from the RWTs to the households (both internal and external), diurnal patterns, energy consumption and specific energy of the pumps. The main parameters studied are discussed in the following sub sections.

2.6.1. Assessment of Total Rainwater Supply and Volumetric Reliability of Rainwater as a Water Supply Source

The difference in total water supplied from rainwater tanks system (TORW) from mains water top-up (MWTU) is the total rainwater supply for an estimated period. The volumetric reliability of household rainwater tanks is defined as the ratio of the volume of rainwater supply from the tank to the total household water demand. Volumetric reliability for households shows the percentage of mains water reductions being achieved in the systems, through the increased usage of harvested rainwater. Harvested rainwater in IPT households acts as a supply source for the connected water end-uses (i.e. flushing of toilet cisterns, washing machine cold tap and external garden taps). The ratio for volumetric reliability helps to determine the volume of rainwater supplied from the tanks based on the total household water usage. The ratio was based on the total household water consumption due to recent studies by Chong *et al.* (2012) showing that the demand from rainwater tanks is high in households with a high total household water usage. Hence, this ratio could be used to optimise

individual tank sizes (volumes) based on the corresponding overall household water usage/requirements. The volumetric reliability (Rv) for the household rainwater tanks was calculated using Equation 1 as follows:

$$Rv = \frac{\sum_{t=1}^T (TORW - MWTU)}{\sum_{t=1}^T TM + \sum_{t=1}^T (TORW - MWTU)} \quad \text{Equation 1}$$

Where:

- Rv = Volumetric Reliability of rainwater in the system (%)
- T = Total monitoring/assessment time period (4 months)
- t = Minute time step
- $TORW$ = Total water supplied from the rainwater tank system (kL)
- $MWTU$ = Mains water top-up (kL)
- TM = Total mains used in household (kL).

The percentage (Pm) of main water top-up ($MWTU$) over total household supply was estimated by using the Equation (2):

$$Pm = \frac{\sum_{t=1}^T MWTU}{\sum_{t=1}^T TM + \sum_{t=1}^T (TORW - MWTU)} \quad \text{Equation 2}$$

Where:

- Pm = Percentage of mains water top-up to allocated end uses (%)

Similarly, the percentage (Pr) of rainwater supply ($TORW - MWTU$) over rainwater demand ($TORW$) in the household was estimated by using the Equation (3):

$$Pr = \frac{\sum_{t=1}^T [(TORW - MWTU)]}{\sum_{t=1}^T (TORW)} \quad \text{Equation 3}$$

Where:

- Pr = Percentage of rainwater supply to the rainwater demand in the rainwater tank system (%)

2.6.2. Diurnal Pattern and Peak Water Demand Analysis

The minute by minute water demand data from continuous monitoring of each home were converted to hourly diurnal demand values. Hourly water demand values for all 20 homes were also combined to generate a 20-home cluster diurnal demand pattern. The diurnal pattern analysis of individual homes, as well as for the 20-home cluster was carried out to understand the water demand patterns in the system in relation to end use consumption. The hourly diurnal water demand patterns and (fine) peak minute demand patterns were used to identify peaks and trends in water use and relate this to the sizing of potable water reticulation pipes required by urban water system designers.

2.6.3. Energy Consumption and Specific Energy

Energy meters installed in the systems measured the electricity used to pump water out of the rainwater tank systems into the households. In case of trickle top-up systems, the rainwater pump supplies the $TORW$ quantity (rainwater + mains water top-up). For houses using switching devices,

the pump supplies only rainwater (i.e. TORW – MWTU). Taking this into account, the specific energy (kilowatt hours of energy per kilolitre of water pumped) of the pumps for an analysis period was calculated as the ratio of the total energy used (EU) to the total water supplied from rainwater tanks (W), where W is TORW in case of trickle top-up system and TORW-MWTU in case of switching device. Hence the specific energy (SE) of the rainwater tank systems was calculated using Equation 4 as follows:

$$SE = \frac{\sum_{t=1}^T EU}{\sum_{t=1}^T W} \quad \text{Equation 4}$$

Where:

S.E = Specific Energy of the rainwater tank systems (kWh/kL)

EU=Energy used to pump water from the rainwater tanks into allocated end uses in the household (kWh)

W=Quantity of water pumped from the rainwater tank in the household (kL)

2.7. Data Challenges

The entire set of data collected was thoroughly checked to ensure for completeness. Discrepancies or ambiguous data sets were identified and rechecked/reloaded from data loggers. Necessary steps were taken to avoid data loss. A majority of data loss events were the result of occasional logger and/or meter failures on sites. Failures of equipment were found to be more frequent during the wet season due to loggers and meters being located in harsh weather conditions, usually outside the houses. Damaged loggers were replaced within a few days of notice, where possible. However, due to constant bad weather conditions in some regions, data loss for longer periods occurred for a limited number of homes. As a result, final values obtained for rainwater consumption (mains water savings) at these homes showed slightly lower values, particularly on days with higher rainfall. In these cases, rainwater savings were projected to represent a 12-month period. Data missing occasionally in smaller patches (< 1 hour) during hours with low water use activities were replaced by numbers generated using the ‘*random number generator*’ tool. However, the monitoring of homes with missing data will be extended for a period equivalent to the number of missing days in order to obtain information for a complete 12-month period.

Another challenge faced was the refusal of one homeowner to allow logging of the potable mains meter. However, mains water consumption for this home was obtained from the Queensland Water Commission using mains water billing records. One home was also excluded from the calculation of average specific energy values due to unusual circumstances arising from the owners not utilising their rainwater tanks often, causing the pump system to consume energy on stand-by (dormant energy) alone.

3. RESULTS AND DISCUSSION

3.1. Household Water Demand

3.1.1. Water Demand Characteristics and Rainwater Availability

Figure 7 shows average total water consumption, rainwater supply and mains water top-up for the 20 households over the monitoring period. The average rainwater use (and hence mains water savings) was 36.1 kL/hh (Table 4, Figure 7(a)) for the 10 months and 27 days for which a complete data set was available during the 12-month monitoring period. Thus the projected rainwater use for the full 12-month period was 39.9 kL/hh/yr (Figure 7(b)). The average recorded total water use (mains water supply + rainwater) from the households was 136 kL/hh, which was equivalent to 151 kL/hh/yr over the full 12-month period. In order to further validate the mains water consumption in each household, water billing data was obtained from the Queensland Water Commission for specific time periods within the 12-month timeframe. The households' billing data showed a correlation coefficient of 0.98 with the monitored mains water consumption data from the households.

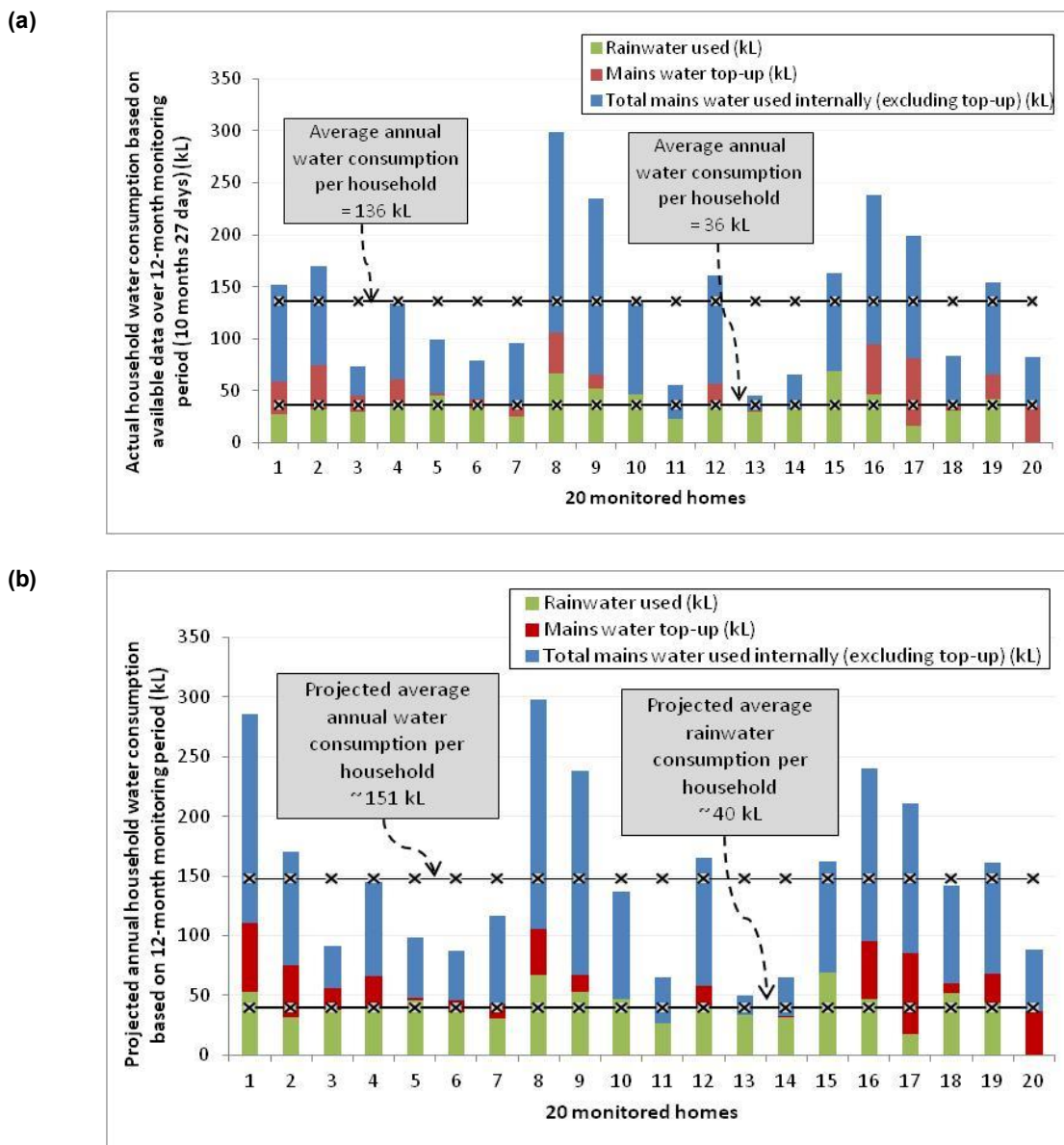


Figure 7: Distribution of water consumption across the 20 homes based on water supply sources (a) Actual consumption obtained for an average of 10 months and 27 days worth of monitoring (b) Projected consumption for 12 months.

In comparison with previous studies conducted by Chong *et al.* (2012) (Appendix 1), who reported average annual mains water savings of 58.8 kL/hh/yr and 58.2 kL/hh/yr for 2009 and 2010 respectively, the average annual water savings obtained in this study is considerably lower at 39.9 kL/hh/yr. This large difference in savings could be attributed to various factors. One probable factor contributing to lower total household water consumptions in the 20 households is due to the majority of households (n = 12) being from the Moreton Bay Regional Council area (Pine Rivers and Caboolture), the two LGAs in the previous study with lower consumption levels (Chong *et al.*, 2012).

Lower water demand in these households could be due to the change in household water use practices attributed to water restrictions introduced in many SEQ regions during the recent millennium drought (Beal *et al.*, 2010), limiting internal household water use and severely restricting the use of water for external irrigation. A total of 12 homes are located in areas with recently enforced severe water restrictions (Pine Rivers and Caboolture) and four homes located in Redlands City Council, where moderate water restrictions were imposed. Following the end of the millennium drought in 2008, rainfall conditions in SEQ returned to average seasonal conditions in 2009, followed by an extremely wet summer and devastating floods across many parts of Queensland in the summer of 2010/11 and a wet summer in 2011/12. Beal and Stewart (2011) noted that external irrigation, which is typically elevated for summer, represented less than 4% of the average total water consumption in summer 2010/11. Irrigation was generally not required due to lower than average temperatures and the very high rainfall experienced. At the 20 monitored households, external irrigation accounted for less than 5% of the average total water consumption for the entire 12-month monitoring period. Moreover, as depicted in Figure 7 (b), seven of the 20 monitored homes had total water consumption less than 100 kL/year against average total water consumption of 151 kL/hh/yr. Two of these homes had total water consumption even close to 50 kL/yr. Thus, these homes contributed to lowering the overall average of the rainwater consumption figures.

Table 4: Actual and projected water and rainwater consumptions at the 20 homes during the monitoring period.

Region	Average number of days with available data	Recorded (actual) rainwater used (mains water savings) (kL/hh)	Projected rainwater used (mains water savings) for 12 months (366 days) (kL/hh/yr)	Recorded (actual) total household water consumption (kL/hh)	Projected total household water consumption for 12 months (366 days) (kL/hh/yr)
Pine Rivers	315	31.6	37.0	125.0	148.5
Caboolture	351	33.1	34.5	78.0	80.6
Gold Coast	321	36.2	42.1	188.8	207.6
Redlands	366	48.2	48.2	142.0	142.1
20 homes combined	332	36.1	39.9	133.0	147.7

*Total household water = Potable mains water supply including top-up into rainwater system + Rainwater used

Another potential reason for the overall lower annual consumption could also be relatively lower rainwater consumption in households located in Gold Coast (n = 4) and Redlands (n = 4) in comparison with previous studies (Beal *et al.*, 2012, Chong *et al.*, 2012), resulting in lower average annual savings for the 20 homes. Chong *et al.* (2012) found the annual rainwater consumption in Gold Coast and Redlands homes to be 88.5 kL/hh/yr and 84.0 kL/hh/yr in 2009 and 81 kL/hh/yr and 71 kL/hh/yr in 2010, respectively (Appendix 1). In comparison, the current study found the projected annual rainwater consumption to be much lower at 42.1 kL/hh/yr and 48.2 kL/hh/yr for the two regions respectively (Table 4).

The rainwater usage in homes belonging to Pine Rivers and Caboolture regions were, however, in a similar range to the results of the *Phase 2* study by Chong *et al.* (2012). Chong *et al.* (2012) found the annual rainwater consumption in Pine Rivers and Caboolture to be 24.5 kL/hh/yr and 37.3 kL/hh/yr in year 2009 and 39.7 kL/hh/yr and 40.9 kL/hh/yr in 2010 respectively (Appendix 1). The current study

found the annual rainwater usage to be 37.0 kL/hh/yr and 34.5 kL/hh/year in homes belonging to Pine Rivers and Caboolture respectively (Table 4). However, Pine Rivers and Caboolture have still shown lower annual savings in comparison to Gold Coast and Redlands, which could be attributed to the comparatively higher total water consumption in Gold Coast and Redlands households.

In order to further assess the water savings being achieved in these regions, similar comparisons in consumption characteristics were made by assessing the per capita water and rainwater consumption values in the households (Table 5). The average household per capita water consumption in the 20 monitored homes has been considerably higher in all four regions in comparison with the corresponding household per capita water usage in 2009 and 2010 data obtained by Chong *et al.* (2012). Similar to the findings by Chong *et al.* (2012), the per capita household water consumption remained lower in Pine Rivers and Caboolture compared to that of Gold Coast and Redlands. However, results also showed the average household per capita water use for the 20 monitored households during the 12 month monitoring was 144 L/p/d, which is significantly lower than the per capita water demand of 158.2 L/p/d (QWC, 2012) reported for SEQ over the same period. The average per capita rainwater consumption across the 20 monitored homes was much lower (40.2 L/p/d) in comparisons to the Chong *et al.* (2012) study, where the average rainwater used in the sample of 691 households was 49.5 L/p/d and 49.0 L/p/d respectively for year 2009 and 2010 (Table 5). Based on assessments of per capita total water and rainwater consumption in the 20 monitored households, the total average household water consumption in the households was much higher than the previous years' findings by Chong *et al.* (2012) (Table 5). In contrast, the average rainwater consumption in the 20 homes was considerably lower in comparison with the study by Chong *et al.* (2012). Thus, a potential reason for lower annual household rainwater consumption could simply be due to lower demand for rainwater in the monitored households.

The study also found that the average household occupancy rates in the regions did not have a significant impact on the total per capita household water and rainwater consumption. However, the occupancy rates may have had a significant impact on the corresponding average annual water and rainwater consumptions. The Caboolture region had the lowest average occupancy of 2.3 persons per household (Table 1); the per capita rainwater usage was higher than the mean consumption (40.2 L/p/d) at 47.1 L/p/d (Table 5). However, the low average occupancy rate in the Caboolture households may have contributed towards the lowest average annual total water consumption (80.6 kL/hh/yr) amongst the four regions (Table 4). Pine Rivers and Gold Coast had higher household occupancy rates of 3.1 and 4.0 respectively, but showed lower per capita rainwater consumptions (30.3 L/p/d and 34.9 L/p/d respectively). The Redlands region had the highest per capita rainwater usage with an average occupancy of 2.8 persons per household.

Table 5: Comparison of per capita total household water and rainwater water usage (mains water savings) with results from Chong *et al.* (2012).

Region	Current study: Per person per day consumption (L/p/d) Sample size = 20		Estimated per person per day consumption in 2009 (L/p/d) Year 2009 (Chong <i>et al.</i> , 2011) Sample size = 691		Estimated per person per day consumption in 2010 (L/p/d) Year 2010 (Chong <i>et al.</i> , 2011) Sample size = 691	
	Mean household water usage	Mean rainwater used (mains water savings)	Mean household water usage	Mean rainwater used (mains water savings)	Mean household water usage	Rainwater used (mains water savings)
Pine Rivers	136.9	30.3	119.4	20.9	109.4	33.6
Caboolture	127.6	47.1	108.5	31.9	108.2	34.8
Gold Coast	152.3	34.9	138.8	72.6	125.7	66.3
Redlands	164.5	62.8	129.1	72.4	121.9	61.2
AVERAGE		40.2		49.5		49.0

Various other factors, such as local rainfall, water pricing, household income and water efficient fixtures (Beal *et al.*, 2012, Barrett and Wallace 2009, Turner *et al.*, 2005) could also influence the variation in the pattern and volume of residential water consumption levels in the monitored households compared to the entire SEQ region. However, the rainwater tanks' reliability (rainwater used in the households as a percentage of total household water use) in the four LGAs was estimated to be 31%, which is comparable to the benchmark analysis (Chong *et al.*, 2012) where the average percentage of per capita mains water savings in the four studied LGAs ranged between 17-36% for 2009 and 22-33% in 2010. The percentage of per capita water savings in the benchmark analysis is very similar to the volumetric reliability of the rainwater tanks, which is discussed further in the next section.

It is imperative to take into consideration that the study by Chong *et al.* (2012) was based on the water billing records and comparing water usage with regional average water consumption figures. A direct statistical comparison of the data from the sample of 20 homes in this study cannot be made with the results obtained by Chong *et al.* (2011) due to its comparatively larger sample size (n = 691 households). However, the benchmark analysis has proved to be a good foundation for the current study. It is important to note that the billing records of these monitored homes matched with the monitored mains water consumption, which is a direct validation of the accuracy of the metering system employed in these homes. The lower water usage pattern of some of the monitored homes impacted on the overall lower rainwater consumption.

3.1.2. Volumetric Reliability

Volumetric reliability of household rainwater tanks is defined as the ratio of the volume of rainwater supply from the tank to the total household water demand. Figure 8 shows the volumetric reliabilities of individual rainwater tanks at the 20 monitored households. The average volumetric reliability across the 20 households was 31%. It was observed that higher rainwater consumption in households resulted in higher volumetric reliability. A recent monitoring study (Ferguson, 2012) on mains water savings in Sydney households with similar characteristic for rainwater tank connections, showed a relatively lower mains water savings of 21% of their total household water consumption; this was attributable to an average of 38 kL/hh/yr of mains water savings, which is very similar to the results obtained in this study (39.9 kL/hh/yr).

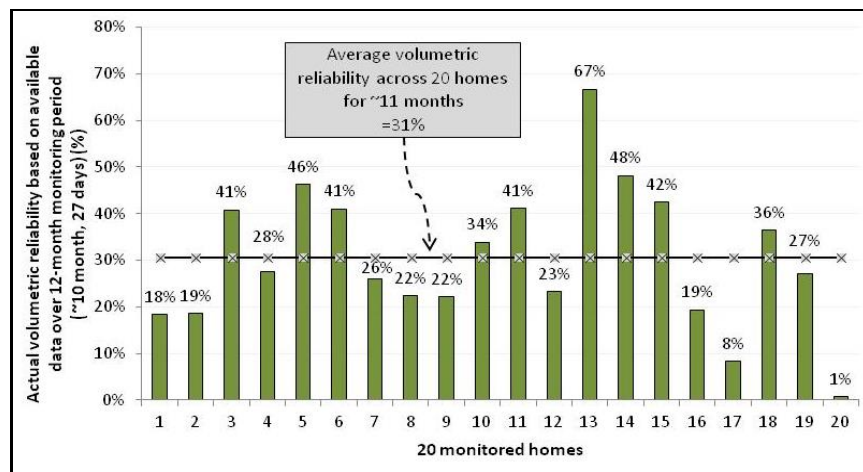


Figure 8: Estimated volumetric reliability of rainwater tank systems at 20 monitored homes.

The mains water top-up (calculated as per Equation (2)) in the rainwater system averaged 13% of the total household water demand. When added to the 31% sourced from roof-harvested rainwater, this suggests that 44% of total household demand could be supplied by rainwater if its supply could be increased by increasing say tank size and/or connected roof area. The percentage (Pr) of rainwater supplied by the rainwater tank systems over the rainwater demand at the connected end uses averaged at 69% in the studied households.

Varying levels of rainfall intensities during the 12 month period at the individual homes did not have a major effect on the rainwater systems' reliabilities of the homes; several homes with similar volumetric reliabilities showed varying levels of local rainfall. This suggests that, although the overall rainwater savings varies significantly across the studied SEQ regions (i.e., Pine Rivers, Caboolture, Gold Coast and Redlands), various other biophysical factors could be heavily influencing the amount of rainwater offsetting mains water savings at individual homes. One such physical factor that was identified during the study was at household No. 20 (Figure 8), which showed extremely low volumetric reliability. In this case, the water supply from the household rainwater tank system to the connected internal end uses could only be operated manually as a result of a faulty pump in the household rainwater tank system. The low volumetric reliability in this case is likely to be due to the faulty rainwater tank pumping system.

This indicates that physical factors in each RWT system at each home, such as rooftop collection areas and rainwater tanks setup, could have a direct impact on the mains water offset and hence the volumetric reliability of the rainwater in the system. Furthermore, a study of biophysical and social characteristics by Mankad *et al.*, (2012) suggested that, when designing future research, differences in system set-up, rainwater end-uses and rainwater acceptability between various communities must be considered, as these important factors are likely to have significant implications on actual household water use; the actual household water use is also likely to influence the amount of potential water savings that could be achieved from the installation of a decentralised system at the domestic level.

3.1.3. Hourly Diurnal Water Demand and Peak Water Demand Analysis

The collated hourly diurnal water demand patterns for the 20 home cluster is shown in Figure 9. The figure shows two distinctive water demand peaks representing the morning (occurring between 8:00 and 11:00 hours) and evening (occurring between 18:00 and 20:00 hours). As the day progresses, the peak patterns show a declining demand for rainwater and an increasing demand for mains water. This is evident in the total water demand met during the morning peak hour where 28% (Figure 10) was met solely through rainwater (i.e. volumetric reliability); this is followed by a declining demand for rainwater for the evening water peak, during which the rainwater demand peaks at only 10% at 19:00 hours. The morning peak hour demand for the cluster-of-20 homes was directly influenced by more prominent and consistent water supply from the household rainwater tanks to end-uses such as toilet flushing, clothes washing and garden tap. Conversely, the evening water peak was mainly attributed to end-uses that draw water directly from the mains water supply such as shower roses, kitchen taps, dishwasher and others. Similar findings were reported by Thyer *et al.* (2007) and Lucas *et al.* (2010) where an increase in the number of connected end-uses such as toilets and showers provided the greatest increase in average water use resulting in higher peak water demand. The peak demand factor for the collated hourly diurnal water demand pattern for the 20 homes was calculated to be 2.07; the peak factor is defined as the ratio of maximum hourly water demand over average hourly demand.

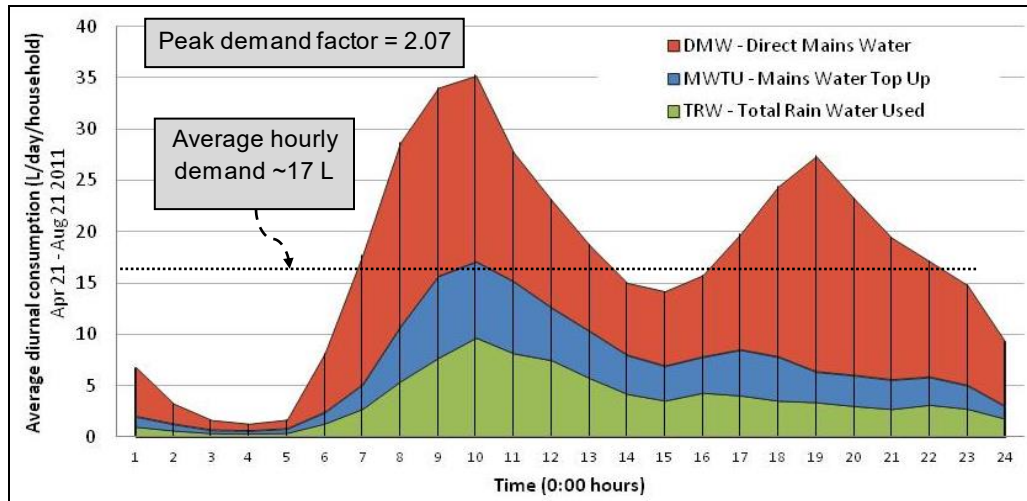


Figure 9: Hourly diurnal consumption patterns for the 20 home cluster.

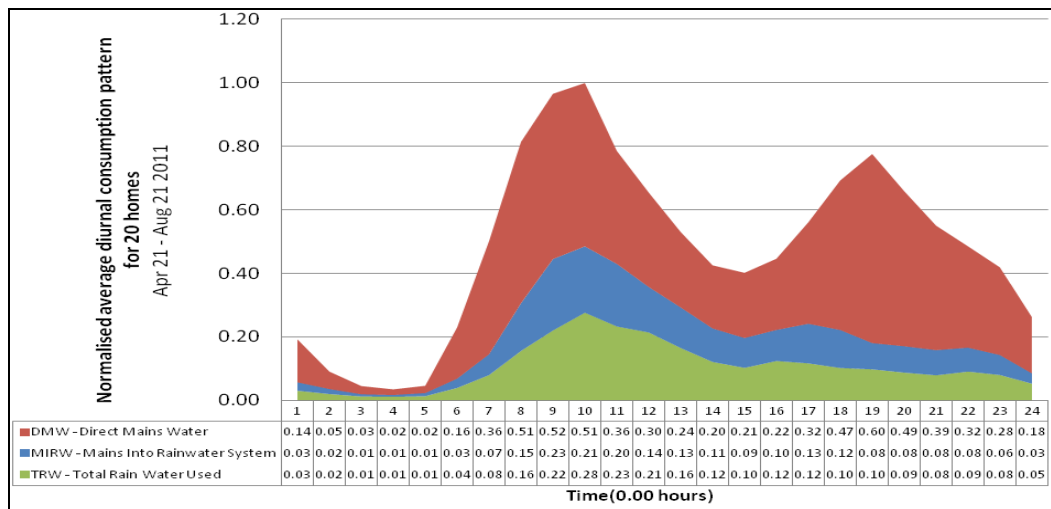


Figure 10: Normalised average diurnal water consumption patterns for the 20 home cluster (proportion of water use relative to peak hour demand).

3.1.4. Peak Demand Analysis at a Finer Time Scale (per Minute Time Scale)

Detailed analysis of daily water demand at a one-minute interval over the 12-month period was also conducted to understand the variation in demand at a finer scale. The median peak minute demand in the households was 26 L/min with an average peak minute demand of 38 L/min. The fine diurnal demand patterns (per minute) also showed a large variation in maximum peak per minute household water demands across the 20 households, ranging from a low of 16 L/min to a high of 93L/min over the monitoring period.

A closer look at the peak minute demand data showed similar dual peaks to those in the hourly diurnal demand patterns. Figure 11 shows the finer scale diurnal demand pattern on 9 August 2011 for one of the studied households (IPT19) plotted on a per minute basis. Each peak represents the water consumption of the household during the corresponding minute. From Figure 11(a) it can be seen that the water demands of the household between 8:30 - 8:35am and 10:05 - 10:10am show peak demands of ~ 21 litres, out of which approximately 11 litres is supplied by the rainwater with the balance (~10 L) from direct mains water supply. Hence, in this case, almost 52% of the peak morning demand

is met by the rainwater, reducing the load on mains water supply. Morning peaks typically showed water demand from both direct mains water supply as well as supply from the rainwater tank. The graph probably represents water use characteristic of a washing machine where both water from the RWT as well as direct mains water (for hot water taps) are being consumed within the same time span. In general, evening peaks were seen to be a factor of end-uses (e.g., shower, kitchen taps/drinking water, dishwasher) that were typical dependent on mains water supply to meet household water demand. These observations imply that during the time of rainwater supply, the short term peak factor in the household mains water demand is considerably reduced.

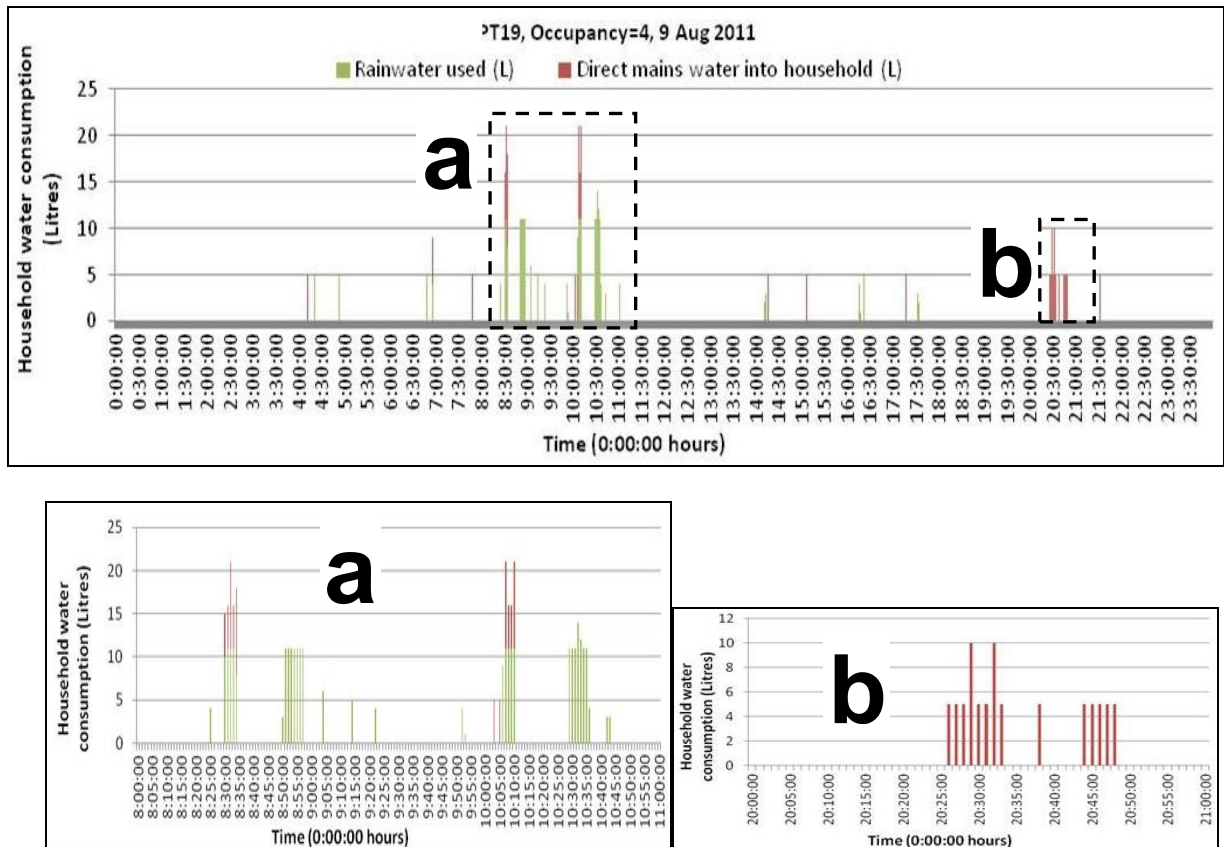


Figure 11: Fine per minute daily water demand at rainwater tank household PT19 on a specific day (a) morning water demand pattern (b) evening water demand pattern.

Similarly, Figure 12 shows the water demand in another household on 3 June 2011 between 8:00am and 9:00am. The peak water demand in this instance is 12 L at 8:15am, where ~7 L is sourced from the rainwater tank and the remaining water demand is met by the direct mains water supply to the household. In this instance, the rainwater contributes almost 58% of the total water demand in the household. Hence, the mains water demand peaks in the households are considerably reduced due to the presence of RWT systems. It is also imperative to determine instantaneous water demands in households due to non-homogeneous and continuous change of water demand/flow patterns based on varying householder water usage practices (Buchberger *et al.*, 1993).

Assessing household water demands using fine per minute peak demands could be the key to gaining a more detailed understanding of the dynamics of the system and the design of household rainwater tank systems. These findings demonstrate the importance of taking each system into account on an individual basis for design considerations.

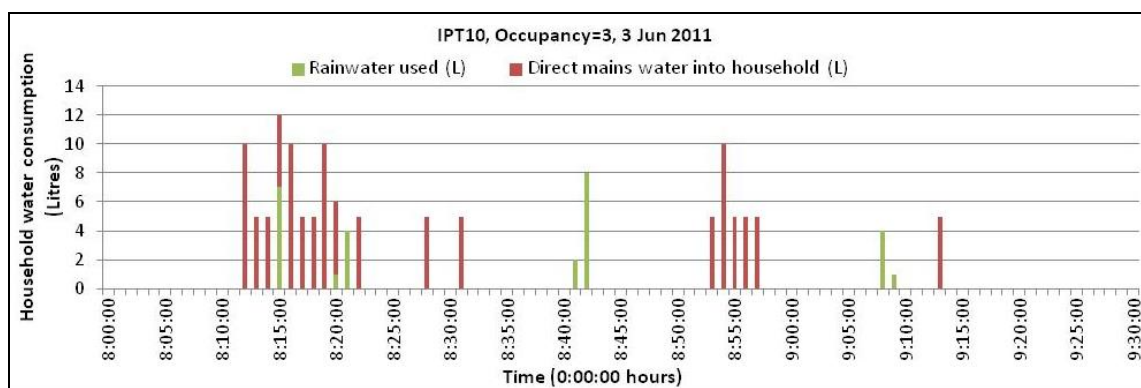


Figure 12: Fine per minute water demand between 8:00am and 9:30pm at rainwater tank household PT10 on a specific day

3.1.5. Rainwater Usage and Rainfall during Monitoring Period

The weather data was extracted individually for each home using *SILO 'Data Drill'* output method by specifying position coordinates. Figure 14 illustrates the average regional rainfall over the studied homes and the corresponding water savings in the homes grouped on their regional locations. The average annual rainfall across the 20 homes was 1,606 mm. It was observed that most homes belonging to high or 'above average' rainfall LGAs had relatively higher annual household water consumption than the other monitored homes. The projected rainwater consumption (equivalent to mains water savings) was also higher in these regions. This was particularly apparent in homes located in Redlands and Gold Coast, where higher annual rainfall of 1,776 mm and 1,696 mm (respectively) coincided with higher projected average rainwater consumption (Table 4). In contrast, the monitored homes located in the 'below average' rainfall climatic LGAs (Pine Rivers = 1206 mm and Caboolture = 1586mm), showed substantially lower per projected rainwater consumption and thus lower mains water savings.

Although households with internally plumbed rainwater tanks have shown significant volumetric reliability on rainfall over longer periods of time, daily rainfall events did not appear to have an immediate influence on the daily water demand from the rainwater tank systems. However, there were exceptions with households which regularly used their external taps for gardening or car washing purposes. During rainy days, there was no rainwater demand for the external tap which reduced water demand from the RWTs for these homes. The average garden tap usage for the 20 homes was 7.2 kL/hh/yr which accounted for only about 5% of the total water demand. However the median value for garden tap use showed that only 3% of household water use was attributed to garden taps usage, which was equivalent to 4.2 kL/hh/yr. Of the 20 households, three showed relatively higher garden tap usage ranging from 17.4 – 25.5 kL/hh/year while the rest ranged from 0 (three households) to 11.2 kL/hh/yr. The water demand from the rainwater tank systems remained unchanged, irrespective of the availability of rainwater in the tanks. This was due to a large part of the demand being from internal end uses (toilets and laundry tap/washing machine) and relatively low external (garden tap) usage. Irrespective of the type of top-up or availability of rainwater in the tank, the usage patterns in the households remain constant, which was also observed in the fine diurnal pattern analysis (Figure 13 (a) and (b)).

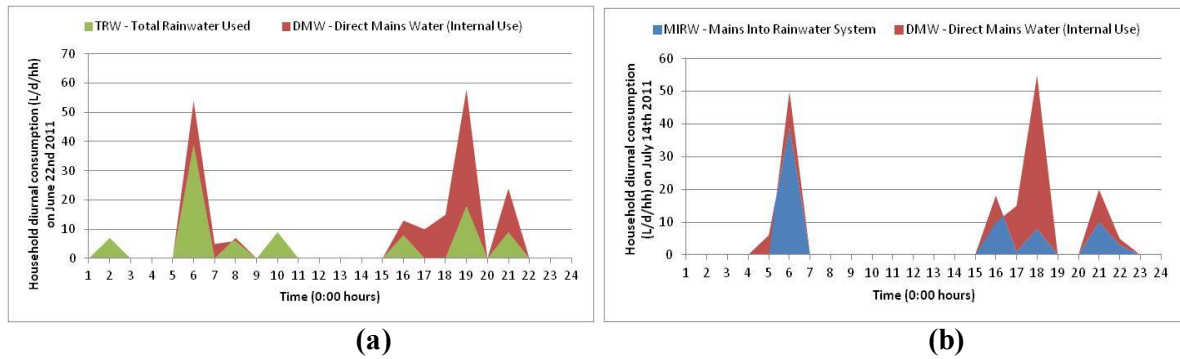


Figure 13: Fine per minute water demand (a) Typical water consumption during rainwater availability (b) Typical water consumption in the household on a day without rainwater availability.

Rainfall pattern had little or no long term influence on the use of rainwater for external use (gardening, car washing, etc.). A brief comparison between average household rainwater consumption and average rainfall is show in Figure 14. End use data measured and analysed by taking seasonal variations into consideration could be the key to water consumption predictions for the design and development of water distribution networks (Beal *et al.*, 2010; Blokker *et al.*, 2010).

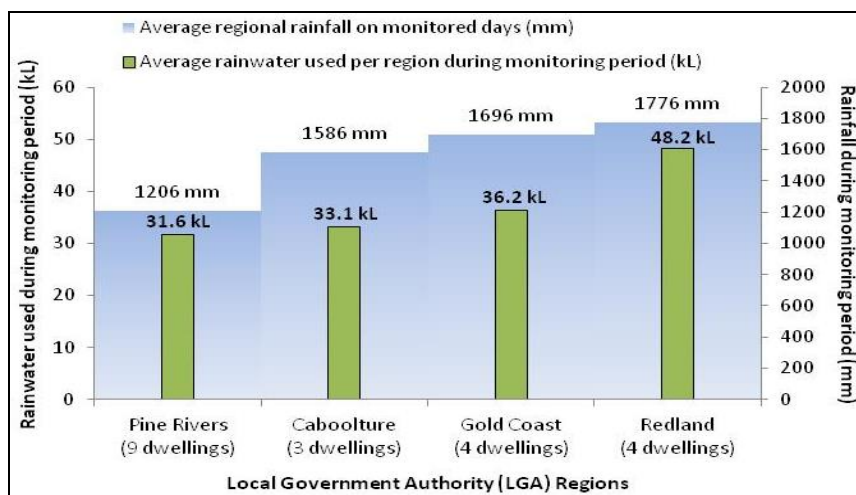


Figure 14: Total rainfall during monitoring period vs. rainwater used.

Furthermore, another study (Chong *et al.*, 2012) based on the bio-physical rainwater tank installation data for the 20 homes involves the modelling of rainwater tanks to investigate the impact on mains water savings of various physical factors (i.e. roof area connectivity and effective tank size) and household characteristics (i.e. household occupancy, water usage practices, etc.). Such modelling will further aid a more in-depth understanding of the performance of plumbed rainwater tanks.

3.2. Household Rainwater Tank Systems' Energy Usage Analysis

3.2.1. Diurnal Energy Usage Pattern Analysis

Figures 15 and 16 show the long-term average diurnal energy usage patterns based on 4 months of energy data for the 20 homes grouped into two categories as per their back-up mechanism:

- i) Homes using the 'trickle top-up' system to supply back up mains water to meet rainwater tank demands.
- ii) Homes using 'automatic water switching devices' to supply mains (back up) water supply to meet rainwater tank demands.

Comparison between the diurnal energy demand patterns of the two groups showed similarity with diurnal water demand patterns with a distinctive peak representing water demand from the RWTs during morning hours, which gradually decreased towards evening hours. This finding is consistent with previous diurnal pattern analysis for the average total household water usage patterns, where the cluster of all 20 homes showed two peak hour demands. The peak hour water demand in the evening showed very little demand from the RWTs (Figure 9 and 10). Households using automatic switching devices typically had lower volumes of water supplied from the rainwater tanks into the households due to the mains water top up bypassing the tank and directly supplying the household (see Figure 5). Hence, the energy consumption at homes belonging to this cluster peaked at 10 kWh (Figure 15). In comparison the hourly energy demand in RWT systems for the group of households using trickle top up systems was significantly higher at 22.5 kWh (Figure 16). The type of top-up system clearly has direct implications on the total energy consumption of the rainwater systems.

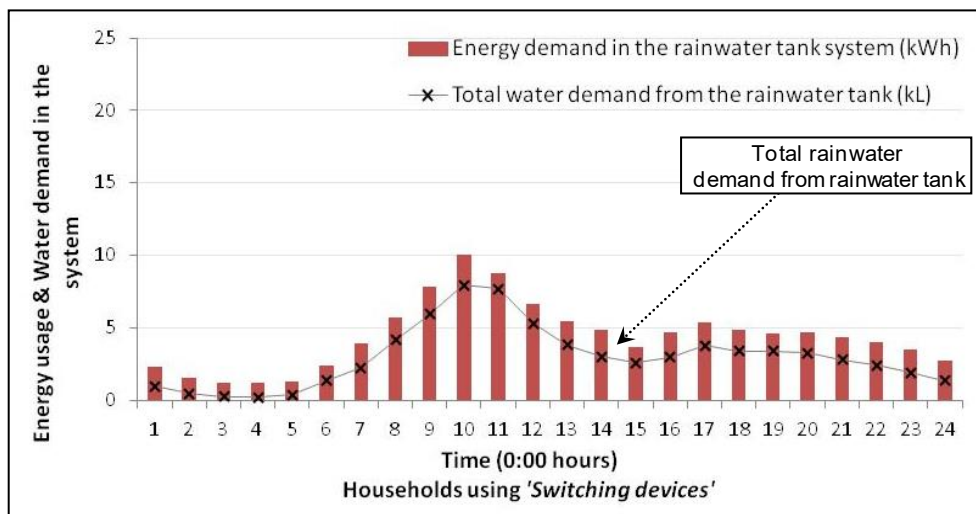


Figure 15: Hourly Energy demand and Water supply from rainwater tanks in households using a 'rainwater switch' system.

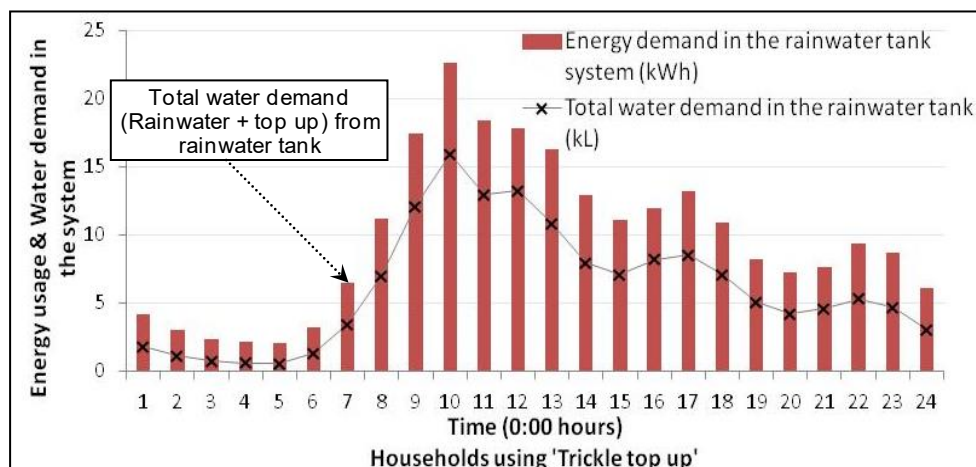


Figure 16: Hourly Energy demand vs. Water supply from rainwater tanks in households using a 'trickle top up' system.

3.2.2. Energy Balance Analysis and Specific Energy (Energy Intensity)

The energy demand for each of the 20 rainwater tank systems was analysed to determine the total energy use for each individual RWT system as well as to establish the energy use per kilolitre of water supplied from the system (the specific energy, SE). The energy use by the rainwater tanks over the 12-month monitoring period ranged from 4.3 kWh/hh/yr to as high as 211.6 kWh/hh/yr (Figure 17). A significant difference was found between the total energy consumptions of homes using trickle top-up and those with automatic switching devices for supplying mains water backup into the household.

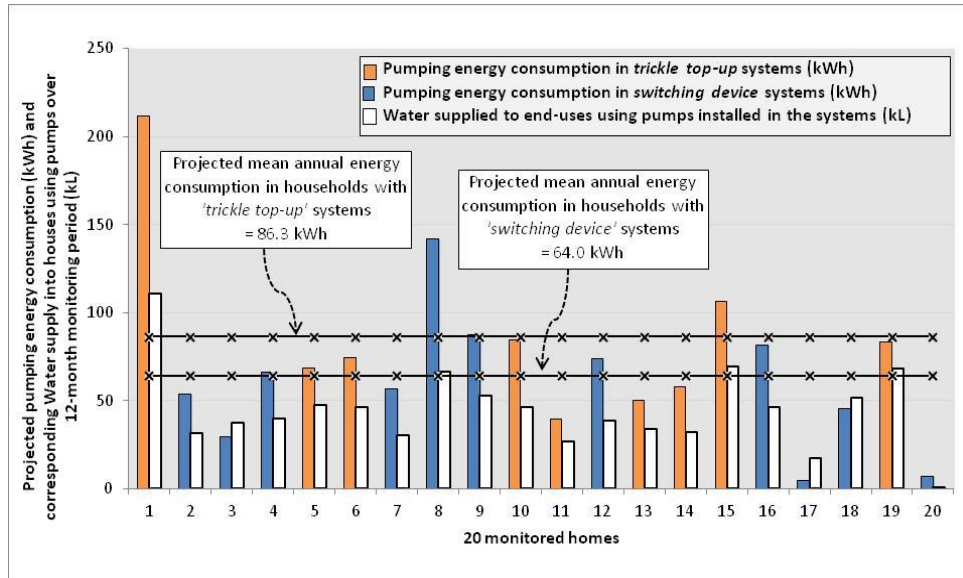


Figure 17: Energy consumption at 20 homes.

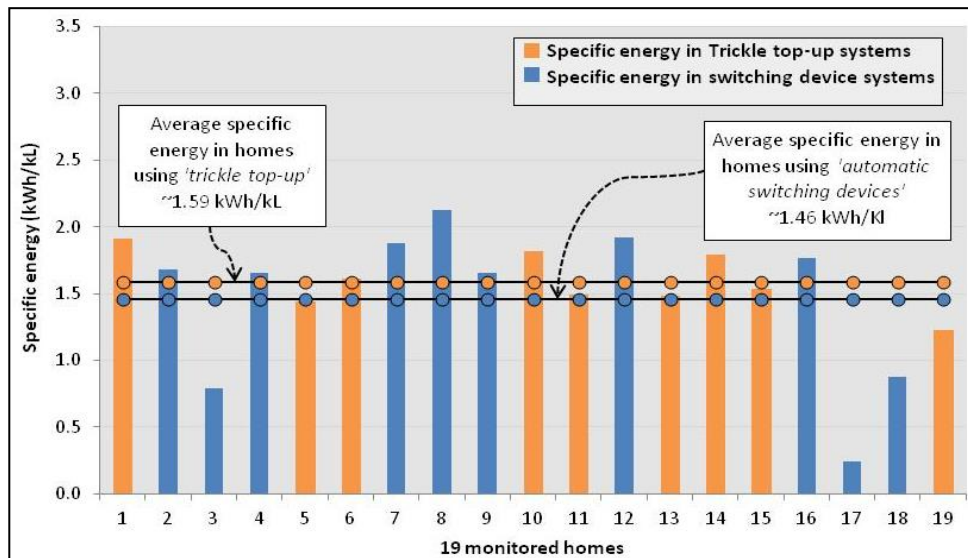


Figure 18: Specific energy consumption across 20 homes.

The mean energy consumption in 9 homes with trickle top-up devices was 86.3 kWh/hh/yr compared to 11 homes with switching devices that consumed around 64 kWh/hh/yr. The average energy usage for all 20 homes was 71.2 kWh/hh/year which is slightly lower than the NSW results reported by Ferguson *et al.* (2012) at 78 kWh/hh/yr: the corresponding average specific energy was 1.48 kWh/kL.

In this study, the median specific energy for the pumping systems at the 19 homes was 1.52 kWh/kL (Figure 18) with the median SE for homes with trickle top up systems (1.59 kWh/kL), being slightly higher than those with automatic switching devices (1.46 kWh/kL). The lower values for SE could be attributed to the installation of low power pumps that typically work close to the household appliance flow requirements and thus have lower specific energy (Tjandraatmadja *et al.*, 2011). The pump sizes varied from 0.35 kW to 0.89 kW in the studied homes and the specific energy across 19 homes ranged from 0.25 kWh/kL to 2.13 kWh/k in comparison with results obtained by Retamal *et al.* (2009) where under similar rainwater tank conditions, the specific energies varied from 0.9 to 2.4 kWh/kL. Of the total 20 homes, one home was excluded from the specific energy analysis due to extremely skewed values for specific energy (10.93 kWh/kL) as a result of a faulty pump in the household rainwater tank system.

The wide range in specific energy may be due to several factors such as: variation in pump make and sizing, operational conditions, presence of pressure vessels, end use pattern including system shutdown energy consumption, pump start-up energy consumption and switching device stand-by energy use (Hauber-Davidson and Shortt, 2011). The values obtained show that rainwater tanks provide a practical alternative water supply option to meet daily water demands in the urban residential sector in comparison to the 133 ML/day seawater desalination plant at Tugun, SEQ, where the specific energy consumption is around 4.3 kWh/kL (Hall *et al.*, 2009).

4. CONCLUSIONS

The study has provided improved insight into the real world performance of internally plumbed rainwater tanks in SEQ. As the implementation of plumbed rainwater tanks is still in its infancy, any monitoring or process validation information on their contribution towards mains water savings is important for water professionals and policy makers. Results showed the average household per capita water use for the 20 monitored households during the 12 month monitoring was 144 L/p/d, which is significantly lower than the per capita water demand of 158.2 L/p/d (QWC, 2012) reported for SEQ over the same period.

The average volumetric reliability of rainwater tank systems to meet daily household water demands (31%) is comparable to previous analyses of rainwater supply conducted in Qld (Chong *et al.*, 2011) and NSW (Ferguson *et al.*, 2012). It was also found that a further 13% of the total household water demand was supplied through the rainwater tank and sourced from mains water top-up. The rainwater tank systems were able to meet an average 69% of the total rainwater demands at the connected end uses in the studied households. This implies that the remaining 31% of the demand at the rainwater tank connected end uses is met by mains water top-up. Thus, a further 13% of the total household water demand or 31% of the water demand at the rainwater tank connected end uses could possibly be supplied by the rainwater tank systems, indicating a potential for improvements in the design of systems to work at maximum capabilities. Some possible improvements can be the increase in connected roof areas and increase in effective tank volumes.

Two distinct water demand peaks that are representative of the morning and evening peak water usage are evident from the diurnal water demand pattern of the cluster of 20 monitored homes based on long-term averages of daily water consumption data. From diurnal pattern analysis, it was also determined that collected rainwater contributed up to a 28% offset in mains water demand over the analysis period. From the finer per minute diurnal water demand analysis, the median per minute peak household demand was 26 L/min whilst the average peak demand was around 38 L/min. The fine diurnal demand pattern also showed a vast variation in maximum per minute household water demands across the 20 households ranging from as low as 16 L/min to as high as 93 L/min. These findings provide some major implications such as the importance of optimisation of rainwater tank pump sizing and plumbing system design, based on the characteristic water usage patterns at individual households.

Differences in household water use based on local rainfall patterns were also determined, with a finding of lower water consumption in areas with lower rainfall which could possibly be attributed to the diligence of people in these areas continuing to abide by previous water restrictions. The local rainfall patterns played an apparent role in the overall annual rainwater savings capacity of the households. The availability of rainwater in a tank is dependent on rainfall patterns of the local area. However rainfall seldom had any effect on the daily water usage pattern of households due to most of the demand being for regular internal end uses.

Examination of the energy consumption characteristics of the rainwater pumps showed that the average energy consumption for the 20 households of 71.2 kWh/hh/yr. The mean energy consumption in nine 'trickle top-up' homes was 86.3 kWh/yr compared to 64 kWh/yr for the 11 'automatic switching device' homes. The reason for this considerable difference is that trickle top-up systems route all water (rainwater + mains water top-up) through the tank and pump system, whilst the automatic switching devices bypass the tank when supplying "back up" mains water. The median specific energy for the pumping systems at 19 homes was 1.52 kWh/kL with the median SE for homes with trickle top-up systems (1.59 kWh/kL), being slightly higher than those with automatic switching devices (1.46 kWh/kL). However, further research is required to compare the energy demand of rainwater tank systems with dam water, dual reticulation recycled water and desalinated sea water.

APPENDIX 1.

Average water savings in IPT households in comparison with annual consumption and benchmark consumption for 2009 (Chong *et al.*, 2012).

Council area (Sample Size)	Pine Rivers (197)	Caboolture (158)	Gold Coast (172)	Redland (164)
Average persons per household	3.21	3.20	3.34	3.18
QWC Annual mains water consumption (L/p/d)	140.4	140.4	211.4	201.5
Average water consumption in IPT households (L/p/d)	119.4	108.5	138.8	129.1
Average water savings in IPT households (L/p/d)	20.9	31.9	72.6	72.4
Average savings per IPT household per year (kL/hh/yr)	24.5	37.3	88.5	84.0
Average savings over all samples (691)	58.8 kL/hh/yr			

Average water savings in IPT household in comparison with annual consumption and benchmark consumption for 2010 (Chong *et al.*, 2012).

Council area (Sample Size)	Pine Rivers (197)	Caboolture (158)	Gold Coast (172)	Redland (164)
Average persons per household	3.21	3.20	3.34	3.18
QWC Annual water consumption (L/p/d)	143.3	143.3	192.0	183.1
Average water consumption in IPT households (L/p/d)	109.4	108.2	125.7	121.9
Average water savings in IPT households (L/p/d)	33.6	34.8	66.3	61.2
Average savings per IPT household per year (kL/hh/yr)	39.7	40.9	81.0	71.0
Average savings over all samples (691)	58.2 kL/hh/yr			

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