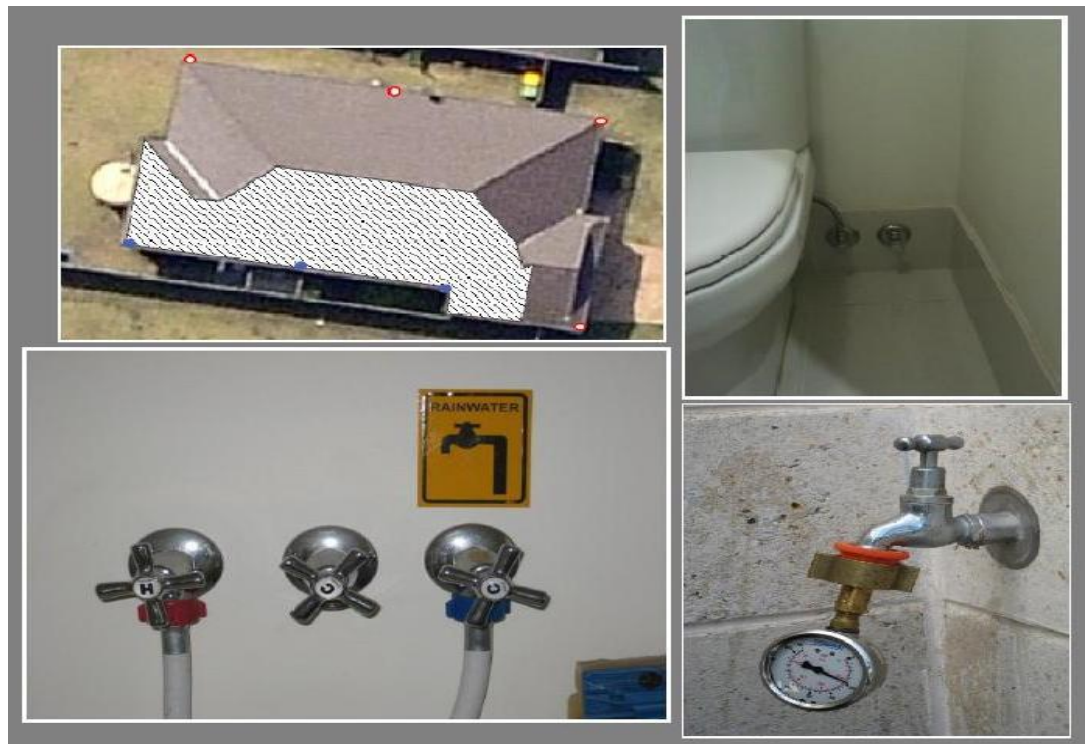


Understanding the Mains Water Saving from Mandated Rainwater Tanks using Water Balance Modelling and Analysis with Inputs from On-Site Audited Parameters

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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

Under the Queensland Development Code (QDC) MP 4.2, it is mandatory for all new detached residential dwellings to save 70 kilolitres per year (kL/yr) of mains water. This can be achieved through the use of various alternative water sources, such as household or communal rainwater tanks, greywater systems, third pipe reticulation systems with purified wastewater or treated stormwater, and other measures, such as use of water efficient appliances. Of all the alternative supply options, implementation of individual household rainwater tanks is the most common practice to achieve the specified mains water saving target. The QDC recommends the following requirements for the rainwater installation to achieve the mains water saving target: (1) have a rainwater tank with minimum volume of 5 kL; (2) connected to at least half or 100 m² of roof catchment area (whichever is the lesser); (3) the rainwater tank supply is internally plumbed to toilet cisterns and at least one cold water laundry tap; (4) connected to at least one external tap for irrigation purpose; and (5) the internal fixtures supplied from the tank must also have a continuous supply of water. Therefore a back-up supply of mains water using a trickle top-up or automatic switching valve is required (DPI, 2010). These recommendations and potential mains water saving (i.e. rainwater yield) are based on a modelling study (WBM Oceanics, 2006) carried out over five climate zones in South East Queensland (SEQ), assuming a high total average daily water demand of 300L/person/day and multiple internal end-uses (i.e. laundry, toilet, shower) and external use of the rainwater.

Since the instigation of the QDC MP 4.2 in January 2007, it is estimated that approximate 60,000 household rainwater tanks (up to year 2010) have been installed in detached residential dwellings. However, investigation of the installation compliance with the QDC MP 4.2 requirements and the actual mains water saving delivered has never been conducted. Biermann *et al.* (2012) report on the results of a physical on-site assessment of mandated rainwater tanks in 223 detached domestic dwellings in four Local Government Areas (LGAs) in SEQ.

This report documents the inspection of the household rainwater tanks installation at 20 selected detached residential dwellings in SEQ, via an on-site auditing program. Various household rainwater tank features such as tank type, dimensions, volumes, connected roof catchment area to tank, rainwater supply connections for toilet flushing, washing machine, external irrigation and other important features were assessed and are discussed in detail. Subsequently, this information was used as the physical parameter inputs to two different rainwater tank simulation models to estimate potential mains water saving for each of the 20 dwellings. This was augmented by linear and multiple regression analysis between the potential mains water saving and dominant governing factors such as tank catchment area, tank size and total average daily water demand. Response surface analysis was also carried out to help visualise the interactions between the modelled mains water saving and the dominant governing factors.

Results from the on-site auditing program showed that a large proportion (90%, 18 out of 20 inspected households) have a manufacturer claimed tank volume greater than 5 kL. However, when the concept of active-to-actual tank volume was accounted for (i.e. discounting for the dead space in rainwater tanks for water storage and overflow), only 45% of the household rainwater tanks achieved QDC MP 4.2 compliance status. On average, it was estimated that only about 80% of the tank volume is effective in rainwater storage which supplies the plumbed end-uses. Regarding connected roof catchment area, it was found that, although all the 20 inspected households had a total roof area exceeding 100 m², only 15% of households achieved the minimum QDC MP 4.2 requirement. On a normalised scale, it was estimated that only about 30% of the roof area was connected to the household rainwater tanks. Other auditing results were satisfactory in that all toilet cisterns were connected to rainwater tanks and only two households did not have a washing machine (but did have a cold water tap from the rainwater tank) or an external water tap sourced from rainwater tank.

Two different rainwater tank models, namely (1) TANK and (2) Urban Volume and Quality model (UVQ), were used to simulate the performance of rainwater tanks based on the 2009 rainfall depth data for four local government areas (LGAs) in SEQ, over which the 20 inspected residential dwellings were located. For 2009, the measured rainfall depth was between 1,171 and 1,582 mm over the four LGAs. The simulation results showed that the modelled mains water saving ranged from

26 kL/hh/yr to 71 kL/hh/yr, with average mains water saving at 49.2 ± 12.0 kL/hh/yr. The reasons for such a large deviation from the specified water saving target of 70 kL/hh/yr are the rainfall depth, active-to-actual tank volumes ratios, the low proportions of compliant connected roof catchment areas and, most importantly, the total household water use patterns. The impacts of these individual key factors were further examined using linear regression and correlation analysis to investigate the extent of each factor on the mains water saving. Further modelling based on 40 years of rainfall data indicated mains water saving in the range of 29 kL/hh/yr to 76 kL/hh/yr, with an average at 52.8 ± 12.6 kL/hh/yr. These savings are in close agreement with the 2009 results based on a single rainfall year.

The linear regression analysis showed that the dominant factor impacting the mains water saving is the total internal household water use. This was evidenced from the high Pearson correlation coefficient value, R^2 of 0.632. This was followed by the tank catchment area ($R^2 = 0.335$), active tank volume ($R^2 = 0.136$) and rainfall depth ($R^2 = 0.119$). A “*what-if*” scenario analysis was also conducted to identify potential ways for internally plumbed mandated rainwater tanks to achieve the QDC MP 4.2 stipulated water saving target of 70 kL/hh/yr. The scenario analysis showed that changing active tank volume to 5 kL does not impact significantly on the modelled mains water saving. Out of the 20 residential dwellings, a 1 kL change in active tank volume contributes a mere 4 kL/yr increase in mains water saving. However, changes in tank catchment area have a more profound effect than the active tank volume. For example, increasing the tank catchment area by 30m² increased the modelled mains water saving by 13 kL/yr. When both the active tank volume and tank catchment area were set to the specified 5 kL and 100 m² respectively, the increase in yearly mains water saving was not significant. Under this condition (i.e., 5 kL and 100 m²), the modelled mains water saving ranged from 36 to 78 kL/hh/yr, with an average value of 54.9 ± 11.5 kL/hh/yr.

In addition to rainwater yield modelling, a response surface analysis (RSA) was conducted to validate the factors’ impact on the eventual mains water savings. From the RSA, it was evident that an increase in tank catchment area yields a higher modelled mains water saving than an increase in active tank volume. This showed that setting up a plumbed rainwater system with a larger tank catchment area (i.e., 150 m²) will provide a cost effective solution to achieve the water saving target. A multiple-regression analysis was also conducted between the modelled mains water saving and the four key physical factors of - yearly rainfall, total household water use, active tank volume and tank catchment area - to develop a simple relationship to estimate mains water saving from plumbed rainwater tanks, without the need for detailed physical modelling. Further validation of the regression equation is required using a separate set of independent modelling data.

1. INTRODUCTION

In Australia, the demands on traditional water supply from the water grid are escalating in conjunction with population growth, rapid industrialisation and booming commercial activities in most of the densely urbanised regions. This is further exacerbated by the adverse impacts of climate change which are likely to affect the adequate and reliable supply of urban water resources. It was projected that by 2026, the total population in the SEQ region could reach as high as 4 million which could place a significant amount of stress on the existing water supply infrastructure (DIP, 2009). This has prompted the State water planning authorities to develop various water strategies and management practices to resolve an impending water shortage issue. As a result, the current SEQ Water Strategy has emphasised a reliance on the sourcing and use of decentralised water systems such as individual household rainwater tanks, greywater diversion and treatment systems, and groundwater bores (NSW Department of Planning 2008; Queensland Water Commission, 2010). These decentralised systems allow households to collect, treat and reuse locally available water sources on a “*fit-for-purpose*” basis, where potable water quality is not required, to reduce the direct reliance on traditional water supply from mains water grids (Tjandraatmadja *et al.*, 2009).

Among the decentralised water systems, rainwater tanks have become an integral component in most of the dwellings in the SEQ region. Gardiner (2009) reported that over 300,000 tanks had been installed in SEQ due to existing government guidelines, tank retrofitting rebates programme or personal investment based on environmental consciousness. Under the Queensland Development Code (QDC) MP 4.2, all new detached residential dwellings in SEQ built after January 2007 (including those applying for extension permits) are required to achieve mains water saving of 70 kilolitres per year (kL/yr). Rainwater tanks are considered as the simplest and most effective way for households to achieve the mains water saving target. The key household requirements proposed in the QDC MP 4.2 to achieve the stipulated 70 kL/yr of mains water saving are: (1) a rainwater tank with minimum volume of 5 kL; (2) 100 m² or at least half of roof catchment area (whichever is the lesser) connected to the rainwater tank; (3) the rainwater supply is internally plumbed for toilet cisterns and at least one cold water laundry tap; and (4) connected to at least one of the external taps for irrigation purpose. The internal fixtures supplied from the tank must also have a continuous supply of water and therefore, a back-up supply of mains water using a trickle top-up or automatic switching valve is required (DPI, 2010). A full compliance to QDC MP 4.2 requirements is important as this will (1) promote a partial self reliance ethos amongst householders, (2) increase the reliability of mains water from dams, and (3) enhance the cost-effectiveness and reliability of rainwater tanks due to increased supply of rainwater.

Since the implementation of QDC MP 4.2 in 2007, approximately 60,000 detached residential dwellings were built with rainwater tanks in SEQ (ABS, 2010). However, the on-site assessment of the actual tank installations and the compliance to the QDC Part MP 4.2 for these new homes has never been conducted in detail. Information on the level of compliance to the QDC MP 4.2 in installing mandated rainwater tanks will help planning authorities to revisit the certification process for rainwater tanks. This information will also help in analysing the impact on potential mains water savings due to mandated rainwater tanks.

The purpose of this study was to understand the implementation of rainwater tank installations at 20 selected detached dwellings in SEQ through on-site household auditing and data gathering. Various rainwater tank features were assessed, such as tank type, dimensions, volumes, connected roof catchment area to tank, rainwater supply connections for toilet flushing, washing machine, external irrigation and other important features. The findings from this study were compared to the estimated mains water saving from a benchmark analysis approach. It was also anticipated that the results obtained from this study would be used to define the physical parameters required in rainwater tank simulation models, in order to accurately predict the water yield from rainwater tank systems.

Further work on monitoring the mains water and rainwater uses for these 20 households with mandated rainwater tanks is currently taking place (see Umaphathi *et al.*, 2012). This research is an important step in achieving a more integrated understanding of mains water saving from mandated rainwater tanks, as well as the associated tank and household physical factors that might affect the household rainwater supply and use.

2. METHODOLOGY

2.1. Study Setting and Time Period

The households for the on-site audit study were selected from four local government areas (LGAs) in the SEQ region: Caboolture, Pine Rivers (now combined into Moreton Bay Regional Council), Redlands and Gold Coast. According to the 2006 Australian Census, these four LGAs contain over 40% of the total urban population in SEQ and dominate new residential areas for housing development. All new residential dwellings built after January 2007 in SEQ have rainwater tanks installed as per the QDC MP 4.2 mandated water savings target (referred to in this report as households with mandated rainwater tanks). Household sample selection was based on geographic location and the weighted-average distribution in household occupancy characteristics. The sample selection process is further discussed in Section 2.2.2. Figure 1 shows the distribution of the 20 selected households for on-site auditing on their mandated rainwater tank installation, individual household settings and other related water features.

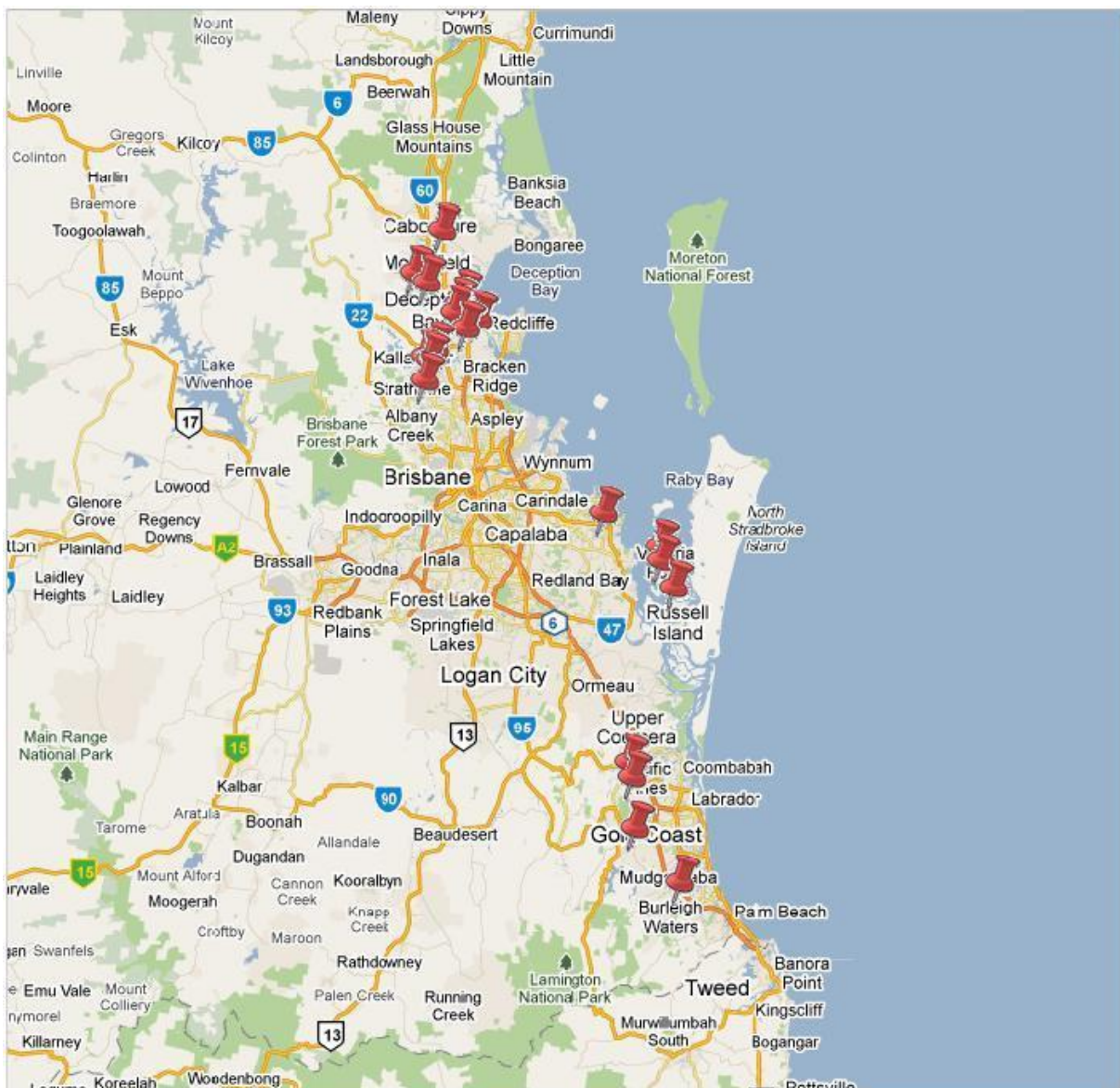


Figure 1: Distribution of the 20 selected households for on-site auditing of their mandated rainwater tank installation, individual household settings and other related water features. (Source: Map modified using Google Maps).

2.2. Participants

2.2.1. Recruitment

Participants were recruited from the four LGAs of Caboolture, Pine Rivers, Redlands and Gold Coast. The Queensland Water Commission (QWC) provided a database of approximately 15,615 home addresses which matched the criterion for QDC MP 4.2 (i.e. new water meter accounts from June/July 2007 to June 2010). The use of this filtering criterion in the database was to assure that most of the addresses were for newly constructed homes with mandated rainwater tanks.

A market research company (TNS Global Research, Brisbane Australia) was contracted to match the database with their telephone numbers (i.e. landlines and mobile phones) and to conduct a telephone survey developed by the CSIRO project team. However, only 5,005 addresses could be matched with their corresponding telephone numbers. Of these 5,005 addresses, only 499 households gave their consents for the CSIRO research team to conduct household auditing and rainwater tank monitoring activities. For this study, we have selected only 20 households for rainwater tank installation auditing and rainwater usage monitoring from mandated tanks.

2.2.2. Sample Selection Matrix

As described in Section 2.1, the main rationale for selecting the 20 households was a combination of geographical location (i.e. LGA classification) and the household occupancy characteristics. A selection matrix using a weighted-average distribution of household occupancy characteristics from the 499 respondents was used to determine the final selection of 20 households.

Prior to the construction of a sample selection matrix, the 499 respondent households were screened to ensure that they were well-suited to our study requirements. Responses obtained from the telephone survey were used to guide the screening process. The screening questions criteria included: (1) households with a rainwater tank at their property; (2) the rainwater tanks are internally plumbed in for toilet cisterns, washing machine cold water tap and at least one external irrigation tap; (3) only owner-occupiers (not renters) were selected; (4) only detached dwellings were selected; (5) only the houses built after 2007 were required; and (6) the households were supplied with mains water but not any other alternative water source such as dual reticulation.

After the screening process, the original sample size of 499 households was reduced to 353 households. From the reduced sample number, a sample selection matrix was constructed which encompassed the different household occupancy characteristics. A 1x3x3 matrix was constructed to randomly select the 20 households for auditing purposes. This matrix is given in Figure 2. As shown in Figure 2, the household characteristics also covered information on the number of adolescents occupying the house (ie, None, One, and More than One Adolescent).

		Household numbers in each characteristic type		
1 Adult	No Child	11	2	2
	1 Child	2	0	0
	> 1 Child	4	2	0
2 Adults	No Child	117	10	11
	1 Child	37	11	1
	> 1 Child	75	2	4
≥ 3 Adults	No Child	35	5	7
	1 Child	5	2	2
	> 1 Child	5	1	0
		No Adolescent	1 Adolescent	> 1 Adolescent

(a)

		Percentages in each characteristic type		
1 Adult	No Child	3.2%	0.6%	0.6%
	1 Child	0.6%	0.0%	0.0%
	> 1 Child	1.2%	0.6%	0.0%
2 Adults	No Child	33.8%	2.9%	3.2%
	1 Child	10.7%	3.2%	0.3%
	> 1 Child	21.7%	0.6%	1.2%
≥ 3 Adults	No Child	10.1%	1.4%	2.0%
	1 Child	1.4%	0.6%	0.6%
	> 1 Child	1.4%	0.3%	0.0%
		No Adolescent	1 Adolescent	> 1 Adolescent

(b)

		Final household numbers in each characteristic type		
1 Adult	No Child	1	0	0
	1 Child	0	0	0
	> 1 Child	0	0	0
2 Adults	No Child	7	1	1
	1 Child	2	1	0
	> 1 Child	5	0	0
≥ 3 Adults	No Child	2	0	0
	1 Child	0	0	0
	> 1 Child	0	0	0
		No Adolescent	1 Adolescent	> 1 Adolescent

(c)

Figure 2: Sample selection matrix for 20 households with mandated rainwater tanks in SEQ selected for this study.

In Figure 2 (a), the overall classification for household characteristics was divided into types with “1 adult”, “2 adults” and “equal or greater than 3 adults”. Within the household characteristic types, each of them was further classified into 9 different combinations based on number of children (3 classes) and adolescents (3 classes). The 353 respondents and screened households were distributed into the relevant classifications to create a percentage-weighted sample selection matrix as per Figure 2 (b), to guide the selection of final 20 households. Figure 2 (c) shows the final distribution of the 20 households chosen for this study as per the households’ demographic characteristic. For example, 2 adults, no child, no adolescent comprised 34% of the sample population. Hence 7 households (34% x 20) with these characteristics were chosen for subsequent monitoring as part of the 20 household cohort.

2.3. On-Site Assessment Procedures

BMT WBM Pty Ltd was contracted by the CSIRO research team to conduct the on-site household auditing program to understand the local settings and installation of mandated rainwater tanks at 20 selected households in SEQ. In a related study, BMT WBM was also engaged to undertake the physical on-site assessment of mandated rainwater tanks in 223 class 1 (detached domestic) dwellings in SEQ (Biermann *et al.*, 2012).

In this study, the household auditing methodologies and approaches described in the following sections were based on the discussions between the CSIRO research team and BMT WBM Pty Ltd.

2.3.1. Tank Catchment Area and Total Roof Area

To determine the total roof areas and proportions that are actually connected to the rainwater tanks, an aerial photograph from Google Earth or NearMap for each house was printed and taken to the sites as initial work sheets. At each of the 20 selected households, the information on the number of downpipes was collected. This was followed by checking whether the rainwater tank system was either of the charged or uncharged type. The plumbing differences between charged and uncharged systems are shown in Figure 3.

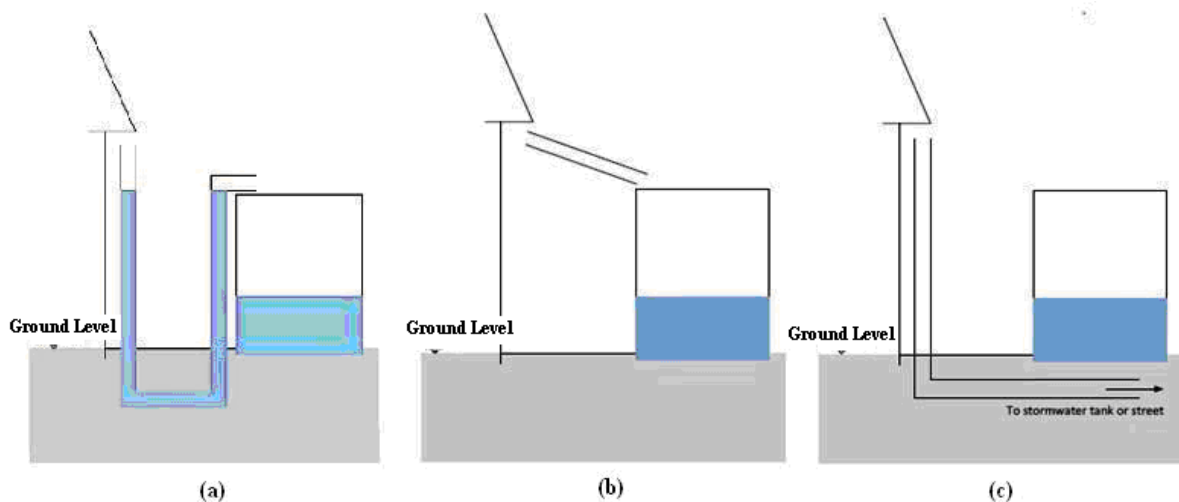


Figure 3: Differences between rainwater tank collection systems. (a) Charged system; (b) Uncharged system and (c) downpipe connection to stormwater drainage

Figure 3 shows the common scenarios for downpipe connection for rainwater tank systems at the audited households. For the charged system, the downpipes connected to rainwater tanks are normally below ground level which makes it difficult to visually determine their connections to rainwater tanks. In this instance, these downpipes are usually full of rainwater. For the uncharged systems, the downpipes connected to the rainwater tank usually do not go underground and thus, can be assessed visually as shown in Figure 3(b). The connection of downpipe to stormwater drainage is shown in Figure 3(c). Thus, all the downpipes that were either charged or uncharged and connected or not connected to rainwater tanks were marked on the relevant aerial photographs.

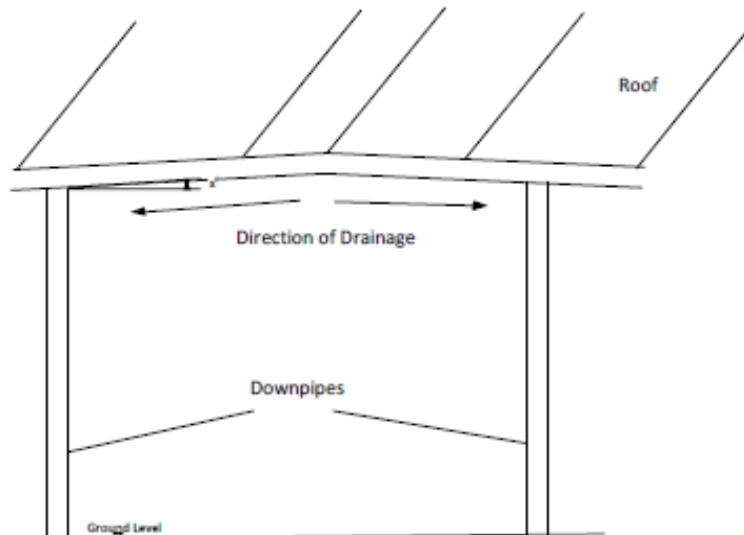


Figure 4: Determination of tank catchment area based on the position and direction of drainage from the gutter slope.

The roof areas connected to rainwater tanks were estimated using the position and direction of roof drainage, the direction of the gutter slope, and location/number of downpipes connected to rainwater tanks. In this instance, the gutter slopes were either determined visually (i.e. for double storey dwellings) or with a spirit level (for single storey dwellings). The inflexion point of the change in slope direction of the gutter between downpipes was marked on the working aerial photograph sheets for each of the 20 households. This is shown in Figure 4. All these working sheets were processed in the office with either Google Earth or NearMap, to mark the location and inflexion points of gutters, as well as determining the tank catchment area and the total roof area. An example of a marked up aerial photograph which is used as the working sheet is shown in Figure 5.

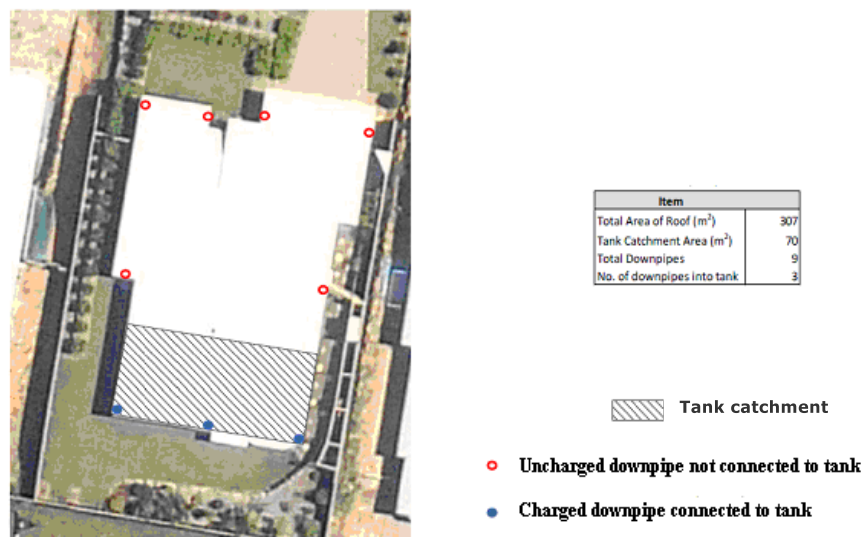


Figure 5: An example of the “marked up” aerial photograph to determine the tank catchment area and total roof area.

2.3.2. Physical Tank Characteristics and Settings

Auditing the physical tank characteristics and settings at the 20 households, was usually carried out either via visual inspection (by the BMT WBM contractors conducting physical measurements) or via information available from manufacturers' claims on attached labels. These included identifying the number of tanks at the premises, tank dimensions, tank manufacturers, manufacturers' claimed tank volume, tank setup, pump make and model, water switching device and others. Table 1 shows the list of physical tank characteristics and settings for the on-site household inspection at the 20 households.

Table 1: List of physical tank characteristics and settings for on-site household auditing at the 20 households.

Parameters for On-Site Households Auditing
1. Oval tank length (mm)
2. Oval tank width at 1/2 Length (mm)
3. Oval tank width at 2/3 Length (mm)
4. Oval tank width at 5/6 Length (mm)
5. Number of identical cylindrical tanks
6. Oval tank manufacturers claimed volume (L)
7. Diameter of cylindrical tanks (mm)
8. Number of identical oval tanks in system
9. Cylindrical tank manufacturers claimed volume (L)
10. Number of identical rectangular tanks
11. Rectangular tank width (mm)
12. Rectangular tank length (mm)
13. Rectangular tank manufacturers claimed volume (L)
14. Height of tank (mm)
15. Height of tank outlet (mm)
16. Height of tank pump cut-off switch (mm)
17. Height of tank overflow (mm)
18. Pump make
19. Pump model
20. Water switch model
21. Water switch make
22. Volume of the pump pressure tank (L)
23. Is there a separate backflow prevention device?
24. How many garden taps are connected?
25. What are the appliances attached to the rainwater?
26. Pressure of system at tap (kPa)
27. Distance of tap from pump (m)
28. Area of roof connected to system (m ²)
29. Size of first flush device (L)
30. Initial mains in meter reading
31. Initial total out meter reading
32. Total area of roof (m ²)
33. Mains meter type
34. Leaf guard present?
35. Mains meter reading
36. Number of downpipes on house
37. Number of downpipes delivering water to system

2.3.3. Rainwater Supply Connections and End-Uses

Toilet Cisterns

A number of methods were adopted to determine if the rainwater was supplied or connected to toilet cisterns (Figure 6) for the 20 households. For instance:

- (1) The toilet was flushed to see if it triggered the rainwater pump and that the cistern filled with (rain) water; and
- (2) The rainwater supply was turned off and the toilet was flushed to see if any (mains) water filled the cistern.



Figure 6: An example of a rainwater supply connection that fills the toilet cistern.

Washing Machine

Similarly, the rainwater supply connection to washing machine (Figure 7) was determined using the same approaches used for the toilet cisterns:

- (1) The washing machine was started in cold wash mode and the pump checked to ascertain if it was triggered and (rain) water flowed into the machine; and
- (2) The rainwater supply was turned off, the cold water tap set in the open position, and the washing machine operated in cold wash mode to see if any (mains) water entered the machine.



Figure 7: An example of the water supply connection to a washing machine. Note the dedicated rainwater tap as well as mains supplied hot & cold water taps.

External Tap

To determine the external tap connection received supply from a rainwater tank, similar approaches to the washing machine and cistern were adopted. Figure 8 shows the pressure measurement at an external tap to determine the flow from the rainwater tank.



Figure 8: Pressure measurement at an external tap to confirm water flow from a rainwater tank.

2.3.4. Other Water Features

Water Switches

Typically, water switches are used to supply the mains water supply to the rainwater tank when the tank level runs low. There are two major types of mains water back up water switches on the market: an electronic water switching valve; and the mechanical trickle top-up device, both of which are shown in Figure 9. The type of water switch installed was identified from a simple visual examination.

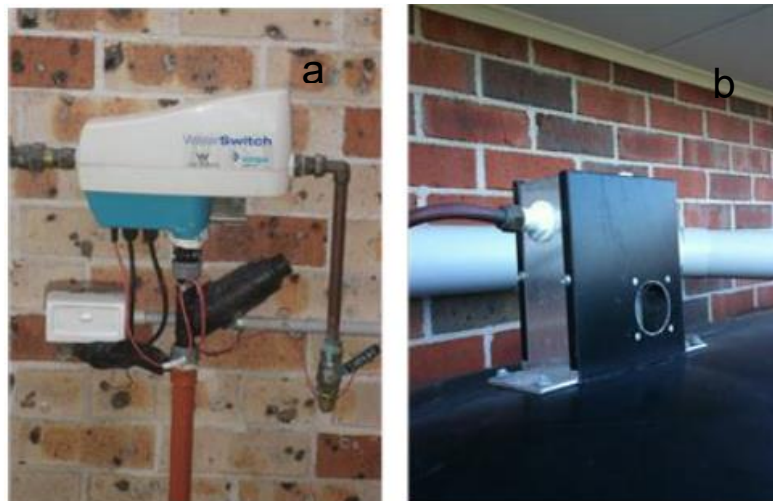


Figure 9: Mains back up water switching devices. The electronic switching valve device is shown in the LHS photo, whilst the mechanical trickle top-up device is shown in the RHS photo. The mechanical device uses a float and rod installed in the tank and connected to a mechanical valve located on the top of the tank.

First flush Devices

The first-flush devices are installed to divert an initial pre-set volume of roof runoff from entering the rainwater tank and thus, reducing the pollutant loads in the rainwater. These devices are easily recognisable, as shown in Figure 10. However, there are some challenges in determining the volume for the first flush device as in Figure 10 (b). In this study, the volume of the device in Figure 10 (b) was estimated by taking measurements (i.e. depth and width) and noting the product name to retrieve information from manufacturers' specifications.

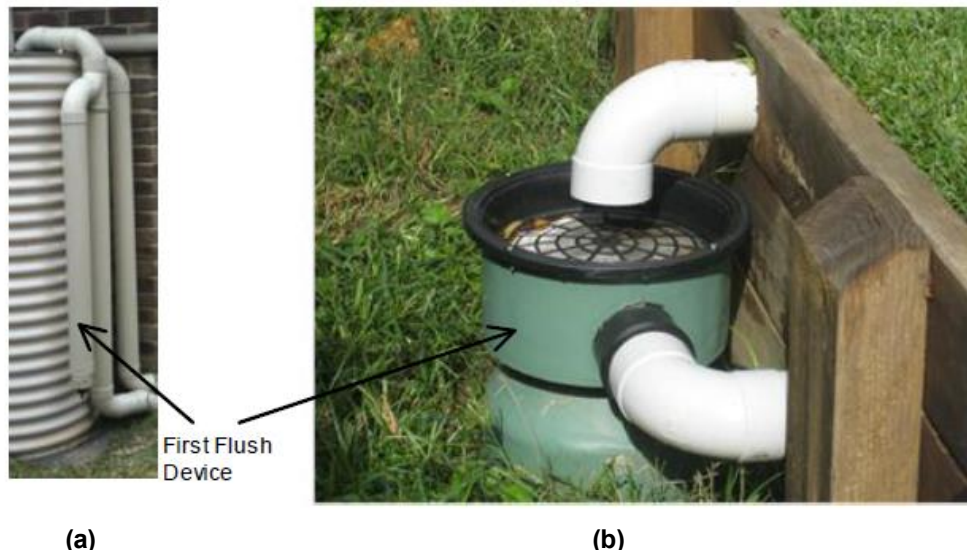


Figure 10: Examples of typical first flush devices.

Backflow Prevention Systems

The backflow prevention systems are usually located either immediately on the upstream side of the mains input to the switching device, or on the mains meter. These systems are quite distinctive as shown in Figure 11, and were easily determined from a simple visual examination.



Figure 11: An example of a backflow prevention device. This prevents rainwater being drawn back into the potable mains supply in the event of a pressure drop in the mains water reticulation system.

2.3.5. Summary of Households Auditing

Table 2 shows the summary outputs for the auditing study on the 20 households examined in this study. Key parameters such as tank capacity, dimensions and setup, plumbed end-uses of rainwater and other important water features that might impact on the mains water saving are listed in the table.

Table 2: Summary of key auditing parameters for the selected 20 Class 1 dwellings in SEQ with mandated rainwater tanks.

Audited Class 1 Dwellings	Number of Rainwater Tank	Shape of Rainwater Tanks (Cylindrical, C or Rectangular, R)	Tank Diameter (for C-tanks) (m)	Tank Height (m)	Tank Length (for R-tanks) (m)	Tank Width (for R-tanks) (m)	Height of Tank Outlet (m)	Height of Tank Pump Cutoff Switch (m)	Height of Tank Overflow (m)	Total Roof Area (m2)	Connected Roof Area to Tank (m2)	Total number of downpipes on house	Number of downpipes connected to tank	Leafguard present at rainhead? (Y-Yes; N-No)	Size of first flush device (L)	Rainwater use for washing machine/laundry? (Y-Yes; N-No)	Number of toilets connected with rainwater	Number of external taps connected with rainwater	Pressure of rainwater system at tap (kPa)	Any backflow prevention device? (Y-Yes; N-No)	Waterswitch Make	Pump Make	Pump Model
IPT1	1	C	2.15	1.80	-	-	0.07	-	1.47	313	127	6	3	Y	-	Y	2	1	350	-	Trickle Top-up	Silver	SJ3504PC
IPT2	1	C	2.50	1.55	-	-	0.09	-	1.18	320	69	8	2	Y	16	Y	2	1	400	N	Onga Waterswitch	Onga	SMH 45
IPT3	3	C	0.72	2.15	-	-	0.03	0.38	2.00	169	27	13	3	Y	12	Y	3	1	200	-	Davey Rainbank	Davey	HP45-05
IPT4	1	R	-	1.85	2.75	1.10	0.05	-	1.75	230	54	9	3	Y	-	Y	2	1	300	N	Onga Waterswitch	Onga	SMH-45
IPT5	1	C	1.80	2.25	-	-	0.10	-	2.00	140	37	7	2	Y	-	Y	2	1	400	N	Trickle Top-up	Monza	NPP 80 L
IPT6	1	C	1.94	1.85	-	-	0.05	-	1.75	316	99	8	4	Y	18	Y	2	1	320	-	Trickle Top-up	Onga	SMH 45
IPT7	1	R	-	1.55	2.81	0.87	0.05	0.16	1.45	255	86	8	2	Y	16	Y	2	1	220	N	Davey Rainbank	Davey	HP 45-05
IPT8	1	R	-	1.86	2.80	1.17	0.05	-	1.76	305	54	10	2	Y	15	Y	3	1	300	Y	Davey Rainbank	Davey	HP 45-05
IPT9	1	R	-	1.87	2.80	1.15	0.05	0.16	1.80	319	48	10	1	Y	11	Y	2	1	350	-	Davey Rainbank	Davey	HS50-06L
IPT10	1	C	1.90	1.85	-	-	0.06	-	1.50	178	90	4	2	Y	-	Y	2	1	250	N	Trickle Top-up	Commercial Electric	CECPP800
IPT11	1	C	2.20	1.80	-	-	0.07	-	1.48	288	135	10	5	Y	-	Y	2	1	300	N	Trickle Top-up	Silver	SJ 3504PC
IPT12	1	C	2.00	2.00	-	-	0.00	-	1.85	300	75	11	3	Y	6	Y	2	1	320	-	Aquasource	Submersible	-
IPT13	1	C	2.00	1.85	-	-	0.07	-	1.50	220	54	5	2	Y	-	N	2	1	300	-	Trickle Top-up	Davey	Aquamate 72111-0
IPT14	1	C	1.80	2.10	-	-	0.09	-	1.80	243	80	10	4	Y	-	Y	2	1	330	Y	Trickle Top-up	Onga	Riva-Flo GPP40
IPT15	1	C	1.97	1.90	-	-	0.05	-	1.65	119	46	6	2	Y	-	Y	1	-	-	-	Trickle Top-up	Blueatron	100
IPT16	1	R	-	1.95	2.60	1.10	0.16	-	1.85	268	94	9	4	Y	-	Y	2	1	300	Y	Water Wizard	Waterboy Wizard	NGD-C45
IPT17	1	C	2.00	1.85	-	-	0.12	0.19	1.50	296	83	7	2	Y	-	Y	2	1	340	Y	Davey Rainbank	Davey	HP45-05
IPT18	1	R	-	1.55	2.92	1.14	0.05	0.24	1.50	307	70	9	3	Y	-	Y	2	1	220	N	Davey Rainbank	Davey	HP 45-05
IPT19	1	C	2.14	1.80	-	-	0.13	-	1.48	234	105	7	3	Y	-	Y	2	1	320	-	Trickle Top-up	Silver	SJ35-04PC
IPT20	1	C	2.30	1.55	-	-	0.13	-	1.40	245	99	6	3	Y	12	Y	2	1	320	-	Onga Waterswitch	Onga	SMH 350

2.4. End-Uses Data for Rainwater Tank Simulations

In order to estimate the potential mains water savings due to changes in key household parameters (eg, tank capacity, active volume, dead volume, connected roof catchment area) associated with internally plumbed rainwater tanks, different scenarios were created and simulated using the rainwater TANK model (Vieritz *et al.*, 2007). Values for the physical household parameters listed in Table 2 were used as the initial inputs to the TANK model. The water end use data from recent studies in SEQ was used to define the demand requirements for external irrigation, washing machine and toilet cisterns, respectively (i.e. which are all mandated end-uses in QDC MP 4.2) (Willis *et al.*, 2009; Beal *et al.*, 2011). Figure 12 summarises the water end uses data from recent studies in SEQ, and the calculated average values.

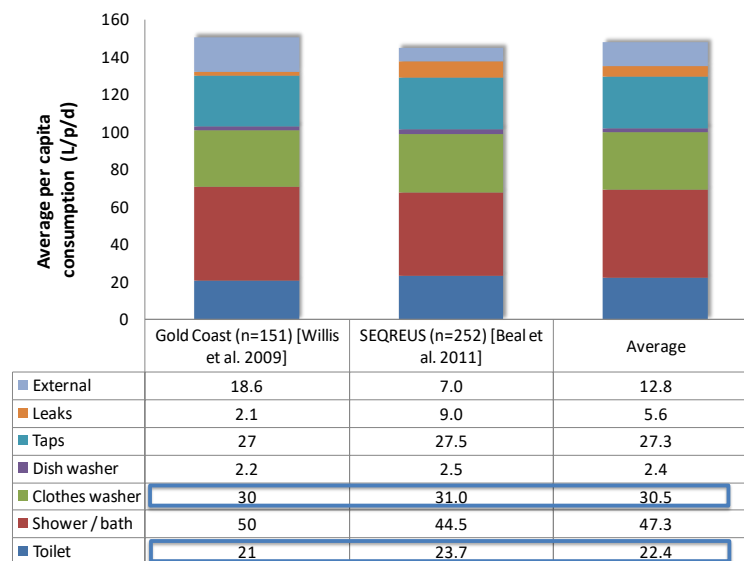


Figure 12: Summary of water end uses from recent end use studies in SEQ (Beal *et al.*, 2011).

3. RESULT AND DISCUSSION

3.1. Basic QDC MP 4.2 Compliance Criteria

Under the QDC MP 4.2, it is proposed that the installed rainwater tanks must have sufficient storage capacity and connected roof catchment area to capture rainfall that will meet the mains water saving target of 70 kL/hh/yr. In this study, the on-site households audit was designed to assess whether the 20 selected Class 1 residential dwellings in SEQ met the basic requirements as specified in the QDC MP 4.2 before a further comprehensive water saving analysis and scenario modelling analysis was undertaken.

3.1.1. Tank Volumes

To validate tank volumes at the 20 residential dwellings information on physical tank dimensions from Table 2 were used. It was found that there were two main shapes of rainwater tanks that were installed: cylindrical and rectangular. From Table 2 data, cylindrical tanks were more common with 65% of households having tanks of this shape. The remaining 35% had rectangular tanks.

Figure 13 shows the estimated actual tank volumes from using simple geometrical relationships. The actual tank volumes for cylindrical and rectangular tanks were estimated using Equations (1) and (2), respectively.

$$\text{Actual Tank Volume (Cylindrical)} = \frac{\pi}{4} \times (\text{Diameter})^2 \times \text{Height} \quad (1)$$

$$\text{Actual Tank Volume (Rectangular)} = \text{Length} \times \text{Width} \times \text{Height} \quad (2)$$

From Figure 13, 90% of the audited homes have tank volumes equal or greater than 5 kL as stipulated in the QDC MP 4.2. Of the households audited, 55% have a tank volume in the range of 5,000-5,999 litres, 30% fall in the range of 6,000-6,999 litres and only 5% have tanks in the range of 7,000-7,999 litres. The remaining 10% of audited households have tank volumes of less than 5 kL, with 5% each in the range of 2,000-2,999 and 3,000-3,999 litres, respectively.

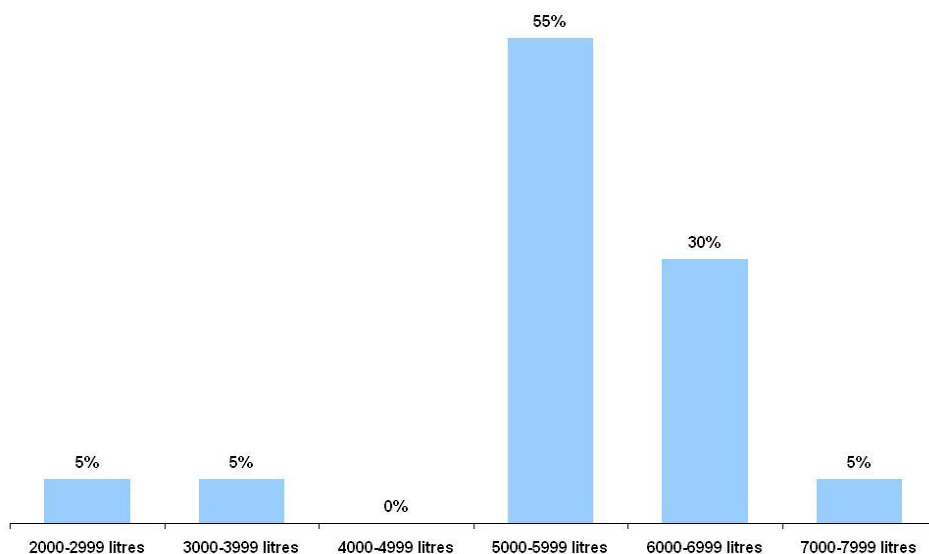


Figure 13: Estimated actual tank volumes at the 20 inspected Class 1 dwellings in SEQ.

When the concept of active tank volumes was taken into account, the number of audited households with tank volumes equal or greater than 5 kL decreased. Figure 14 illustrates the concept of active tank volumes where the “working” tank volume for rainwater storage was highly influenced by the local tank settings by plumbers. Two different active tank volume scenarios are shown in Figure 14. In Figure 14 (a), which represents almost all the cylindrical tanks examined, the actual tank volumes that contributed to rainwater storage and use were reduced when the dead tank spaces below the tank outlet and above the overflow level were taken into account. In Figure 14 (b), seen mostly in the rectangular tanks, the tanks were fitted with a “pump cut-off” water level of approximately 15-20 cm above the tank outlet to prevent the rainwater pumping line from sucking in air. Such a local pump setting height further reduces the active tank volume available for rainwater storage and supply to plumbed-in households.

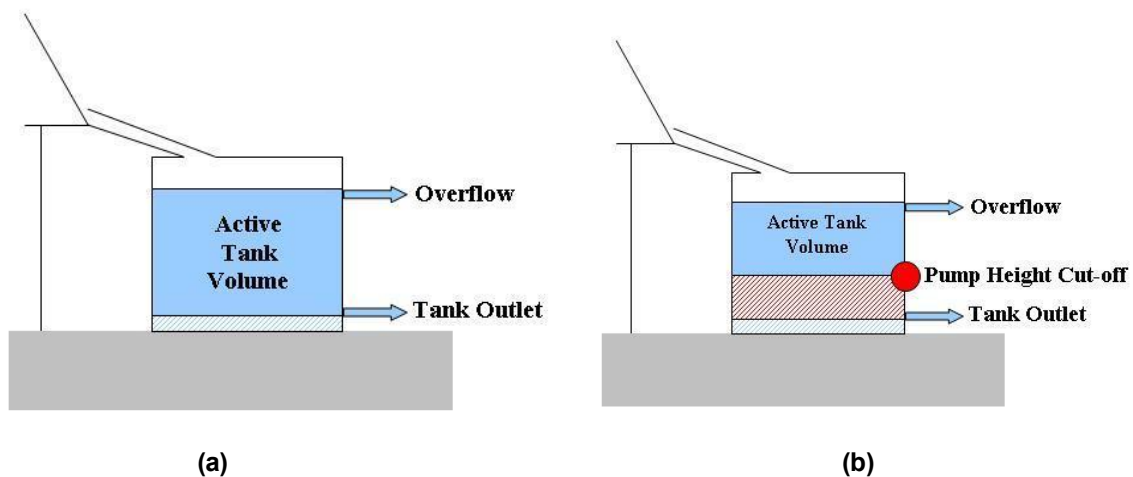


Figure 14: Illustrations for the concept of active tank volumes observed at the selected Class 1 dwellings in SEQ - (a) active volume as the capacity of tank (b) active volume reduction due to pump cut-off height.

It can be seen that the number of tanks with volume greater than 5,000 litres was reduced when the active tank volume was taken into account (Figure 15). Only 45% of the inspected households have tank volumes of greater than 5,000 litres as stipulated under the QDC MP 4.2, with a further 45% having volumes in the range 4000 to 4999 litres. Figure 16 shows the comparison and percentages distribution change of actual-to-active tank volume scenarios. The 90% of households with actual tank volumes greater than 5,000 litres were halved to 45% when active tank volumes were considered. Most of the inspected households were found to have active tank volumes in the range of 4,000 – 4,999 litres (45%) and this may have a major impact on the final mains water saving from internally plumbed rainwater tanks. A scenario analysis using TANK modelling was conducted in Section 3.6 to investigate the various impacts of active tank volumes on the mains water saving.

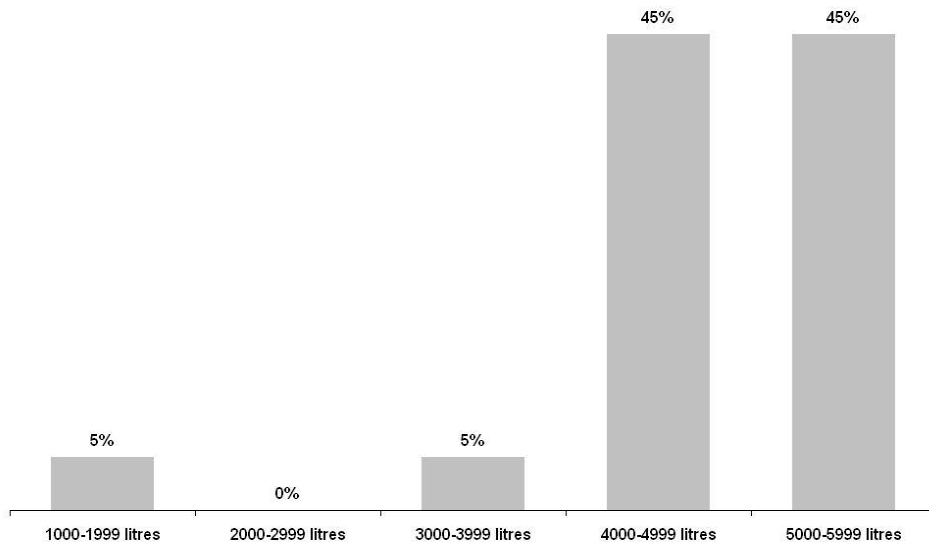


Figure 15: Estimated active tank volumes at the 20 inspected Class 1 dwellings in SEQ.

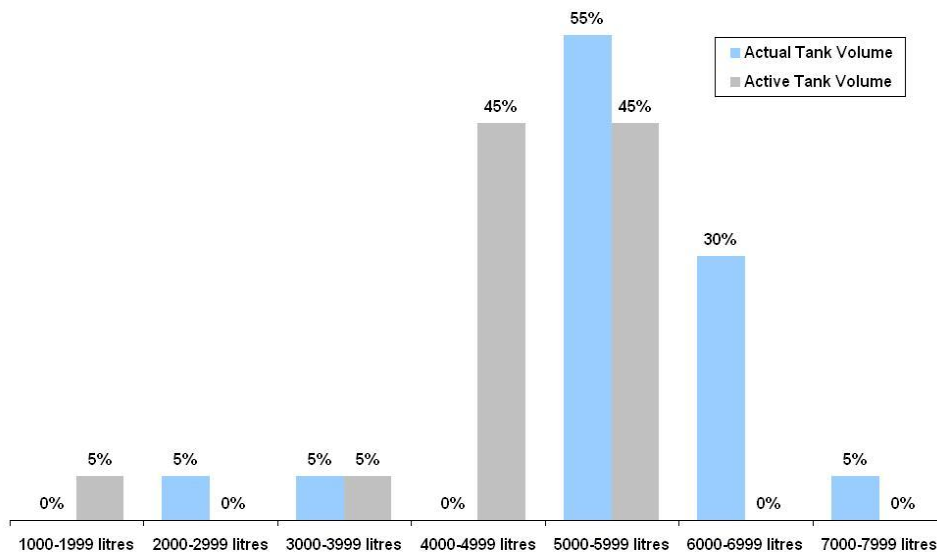


Figure 16: Comparison of percentages change in actual-to-active tank volumes.

Figure 17 shows the normalisation graph of active tank volumes compared to actual tank volumes for each 20 dwellings inspected. It can be concluded from Figure 17 that, on average, the active “working” volume is around 80% of the actual volume, with the remaining 20% as “dead” volume as far as rainwater storage is concerned. Further details on the rainwater tank dimensions for each of the 20 dwellings are given in Table 2.

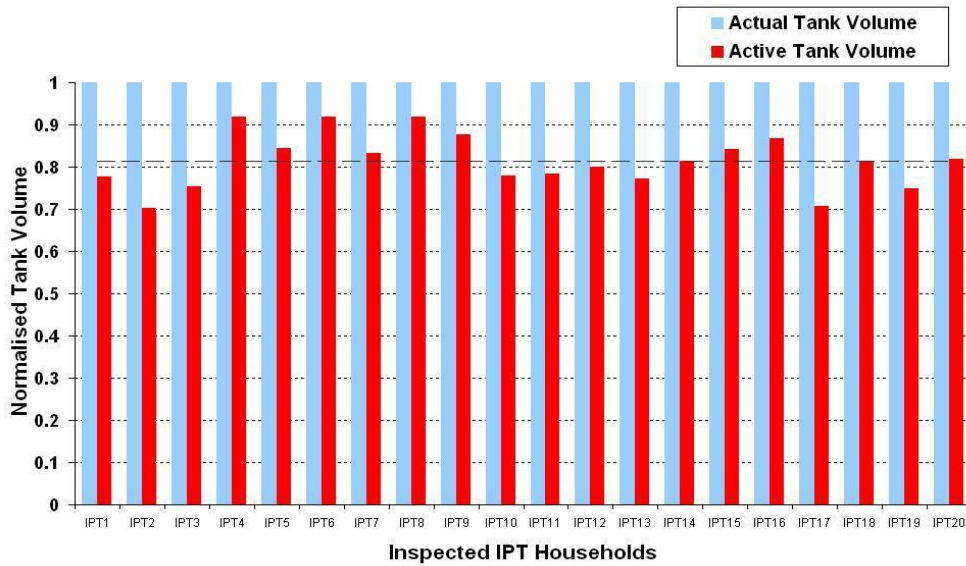


Figure 17: Normalised active to actual tank volumes for each of the 20 inspected Class 1 dwellings in SEQ.

3.1.2. Tank Catchment Area and Total Roof Area

The methodology to determine the total roof area and the proportion connected to rainwater tanks is described in Section 2.3.1. Different rainwater setups were encountered at the 20 dwellings, being comprised of either charged or uncharged downpipes connecting to the rainwater tank systems. Figure 18 shows the distribution of estimated total roof area for the 20 inspected dwellings using a combined aerial photography and on-site validation method. Results showed that the estimated total roof area for all 20 dwellings was above 100 m², with most of the inspected homes (45%) falling in the range of 200-299m² followed by 35% in 300-399m² and 20% in 100-199m² (Figure 18).

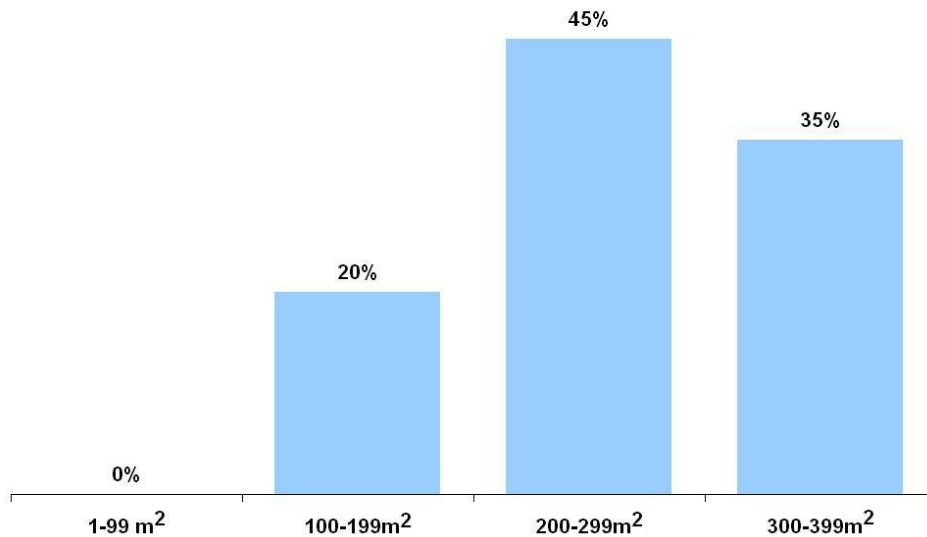


Figure 18: Estimated total roof area distribution for the 20 inspected Class 1 dwellings in SEQ.

However, the main interest in assessing the total roof area is to verify the proportion of roof area that directs rainfall to the rainwater tank. This parameter is crucial as it has a direct impact on the quantity of rainfall captured into the rainwater tanks for household use (i.e. toilet cisterns, cold tap washing machine and external irrigation). When only the tank catchment area was considered, most of the households had less than 100 m² of tank connected roof area. Figure 19 shows that 85% of the inspected households have tank catchment areas of less than 100 m².

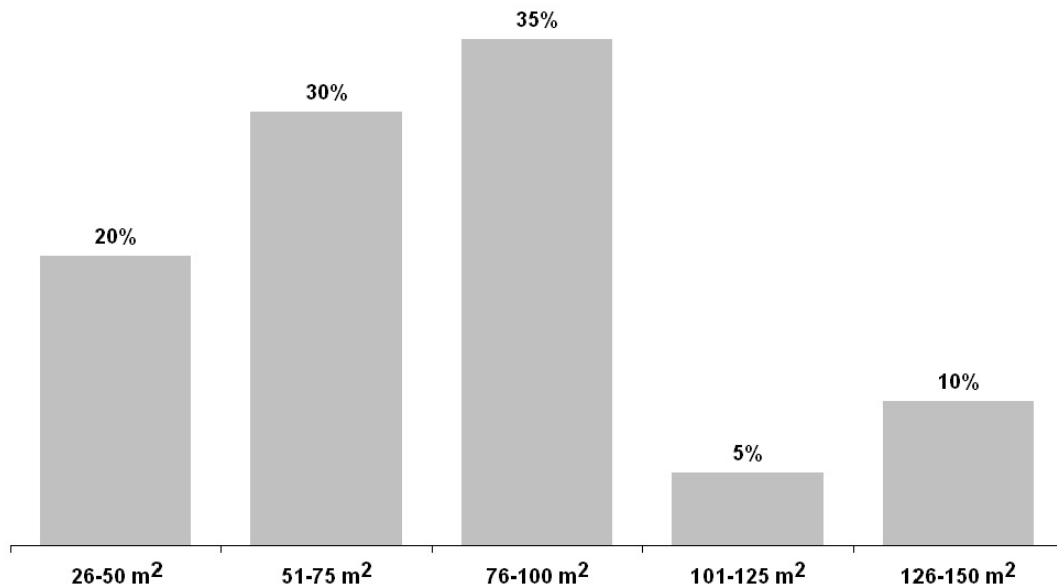


Figure 19: Estimated tank catchment area at the 20 inspected Class 1 dwellings in SEQ.

The impact of tank catchment area on mains water saving was assessed by TANK modelling using the physical parameter inputs obtained from the audit study. The ratio of tank catchment area to the total roof area for each inspected dwelling was calculated and results are shown in Figure 20 as a normalisation graph. The average value is 30%, and this value was adopted for subsequent modelling and simulation activities. Further details on the total and connected roof area for each of the 20 dwellings are given in Table 2.

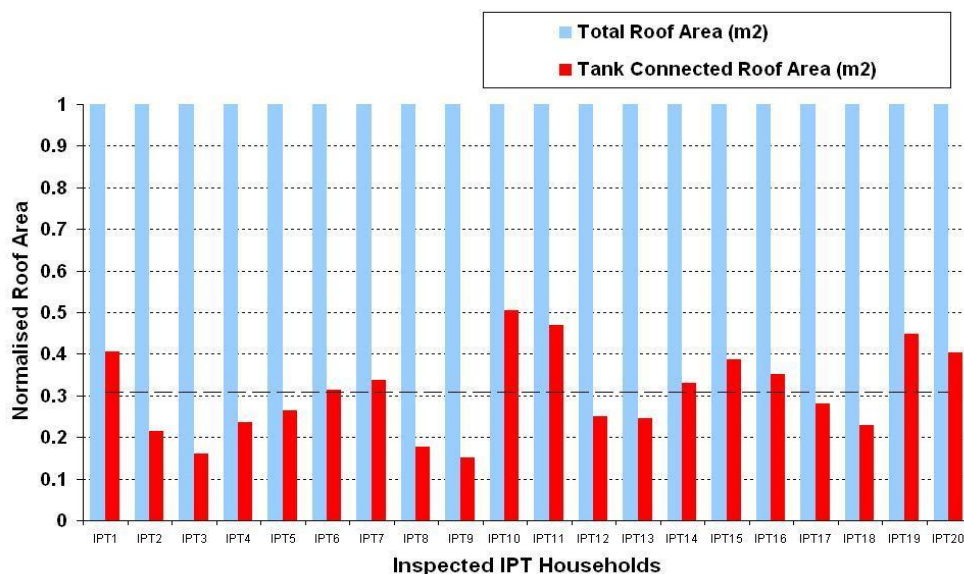


Figure 20: Normalised tank catchment area to the total roof area for each of the 20 inspected Class 1 dwellings in SEQ.

3.1.3. Rainwater Supply Connections and End-Uses

The rainwater supply from rainwater tanks for non-potable household applications (i.e. toilet cisterns, cold tap washing machine and external irrigation) is intended to augment the traditional mains water sources. It is well-established that if more household appliances (or frequency of use) are connected to the rainwater tank, the more rapid the water level in rainwater tanks will be drawn down, resulting in a higher rainwater capture yield due to reduce overflows from the tank.

Figure 21 shows a histogram on the number of toilet cisterns connected to the rainwater tanks. Most of the inspected households (85%) had two toilet cisterns connected to rainwater tanks, with 10% having three toilet cisterns and 5% having only one toilet cistern connected to rainwater tank supply (although it is noted that it is unlikely that toilet water use per person per day responds to the number of toilets per dwelling). Also, 95% of the inspected households had washing machines and external water taps connected to rainwater tank supply. Only two inspected households were found to have either a washing machine cold water tap or an external water tap not sourced from the rainwater tank. This is summarised in Table 2.

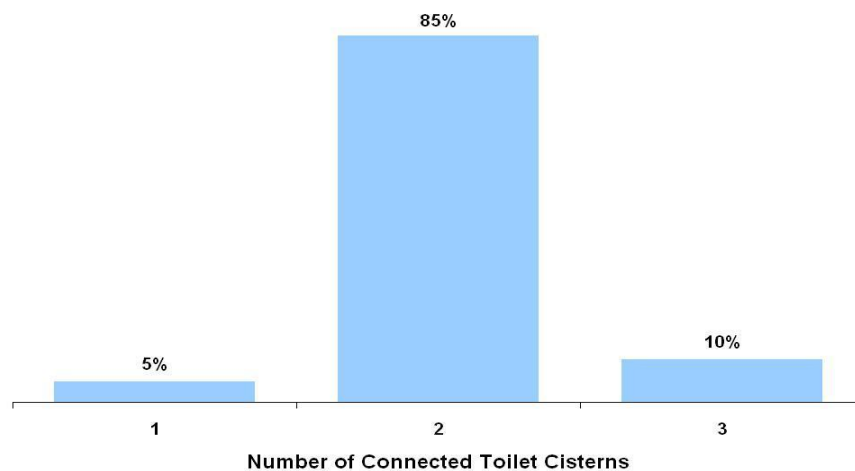


Figure 21: The numbers of toilet cisterns connected to rainwater supply.

3.1.4. Other Rainwater Tank Features

Apart from the physical parameters of rainwater tank setup (listed in Table 2) that might potentially impact the final mains water saving in the households, other rainwater tank features were also highlighted. Figure 22 shows the recorded total number of downpipes for each house as well as the number of downpipes connected to the rainwater tank. The average number of downpipes actually conveying rainwater from the roof catchment into the tanks was 2.75. In comparison, the average number of total downpipes per dwelling for the 20 inspected houses was 8.15. This indicated that approximately 30% of the downpipes were connected to a rainwater tank, with the remaining 70% of downpipes discharging rainwater to the stormwater system. To minimise the potential water quality deterioration in the rainwater tank, some of the inspected householders (40%) also installed a first flush device to trap the higher pollutant loads during the initial wash-off from each storm event (see Table 2).

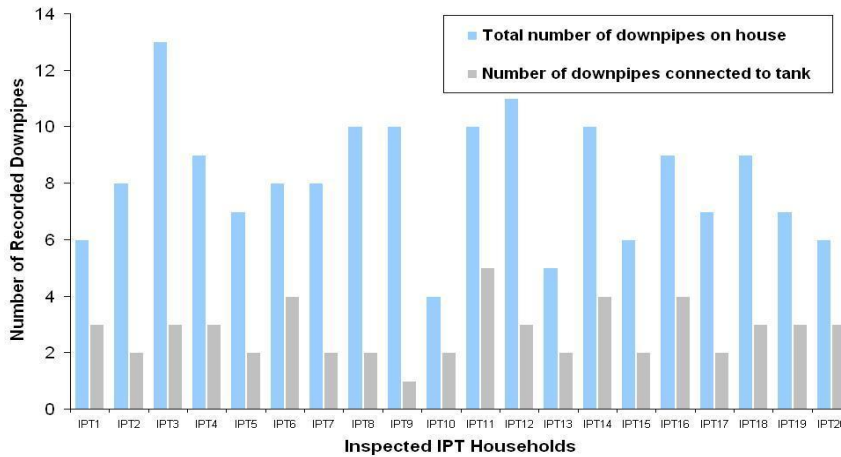


Figure 22: Total number of downpipes and number of connected downpipes to the rainwater tank at each of the 20 inspected Class 1 dwellings in SEQ.

Lastly, the pump capacity at each inspected dwelling was also recorded to understand the energy use implications of pumping rainwater. Figure 23 shows that most of the rainwater pumps (35%) fall in the capacity range of 750-999 Watt, followed by 25% in the 250-499 Watt range and 5% were less than 250 Watt in capacity. Pump capacity in 35% of households could not be identified due to access limitations.

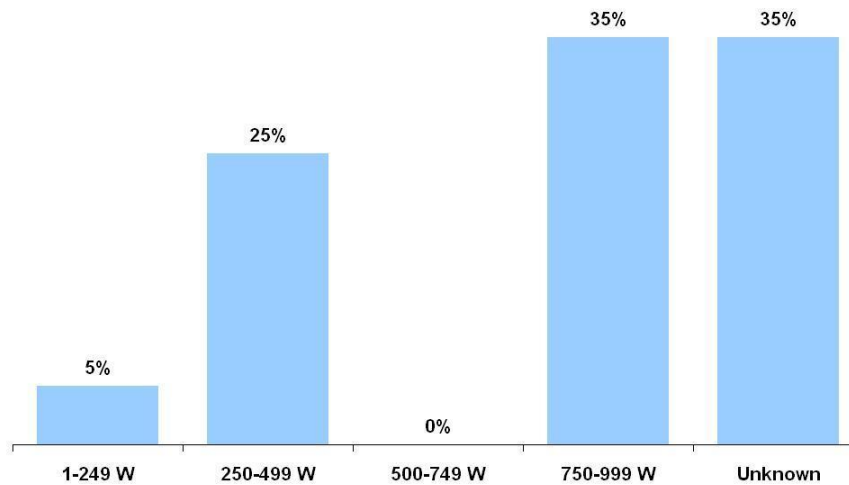


Figure 23: Recorded rainwater pump capacity for each of the 20 inspected Class 1 dwellings in SEQ.

3.2. Estimating Mains Water Saving Using Rainwater TANK Model

In this section, the audited physical parameters for mandated rainwater tank setup for the 20 Class 1 dwellings in SEQ were used to model the potential mains water saving for the year 2009. The average per capita mains water use (or household water demand) was obtained from their mains water billing records and the household occupancy rate recorded during the study. Two households (IPT 3 and 15) were excluded from this modelling study due to unavailability of matching data sets (i.e. household occupancy and mains water billing records). The estimated active tank volumes (from Section 3.1.1) and tank catchment area (from Section 3.1.2) were used for the rainwater TANK simulation model setup. Roof catch losses of 20% and adhesion depth of 1 mm were assumed for TANK modelling (Millar *et al.*, 2003). The recorded rainwater supply connections for each inspected dwellings were used, in conjunction with water use from published end-use studies in SEQ for toilet cisterns and

laundry purposes (Willis *et al.*, 2009; Beal *et al.*, 2011). A slight modification on the water end-use for households with different number of plumbed toilet cisterns was made according to the rainwater setup at each inspected household. No external rainwater use was assumed to minimise the uncertainties associated with this (small) water end-use (see Figure 12). An “empty tank” assumption at the start of the modelling period was made to simulate the scenario at each household. However a partially full assumption at the start can also be considered and this will create a small difference in the annual modelling outcomes. For long-term modelling (40 years), this assumption will make little difference.

Thus, the mains water savings obtained from this modelling activity were only capturing the internally plumbed rainwater connections of toilet cisterns and cold tap washing machine. A summary of the household water end-use used in this TANK modelling activity is given in Section 2.4. The rainfall data for 2009 was obtained from the SILO website for TANK modelling. The total rainfall for year 2009 (1367 mm) was higher than the long term average rainfall of 1301 mm.

Table 3 shows the summary of rainwater tank simulation outcomes using rainwater tank setup parameters for each of the 20 audited dwellings. During 2009, the rainfall depths (mm) across the four LGAs were between 1,171 to 1,582 mm. The active tank volume ranged from 3,150 to 5,600 litres with an average at 4,800 litres. Similarly, the tank catchment area ranged from 37 to 135 m², with an average at 81 m². The total household mains water use varied between 118.6 to 736.4 L/hh/d, with an average of 343.6 L/hh/d. Results from the TANK simulation showed that the potential mains water saving ranged from 26 kL/hh/yr to 71 kL/hh/yr with an average saving of 49.2±12.0 kL/hh/yr.

Possible reasons for such a large discrepancy from the QDC MP 4.2 target of 70 kL/hh/yr include rainfall depth, active-to-actual tank volumes, low proportions of connected roof catchment areas, and total household water use patterns. The impacts of these key factors were further examined using linear regression and correlation analysis in Section 3.3 to investigate the extent to which each factor impacts the rainwater supply and usage. A “what if” scenario analysis is also reported in Section 3.4 to investigate the potential ways of achieving the 70 kL/hh/yr mains water saving target specified in QDC MP 4.2.

Table 3: Summary of the mains water saving from rainwater supply using the TANK rainwater model with physical tank setup parameters obtained from the on-site audit of 20 households in SEQ.

Inspected Class 1 Dwellings	2009 Rainfall (mm)	No. of Occupants	Per capita Mains Water Use (l/p/d)	Total Water Use (L/d)	Active Tank Volume (L)	Tank Catchment Area (m²)	Cold Tap Washing Machine	No. of Connected Toilet Cisterns	Estimated Mains Water Saving (kL/yr)
IPT1	1,367	4	127.4	509.6	5,080	127	Y	2	71
IPT2	1,171	4	111.5	446.0	5,350	69	Y	2	47
IPT4	1,367	2	143.0	286.0	5,140	54	Y	2	41
IPT5	1,171	1	118.6	118.6	4,840	37	Y	2	26
IPT6	1,367	3	58.3	174.9	5,030	99	Y	2	44
IPT7	1,367	4	56.9	227.6	3,150	86	Y	2	42
IPT8	1,367	4	107.7	430.6	5,600	54	Y	3	46
IPT9	1,582	4	138.4	553.6	5,260	48	Y	2	51
IPT10	1,171	3	110.0	330.0	4,100	90	Y	2	49
IPT11	1,367	4	31.5	126.0	5,360	135	Y	2	39
IPT12	1,508	2	141.5	283.0	5,030	75	Y	2	50
IPT13	1,508	2	131.0	262.0	4,500	54	N	2	41
IPT14	1,508	2	117.3	234.6	4,350	80	Y	2	36
IPT16	1,582	6	75.9	455.4	4,830	94	Y	2	67
IPT17	1,582	4	184.1	736.4	4,120	83	Y	2	69
IPT18	1,582	2	122.1	244.2	4,200	70	Y	2	47
IPT19	1,367	4	107.7	430.8	4,860	105	Y	2	61
IPT20	1,367	1	335.3	335.3	5,280	99	Y	2	58

3.3. Comparison in Water Balance Modelling Outcomes Using the Rainwater TANK and UVQ Models

In order to confirm the validity of the water balance outcomes from the rainwater TANK model, another set of simulations using the rainwater tank simulation model *Urban Volume and Quality* (UVQ) were used with identical physical set up parameters to those used in Section 3.2. The UVQ model also operates on a daily time step to calculate urban water flows (Mitchell and Diaper, 2010). Figure 24 shows the comparison in potential mains water saving as estimated from the TANK and UVQ models. The outputs from the two simulation models used were found to be correlated with a R^2 value of 0.9. However, the UVQ model returned a slightly lower range of mains water saving of between 21 kL/hh/yr to 64 kL/hh/yr. In comparison, the TANK model showed that the potential mains water saving ranged from 26 kL/hh/yr to 71 kL/hh/yr. A detailed comparison of the algorithms used in these two models would be required to understand the differences in the outputs. It is to be noted that both rainwater simulation models returned water saving values lower than the stipulated value of 70 kL/hh/yr. Only the TANK model was used to further investigate the impacts of various key factors on the potential mains water saving in households with internally plumbed rainwater tanks.

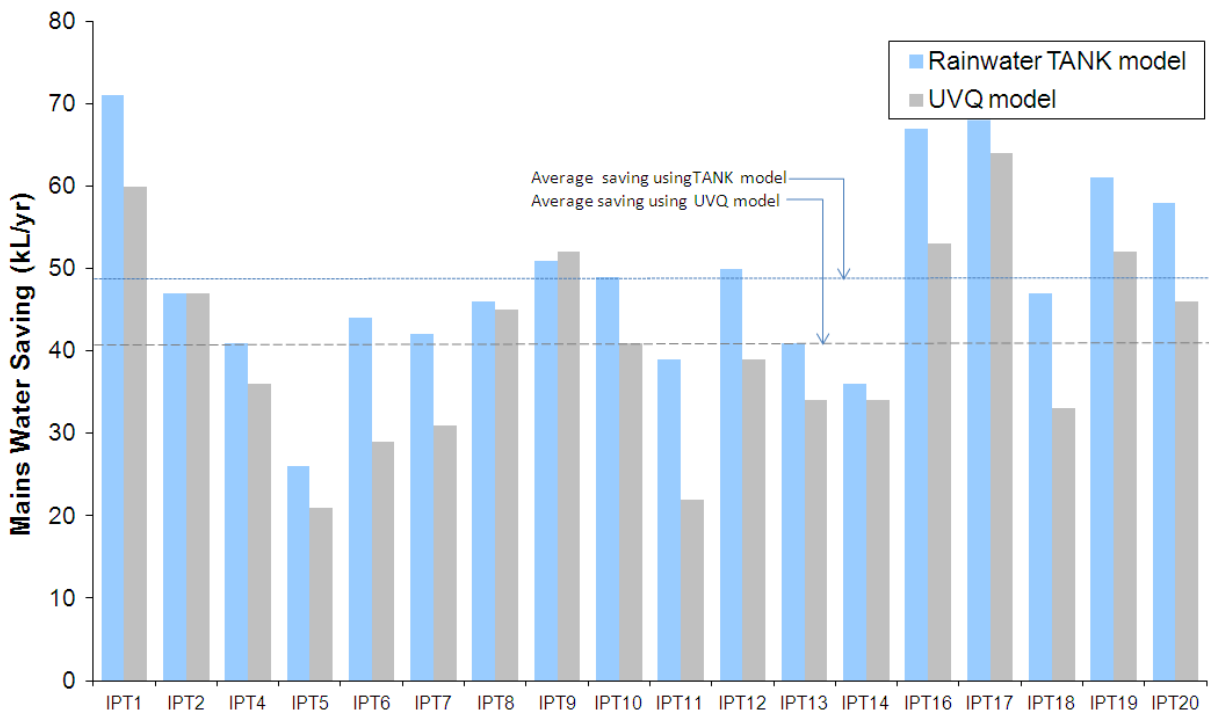


Figure 24: Comparison of annual mains water saving from rainwater supply for 2009 using the TANK and UVQ rainwater models.

3.4. A 40-year (1972-2011) Simulation on Mains Water Saving Using Rainwater TANK Model

A long term rainwater supply simulation was conducted using 40-year climate data across the four LGAs. This simulation was conducted to understand the temporal variation in rainwater savings that would not necessarily be captured in the results from the 2009 climate data. In addition, water balance modelling conducted using a 40-year daily rainfall data would also minimise the impact in mains water saving arising from the “empty tank” assumption adopted at the beginning of the simulation period.

Figure 25 shows the differences in mains water saving computed from using one-year rainfall data against 40-year data for each of the 18 inspected detached dwellings. The input parameters used (ie, tank catchment area, active tank size and total internal water demand) for the simulation remained the same as listed in Table 3. Average results from the 40-year simulation were of a similar value to those based on the 2009 rainfall data. The mains water saving was estimated to be in the range of 29 kL/hh/yr to 76 kL/hh/yr, with an average at 52.8 ± 12.6 kL/hh/yr. This is just a 7% increase over the one-year simulation outcome of 49.2 ± 12.0 kL/hh/yr. It may seem counter intuitive that while annual rainfall was higher in 2009 compared to the annual average of 40 year data, the mains water saving was lower in 2009. This can be explained by the distribution of daily rainfall over the year. For example, if monthly rainfall is concentrated over fewer rain days, then it is more likely to spill due to insufficient tank storage capacity. Nonetheless, using the rainwater tank setups at the 20 audited houses, we conclude that a long-term mains water saving of 52.8 ± 12.6 kL/hh/yr from internally plumbed rainwater tanks can be achieved in SEQ.

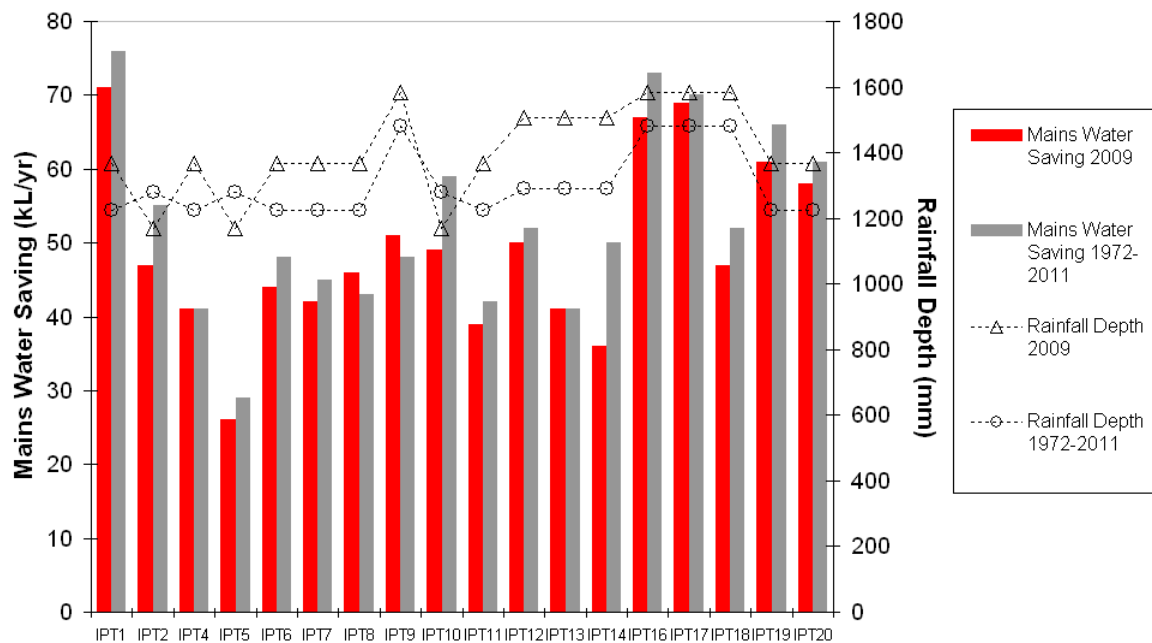
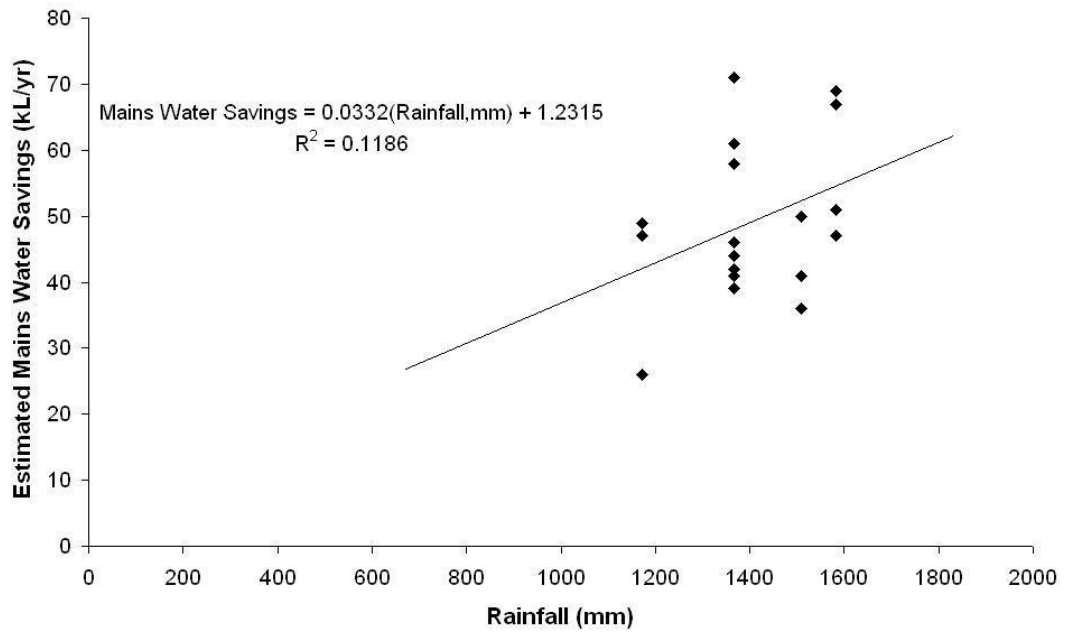


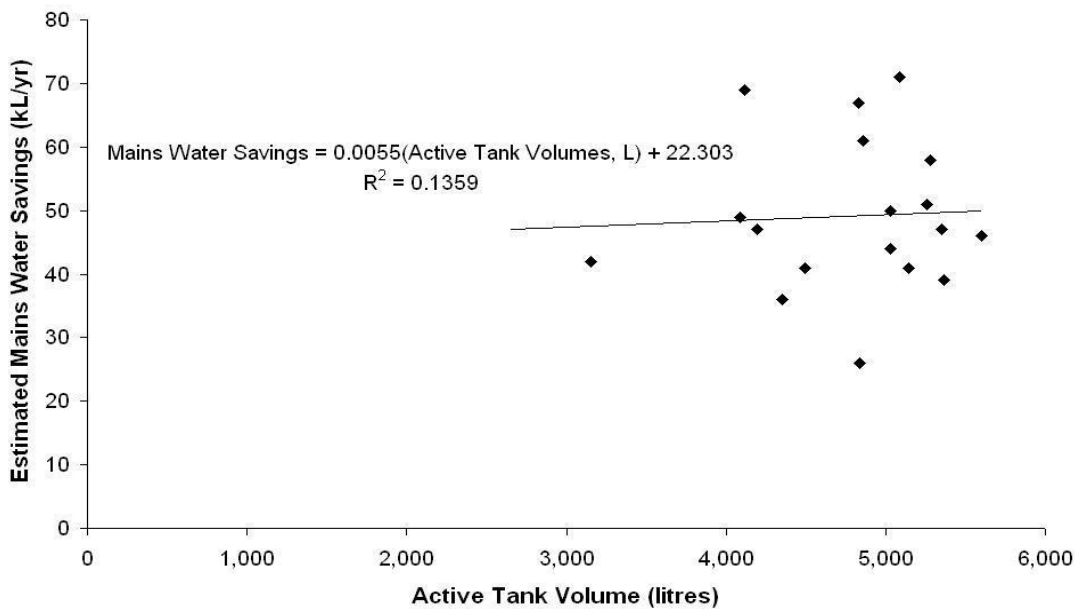
Figure 25: Differences in mains water saving computed from using 1-year data against 40-year precipitation data.

3.5. Identification of Key Factors Impacting on Mains Water Saving: Regression and Correlation Analysis

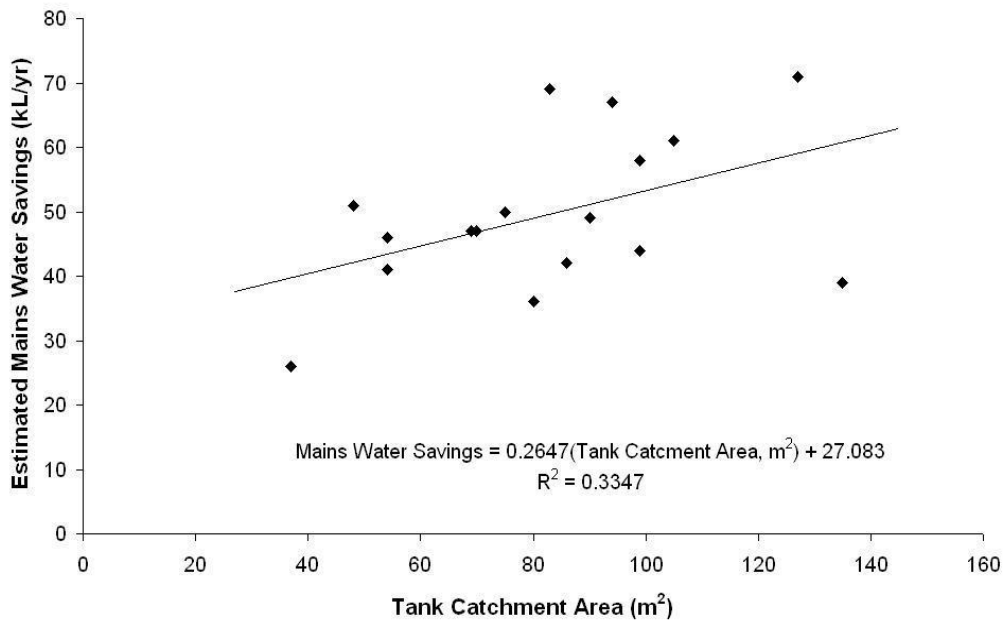
A linear regression and correlation analysis was conducted to understand the impacts of key physical factors that might impact on the final mains water saving. The mains water savings obtained from the rainwater tank simulations using 2009 rainfall data were regressed against the factors such as rainfall depth (mm), active tank volume (L), tank catchment area (m^2) and total household water use (L/hh/d). Figure 26 (a)–(d) show the linear regression analysis for mains water saving against each respective key physical factors of as rainfall depth (mm), active tank volume (L), tank catchment area (m^2) and total household water use (L/hh/d).



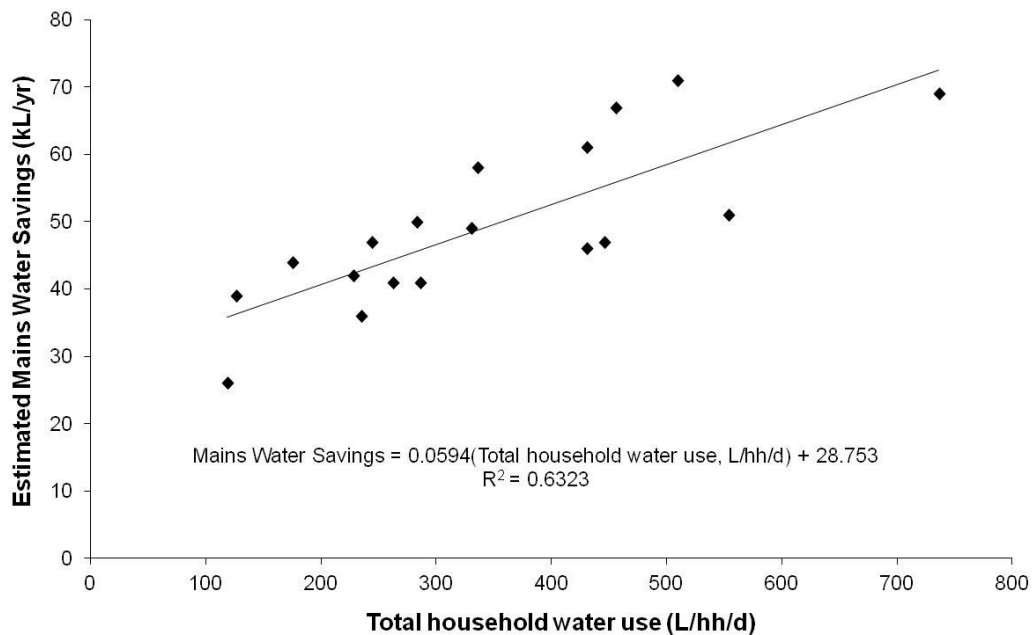
(a)



(b)



(c)



(d)

Figure 26: Linear regression analysis for mains water saving against each respective key physical factor of (a) Rainfall depth (mm); (b) Active tank volume (L), (c) Tank catchment area (m²) and (d) Total household water use (L/hh/d).

Results from the linear regression analysis showed that the most dominant factor that impacted on the mains water saving is the total household water use (L/hh/d). This was evidenced from the high Pearson correlation coefficient value, R² of 0.632. This was followed by the tank catchment area (R² = 0.335) and active tank volume (R² = 0.136). For year 2009, the nominal range of rainfall depth between 1,171 to 1,582 mm across the four LGAs showed the least impact on the final mains water saving at the inspected households. The R²-value for the rainfall effect was found to be 0.1186. Thus, the rank of key physical factors that impact on the final mains water saving in households with Understanding the Mains Water Saving from Mandated Rainwater Tanks using Water Balance Modelling and Analysis with Inputs from On-Site Audited Parameters

mandated rainwater tanks are: Total household water use (L/hh/d) > Tank catchment area (m²) > Active tank volume (litres) > Rainfall depth (mm). A multi-correlation analysis was conducted using the statistical data analysis tool pack in Excel™, to validate the findings from this linear regression analysis.

Table 4 shows the correlation coefficient values for the key physical factors we have selected. The last row in Table 4 confirms the relative impact of key physical parameters on mains water savings as identified in the linear regression analysis. As for individual correlation values, there is only one negative correlation and this occurred between the rainfall depth and active tank volume. It is a valid, but non causal, relationship. Further scenario analysis was conducted using the rainwater TANK model and the results are reported in Section 3.6. This scenario analysis identified the potential mains water saving for households having a combination of an active tank volume of 5,000 litres and a tank catchment area of 100 m².

Table 4: A multi-correlation analysis on the key physical factors that might impact on the final mains water saving.

	Rainfall Depth (mm)	Total Household Water Use (L/hh/d)	Active Tank Volume (litres)	Tank Catchment Area (m ²)	Estimated Mains Water Saving (kL/hh/yr)
Rainfall (mm)	1.000				
Total water use (l/p/d)	0.323	1.000			
Active Tank Volume (litres)	-0.048	0.083	1.000		
Tank Catchment Area (m ²)	0.002	0.014	0.323	1.000	
Estimated Mains Water Saving (kL/hh/yr)	0.344	0.795	0.369	0.579	1.000

3.6. Rainwater TANK Modelling: Scenario Analysis

In this study, scenario modelling using the TANK model has been conducted based on known physical parameters of the physical raintank setup at all the 20 households. Such information permits better modelling of rainwater yield using the measured connected roof area and tank size after home inspection and then undertaking scenario analysis by changing tank setup parameters and assessing their impact on mains water savings. In this section, three different scenarios were examined (i) changing active tank volume to 5,000 litres (but keeping actual tank catchment area the same); (ii) changing tank catchment area to 100 m² (but keeping actual active tank volume the same) and (iii) changing both active tank volume and tank catchment area to 5,000 litres and 100 m², respectively. The household water demand was based on the water consumption data for these 20 homes. The rainfall data for a period of 40 years (1972-2011) was used for the modelling.

The simulation outcomes as listed in Table 5 highlights that changing the active tank volumes of all 18 households to 5,000 litres do not impact significantly on the modelled mains water savings. This is in line with the findings from the previous linear regression and correlation analysis, where the changes in active tank volume did not impact much on the mains water saving. The maximum change of 1,846 litres (approximately 60% increase) in active tank volume only contributed to an additional 7 kL/yr (approximately 17%) of mains water saving at IPT 7 household.

Figure 27 shows the linear plot of change in modelled mains water saving or rainwater yield (kL/yr) vs. the change in active tank volume (litres). From Figure 27, it was evident that a 1,000 litre change in active tank volume only contributes a small 4 kL/yr increase in mains water saving. Other factors such as rainfall depth and total household water use were not taken into account for the simultaneous impact on mains water saving. The modelled mains water saving for Scenario (i) (this analysis) ranged from 26 to 72 kL/hh/yr, with an average saving for the 18 homes of 49.6±12.1 kL/hh/yr. The average difference in modelled mains water savings under this scenario with a 5 kL tank, compared to the modelled mains water saving as per the actual tank set up for each household (Table 3) was a mere 0.8%.

Table 5: Scenario analysis of (i) changing active tank volume to 5,000 litres (but keeping actual tank catchment area); (ii) changing tank catchment area to 100m² (but keeping actual active tank volume) and (iii) changing both active tank volume and tank catchment area to 5,000 litres and 100m² on modelled mains water savings for each of the 20 audited homes. The simulation period is 40 years.

Using actual physical tank set up for each home		(i) Changing Active Tank Volume to 5,000 litres				(ii) Changing Tank Catchment Area to 100 m ²				(iii) Changing to the Combination of 5,000 litres and 100m ²	
Inspected Class 1 Dwellings	Modelled Mains Water Saving (kL/yr)	Actual Tank Catchment Area (m ²)	Modelled Mains Water Saving (kL/yr)	Differences in Saving to Actual (kL/yr)	Differences in Volume between actual and 5,000 litres tank (L)	Actual Active Tank Volume (litres)	Modelled Mains Water Saving (kL/yr)	Differences in Saving to Actual (kL/yr)	Differences in Tank Catchment Area to Actual area (m ²)	Modelled Mains Water Saving (kL/yr)	Differences in Saving to Actual (kL/yr)
IPT1	71	127	70	-1.0	-84.8	5,085	63	-8	-27.0	62	-9.0
IPT2	47	69	46	-1.0	-352.7	5,353	60	13	31.0	58	11.0
IPT4	41	54	40	-1.0	-142.5	5,143	56	15	46.0	55	14.0
IPT5	26	37	26	0.0	163.1	4,837	36	10	63.0	36	10.0
IPT6	44	99	44	0.0	-27.1	5,027	44	0	1.0	44	0.0
IPT7	42	86	49	7.0	1846.3	3,154	44	2	14.0	51	9.0
IPT8	46	54	43	-3.0	-602.0	5,602	62	16	46.0	60	14.0
IPT9	51	48	51	0.0	-257.8	5,258	74	23	52.0	72	21.0
IPT10	49	90	52	3.0	915.5	4,084	52	3	10.0	54	5.0
IPT11	39	135	38	-1.0	-362.0	5,362	37	-2	-35.0	37	-2.0
IPT12	50	75	49	-1.0	-28.6	5,029	53	3	25.0	52	2.0
IPT13	41	54	41	0.0	505.7	4,494	49	8	46.0	51	10.0
IPT14	36	80	38	2.0	646.8	4,353	38	2	20.0	39	3.0
IPT16	67	94	67	0.0	166.6	4,833	69	2	6.0	69	2.0
IPT17	69	83	72	3.0	882.9	4,117	74	5	17.0	78	9.0
IPT18	47	70	49	2.0	805.7	4,194	51	4	30.0	54	7.0
IPT19	61	105	62	1.0	142.4	4,858	60	-1	-5.0	60	-1.0
IPT20	58	99	56	-2.0	-278.7	5,279	58	0	1.0	57	-1.0

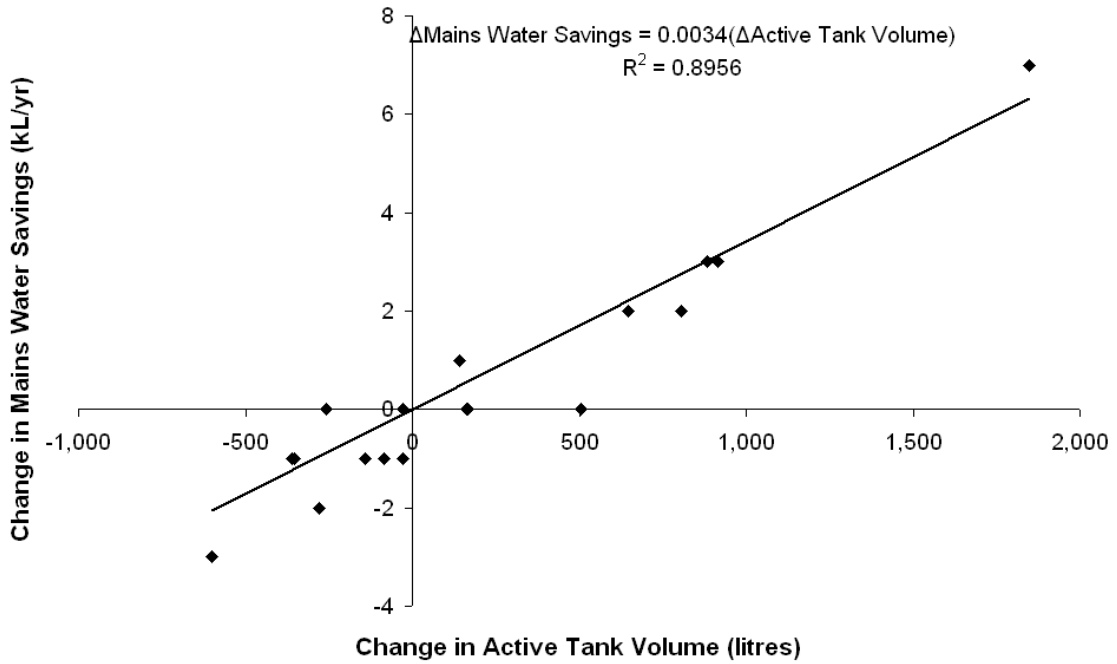


Figure 27: Linear plot between the changes in modelled mains water saving (kL/yr) to the changes in active tank volume (litres) using the TANK model.

However, changes in tank catchment area were found to have profound impacts on the modelled mains water saving. The significance of tank catchment area over active tank volume was also illustrated in the linear regression and correlation analysis (Section 3.5). In this modelling scenario (Scenario ii) the difference in mains water savings were compared using the actual roof catchment area for each household with a roof catchment of 100 m² for all households. The other modelling factors were unchanged. Figure 28 shows the linear plot of changes in modelled mains water saving (kL/yr) to the changes in tank catchment area (m²).

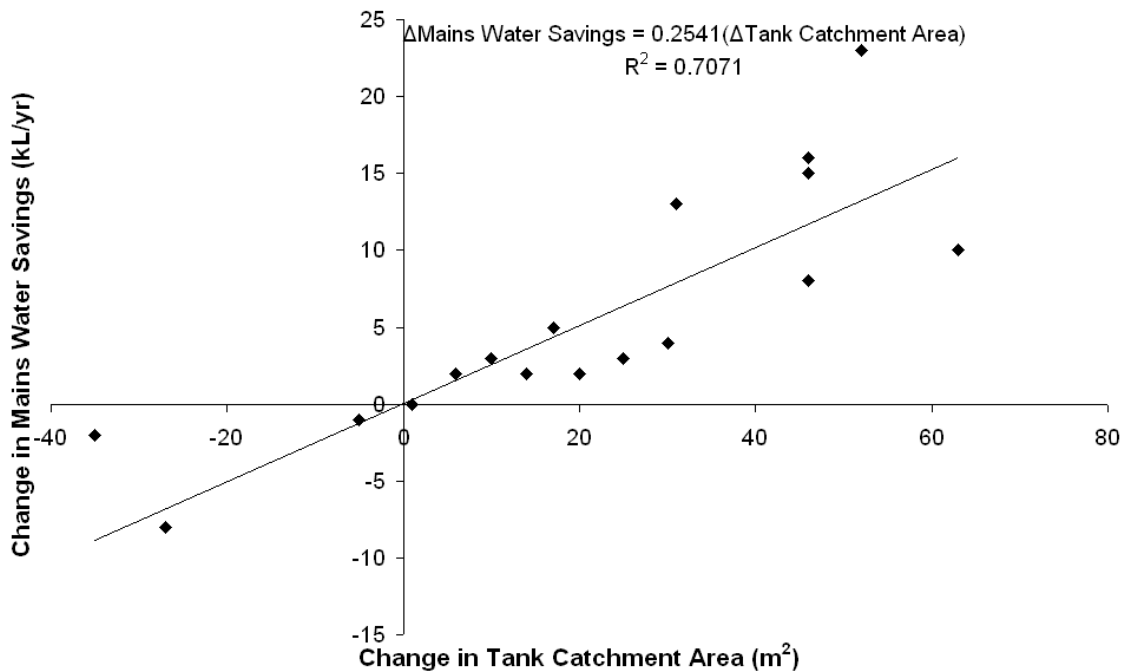


Figure 28: Linear plot between the changes in modelled mains water saving (kL/yr) to the changes in tank catchment area (m²).

The maximum change in tank catchment area of 31 m² (approximately 44.9%) increased the modelled mains water saving by 13 kL/yr (approximately 28%) for household IPT 2. However, it should be emphasized that the linear plot in Figure 28 only considers the relationship between tank catchment area and the mains water saving. Other factors such as variation in rainfall depth and total household water use were not accounted for. The modelled mains water saving for this scenario ranged from 36 to 74 kL/hh/yr, with an average saving for 18 homes of 54.4±11.8 kL/hh/yr. In this instance, the difference in the modelled average mains water saving using the actual physical set up (Table 3) to the model average value using 100 m² of connected roof was a very substantial 11%.

When both the active tank volume and tank catchment area were increased to 5,000 litres and 100 m² respectively, as recommended in the QDC MP 4.2, the changes in final mains water savings for the 18 Class 1 dwellings were not that significant as compared to Scenario (ii). Figure 29 shows a comparison plot between the mains water savings based on the actual physical setup and modelled water saving under the combination of a 5,000 litres tank and 100 m² tank catchment areas. Under this scenario, the modelled mains water savings ranged from 36 to 78 kL/hh/yr with an average value of 54.9±11.5 kL/hh/yr. This was equivalent to 11.6% increase in mains water saving in comparison to the modelled mains water saving presented in Table 3. As shown in Figure 29, there is generally an increase in annual rainwater yield for Scenario (iii). However, in some households, the average water savings have decreased due to the reduction in tank catchment area used in the modelling.

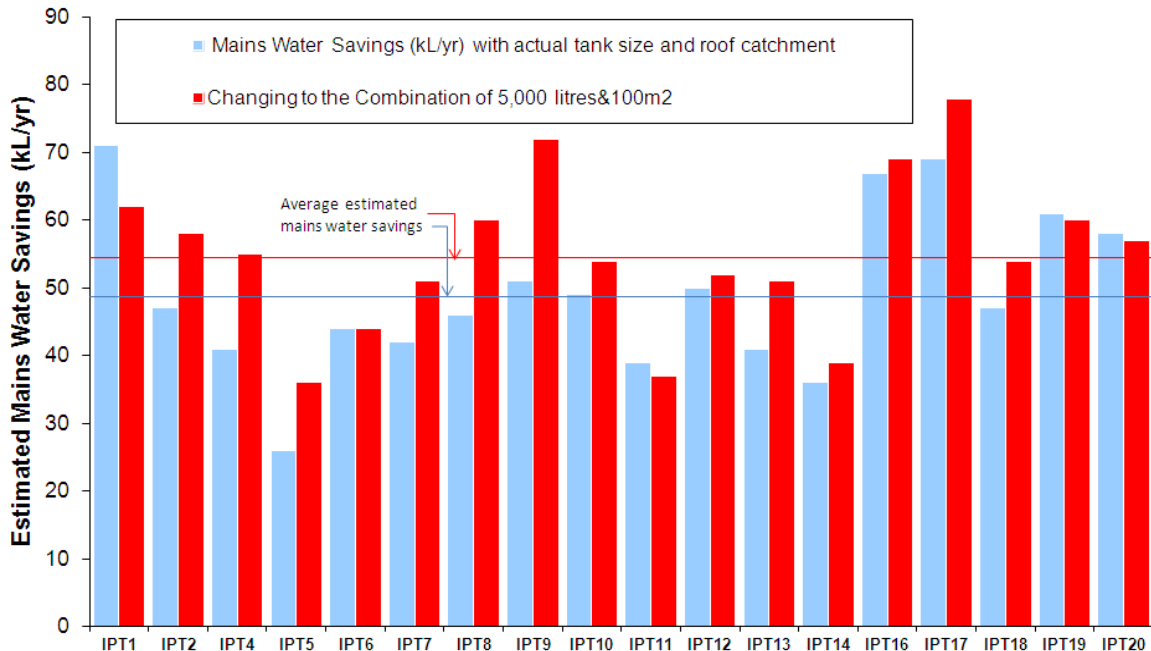


Figure 29: Comparison between the modelled mains water saving using actual physical set up and modelled water saving under the combination of 5,000 litres tank volume and 100 m² tank catchment areas for each of the 20 audited homes. 40 years of rainfall data was used in the simulations.

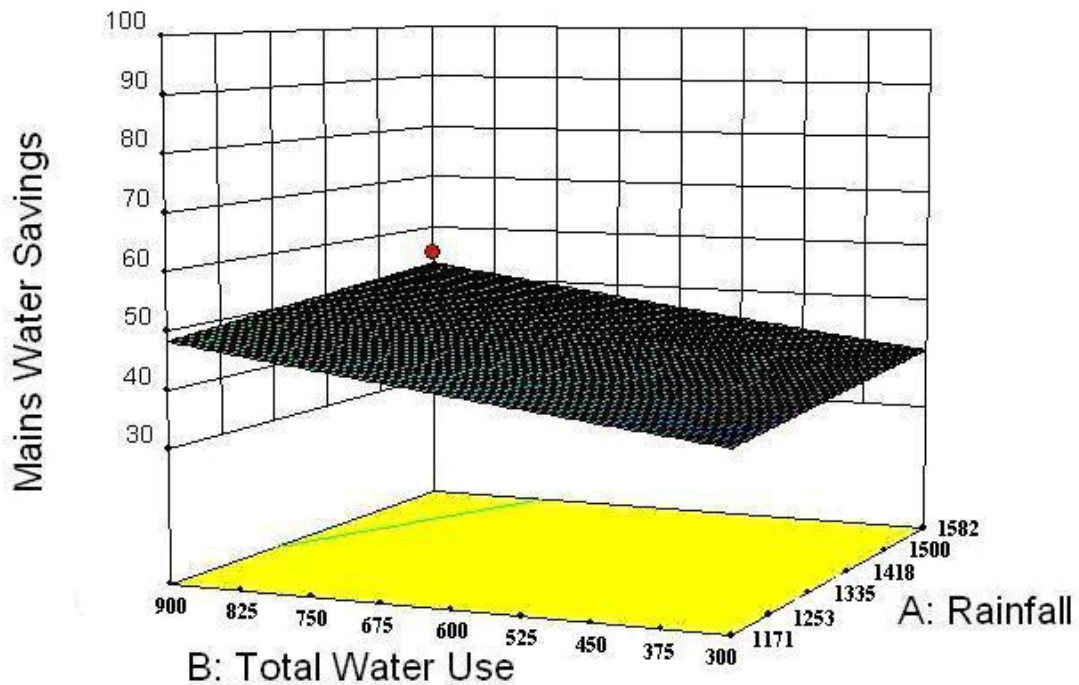
From these three scenario analyses, it can be concluded that an increase in tank catchment area has a significantly higher impact on the mains water saving than an increase in the active tank volume. The analysis is limited to the adopted (rainwater) demand and rainfall depths. Further analysis will be required to investigate the impact of high/low water demands and different annual rainfall depths. However, it can be clearly seen that even the physical setup of rainwater tank according to the QDC MP 4.2 will not deliver an average mains water saving of 70 kL/hh/yr. This indicates that other parameters such as total household water use (including external use) or rainfall depth may have significant impacts on mains water saving from households with mandated rainwater tanks. A further multiple-regression analysis was conducted in Section 3.7 to develop a generalized linear regression model to explain the contributory effects of other factors in realising the 70 kL/hh/yr mains water saving target. The summary of results from Scenarios (i, ii and iii) is provided in Table 5.

3.7. Factors Interaction and Water Saving Optimisation Using Response Surface Analysis

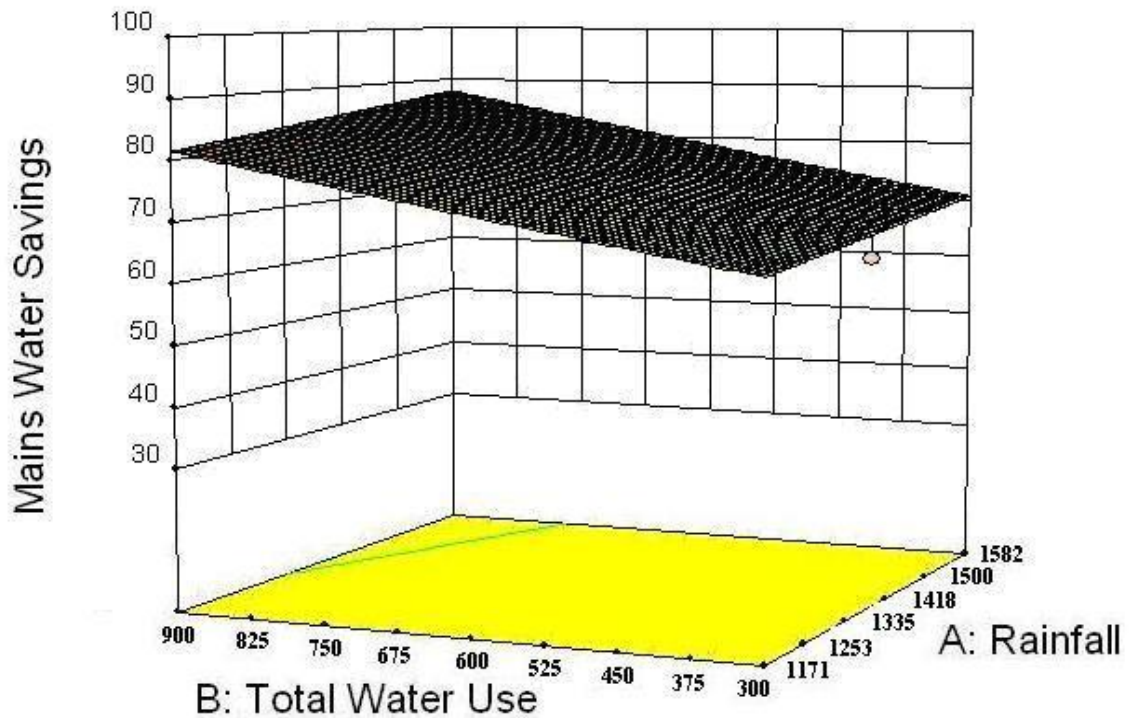
3.7.1. Changing of Tank Catchment Area

Since the modelled rain water yield from internally plumbed rainwater tanks involves a number of key factors (ie, tank catchment area, tank size, total water use and rainfall), it is difficult to understand the interaction of various factors on the mains water saving. Recently, a number of statistical experimental design and data analysis techniques have been employed in various science and engineering tasks for process optimisation. Among these techniques, the response surface analysis (RSA) is well recognised as a simple and reliable tool for the interpretation of a multivariable system. The data analysis using RSA has been employed in various fields of process optimisation to analyse the effects of several independent variables without any knowledge on the relationship between the objective function and variables (Chong *et al.*, 2010). The robustness of RSA includes building models, evaluating the effects of several factors, and optimising the process operating conditions to achieve desirable outcomes.

Figure 30 shows the RSA plots for the impact of changing tank catchment area on the modelled mains water saving. For Figure 30(a), the rainfall depth of 1,171 to 1,582 mm (on axis A) was plotted against the total internal household water use of 300 to 900 L/d (on axis B) using a tank catchment area of 50 m² and an active tank volume of 5 kL. It was evident that the total internal water use (axis B) had a much larger impact on mains water saving than the rainfall depth (axis A) as indicated by their relative slope steepness. When the tank catchment area was increased to 150 m² (Figure 30(b)), it can be seen that the response surface is elevated, and that a higher modelled mains water saving is achieved for any given value of nominal internal household water use.



(a)

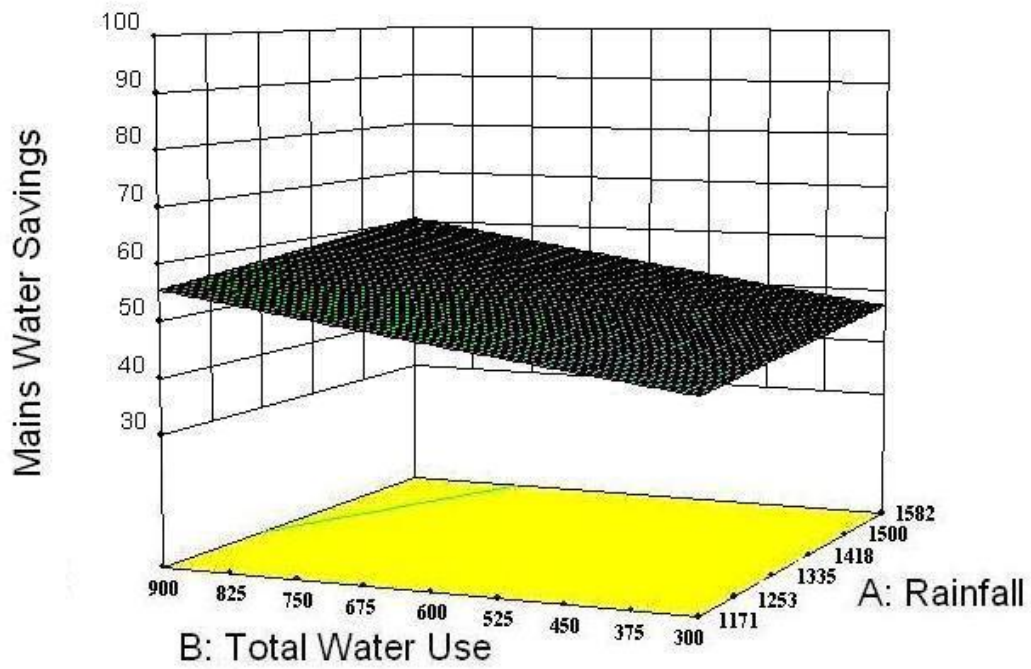


(b)

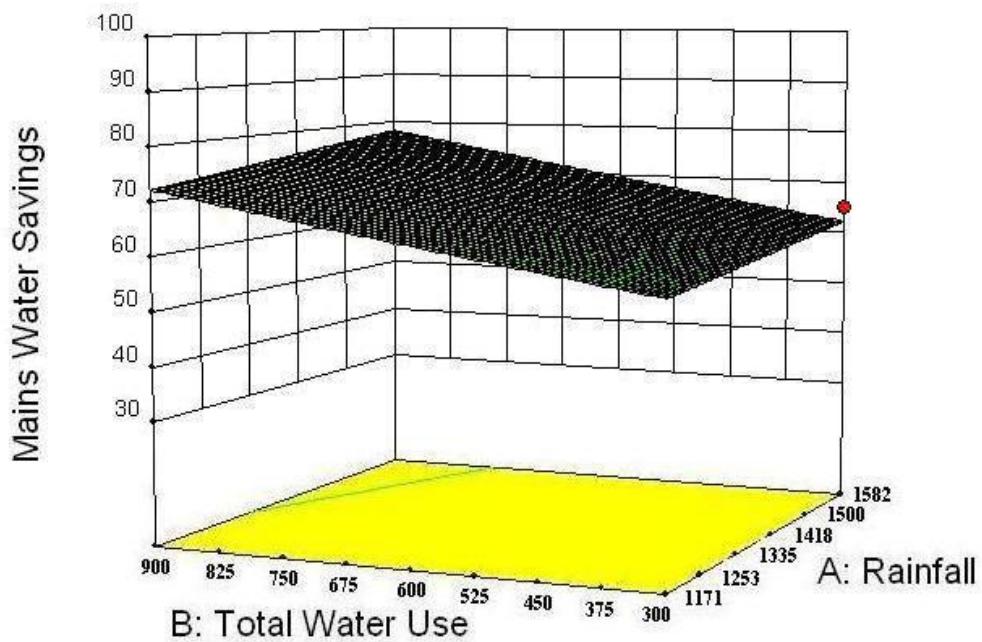
Figure 30: Response Surface Analysis of rainfall depth (axis A) and total internal water use (axis B) against modelled mains water saving (kL/yr) using an active tank volume of 5 kL and (a) a tank catchment area of 50 m² or (b) a tank catchment area of 150 m².

3.7.2. Changing of Active Tank Volume

RSA plots were also used to investigate the impact of changing the active tank volume on the mains water saving. Figure 31 shows the rainfall depth (on axis A) and total internal water use (on axis B) against the modelled mains water saving (kL/yr) with the tank catchment area set at 100 m². For an active tank volume of 2.5 kL, Figure 31(a) shows both the slope and highest value of the modelled mains water saving is relatively low. When the active tank volume is increased to 7.5 kL (Figure 31(b)), the response surface is both more elevated and increased in slope, reflecting an increase in the modelled mains water saving. However, the elevation in response surface (ie, the modelled mains water saving) is not that significant when compared to the scenario of changing the tank roof catchment area (Figure 30(b)). This shows that setting up a plumbed rainwater system with a larger tank roof catchment area will provide a more cost effective solution in achieving the 70 kL/hh/yr water saving target as specified in QDC MP 4.2.



(a)



(b)

Figure 31: Response Surface Analysis of rainfall depth (axis A) and total internal water use (axis B) against modelled mains water saving (kL/yr) using a tank catchment area set at 100 m² and (a) an active tank volume of 2.5 kL or (b) an active tank volume of 7.5 kL.

3.7.3. Multi-Regression Analysis and Modelling

In this section, an attempt has been made to develop a simple equation for estimating rainwater usage or mains water savings using the known parameters of: annual rainfall in mm, total household water demand in litres per year (L/yr), active tank volume in L, and tank roof catchment area m². As this equation used the full 20 households data set, it could not be validated with a similar but independent data set. Hence the equation is more of academic interest, and further validation is required before its application can be recommended. A multiple-regression analysis was conducted between the modelled mains water saving and the four key physical factors listed above. The generalized linear multiple regression model has the form given in Equation (3):

$$Y = b_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + u \quad (3)$$

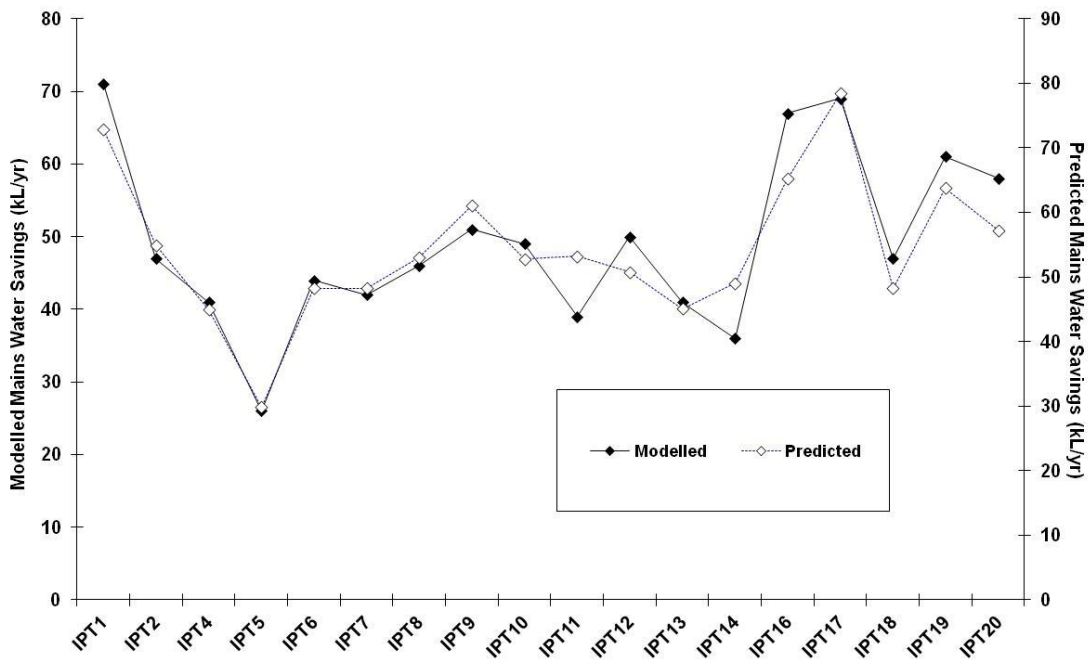
where, Y is the estimated mains water saving (kL/yr), b_1 is the intercept value, $b_2 - b_5$ are the regression coefficients and u is the standard error. Here, x_2 is the rainfall depth (mm), x_3 is the total daily household water use (L/hh/d), x_4 is the active tank volume (litres) and x_5 is the tank catchment area (m²). Thus, Equation 3 can be rewritten as follows:

$$\begin{aligned} \text{Mains Water Saving (kL/yr)} &= 1.099x10^{-2}(\text{Rainfall, mm}) + 5.579x10^{-2} \\ &(\text{Total household water use, L/hh/d}) + 1.173x10^{-4}(\text{Active tank volume, L}) \\ &+ 2.112x10^{-1}(\text{Tank catchment area, m}^2) + 1.988 \end{aligned} \quad (4)$$

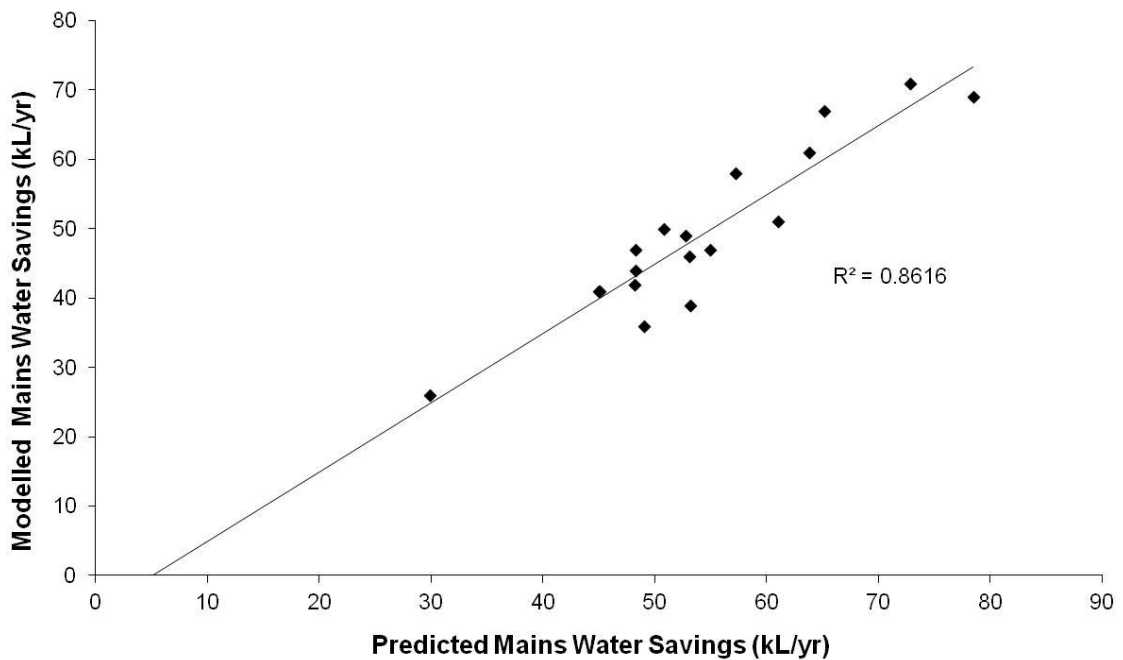
Table 6 shows the summary of this multiple-regression analysis.

Equation 4 was then used to “predict” the mains water saving for the 18 Class 1 dwellings. It should be noted that Equation 4 is strictly only valid within the operational regime of: (1) rainfall depth: 1,171 to 1,582 mm; (2) total household water use: 118 to 736 L/d; (3) active tank volume: 3,100 to 5,600 L; and (4) tank catchment area: 37 to 135 m². The estimated mains water savings using Equation 4 will give an integrated error of ± 2.00 kL (ie, where the values of b_1 and u were merged) for household with typical plumbed settings of 2 toilet cisterns, 1 washing machine tap and 1 external irrigation tap. The details of physical rainwater tank setup parameter for each household are listed in Table 3.

Figure 32(a) and (b) shows the comparison between the modelled (data from Table 3) and predicted mains water saving using Equation 4. It was evident Equation 4 is quite robust to predict the mains water saving, given a high Pearson correlation coefficient (R^2) of 0.8616 was obtained (Figure 32b). The adjusted R^2 and multiple R values were 0.8190 and 0.9282, respectively, which is statistically significant at the 95% probability level. However for more general use, the equation needs to be updated and validated with a larger independent data set.



(a)



(b)

Figure 32: Comparison between TANK modelled mains water saving and savings predicted using the multiple-regression model (as per Equation 4) for each of the 20 audited households. Figure 32(b) shows the same comparison using a linear regression format.

Table 6: A multi-regression analysis relating modelled mains water savings to various key physical parameters for the 20 audited households with mandated rainwater tanks. The table refers to the variables listed in Equations 3 and 4.

Parameters	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-3.124	17.831	-0.175	0.864	-41.645	35.396
2009 Rainfall (mm)	1.099×10^{-2}	0.010	1.154	0.269	-0.010	0.032
Total water use (L/p/d)	5.579×10^{-2}	0.008	6.781	0.000	0.038	0.074
Active Tank Volume (L)	1.173×10^{-4}	0.002	0.057	0.956	-0.004	0.005
Tank Catchment Area (m ²)	2.112×10^{-1}	0.047	4.532	0.001	0.111	0.312

4. CONCLUSION

The purpose of this study was to understand the rainwater tank installation and local settings at 20 selected detached dwellings in SEQ via an on-site household auditing, in order to measure their compliance with QDC MP 4.2. The various rainwater tank features assessed included tank type, tank dimensions, volumes, connected roof catchment area to tank, rainwater supply connections for toilet flushing, washing machine, external irrigation and other related features, such as first flush devices and mains water switching valves. Subsequently, these parameters were used as the physical input variables into two different rainwater tank simulation models (TANK and UVQ) to estimate potential mains water saving for each of the 20 dwellings. This was followed by linear- and multiple regression analysis between the (modelled) potential mains water saving and dominant governing factors such as tank catchment area, tank size and total daily water demand. Response surface analysis was also conducted to help visualise the interactions between the modelled mains water saving and these governing factors.

Results from the on-site auditing program showed that a large proportion (90%) of the 20 inspected households have a manufacturer claimed tank volume greater than 5 kL. However, when the active tank volume was considered, only 45% of the households achieved the 5 kL QDC MP 4.2 compliance status. On average, approximately only 80% of a tank size is effective in rainwater capture, storage and supply to the internally plumbed end-uses. The 20 inspected households all had a total roof area exceeding 100 m², but only 15% achieved the minimum QDC MP 4.2 requirements for roof area connectivity to the rainwater tank (100 m² or 50% of total roof area). On a normalised scale, it was estimated that only 30% of the roof area is connected to the household rainwater tank. Results from other auditing criteria results were satisfactory, such as all toilet cisterns were connected to rainwater tanks.

Two different rainwater tank models were used to determine the potential mains water saving from having internally plumbed rainwater tanks. Results using 2009 rainfall data in the TANK rainwater model showed that the potential mains water saving ranged from 26 kL/hh/yr to 71 kL/hh/yr with an average mains water saving of 49.2±12.0 kL/hh/yr. The UVQ model returned a slightly lower range of potential mains water saving between 21 kL/hh/yr to 64 kL/hh/yr with an average mains water saving of 41.1±12.2 kL/hh/yr. However, the rainwater yields from the two rainwater tank models were found to be highly correlated with a R² value of 0.9. Based on a 40-year period of rainfall data using the TANK model, water saving were estimated to be in the range of 29 kL/hh/yr to 76 kL/hh/yr, with an average at 52.8±12.6 kL/hh/yr.

The linear regression analysis showed that the most dominant factor determining the mains water saving was total internal household water demand (R² = 0.6323). This was followed by the tank catchment area (R² = 0.3347), active tank volume (R² = 0.3347) and rainfall depth (R² = 0.1186). The scenario analysis highlighted that the changes in tank catchment area were more important than changes in active tank volume in affecting modelled mains water saving values. A Response Surface Analysis also showed that an increase in tank catchment area yielded a higher modelled mains water saving than an increase in active tank volume. This analysis showed that installing a plumbed rainwater system with a larger tank catchment area (ie, 150 m²) will provide a more cost-effective solution in achieving the QDC MP 4.2 water saving target of 70 kL/hh/yr.

A multiple-regression analysis was developed to relate modelled mains water saving to the four key physical factors of rainfall, total household water use, active tank volume and tank catchment area. This equation provides a simple estimate of mains water saving for internally plumbed rainwater tanks. However, we caution this equation is based on a limited data set, and needs to be validated with a larger data set of parameter values before its application can be used with confidence in SEQ.

In conclusion, we found that a mains water saving of 50 kL/hh/yr to 63 kL/hh/yr can be achieved using the current tank setup conditions at the 20 detached dwellings. As this modelling work did not include external water use, the mains water savings can be higher if external water use is included. However, external water usage has been estimated to be only 7.2 kL/hh/yr, based on the monitoring work of the same 20 homes by Umapathi *et al.* (2012).

We believe our research is an important step in achieving a more integrated understanding of mains water saving from mandated rainwater tanks, as well as the associated tank and household physical factors that affect rainwater supply and use.

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