Technical Paper

Effectiveness of Rainwater Harvesting System in Peri-Urban Region: A Case Study for the Greater Sydney [1]

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Abstract: *In recent years, rainwater harvesting has become quite popular in Australia. In main cities, rainwater tanks are used to save mains water, but in peri-urban and rural areas, rainwater tanks are used as a sole water supply means to many households. In this case, the reliability of rainwater tank to meet given water demand is important. This study presents the development of a rainwater tank model that can determine the tank size which can meet most of the water demand in peri-urban areas. The model considered is a continuous simulation type, with a daily time step. The model is applied to 10 different locations in the Greater Sydney area and assesses the feasibility of 8 different rainwater tank sizes, 1 kL to 20 kL at ten study locations. Nine of these ten locations are situated in the peri-urban areas of Greater Sydney, which are Campbelltown, Hornsby, Penrith, Richmond, Castlereagh, Wallacia, West Pennant Hills, Moss Vale and Cataract Dam. The other location (Parramatta) is situated in the approximate centre of the Greater Sydney, which is used for bench marking the water use in peri-urban and metropolitan Sydney regions. The daily rainfall data at each of the ten selected locations was obtained from the Australian Bureau of Metrology. The rainfall data lengths were in the range of 31 years to 150 years, with an average of 73 years. In this study it has been found that a 7.5 kL tank can meet almost 100% of the demand for toilet and laundry use, but in case of the irrigation use a much larger tank is needed. It has been shown that irrigation demand cannot be met 100% even with a tank size of 20 kL. A set of regression equations are developed which can be used to estimate water savings and reliability using the mean annual rainfall data. The method presented in this paper can also be adapted to other Australian states and countries to estimate water savings and reliabilities of rainwater harvesting system using daily rainfall data.*

Keywords: *Rainwater tanks, rainwater harvesting system, reliability, water saving, peri-urban region, water sensitive urban design.*

1. Introduction

In recent years, rainwater tank has become popular in Australia. This is due to a greater environmental awareness among the general public, a long-lasting drought in the last decade and subsidy provided by various government authorities in Australia to install a rainwater harvesting system (RWHS) (Coombes et al., 2003). Several alternative water sources have been examined in recent years, the most popular one is the RWHS as it is a simple low-cost technique requiring minimum expertise to operate. Most of the local councils in Australia encourage installation of RWHS by increasing rebate for the RWHS (Eroksuz and Rahman, 2010).

The major advantages of the RWHS in urban areas include saving mains water and achieving a greater flexibility in water use during water restriction period as rainwater can be used for non-potable purposes such as gardening, washing of cars and hard surfaces during the period of water restrictions imposed by urban authorities during low water level period in reservoirs. However, in rural and peri-urban regions of Australia where mains water is not available, RWHS are used to source water for meeting principal water demand such as drinking, washing and gardening. It should be recognized that, the design of a RWHS is concerned with determining the tank size required to maintain enough water in the tank to ensure water supply for the desired purposes without much reliance on other water sources. In this regard, reliability can be defined as the proportion of days when a RWHS is likely to meet the intended water demand. An unnecessarily large tank is a misuse of resources and space; on the other hand, a RWHS, which is too small, may not serve its intended purpose and there is likely to be a shortage of water from the tank on a regular basis, and users will have to depend on other water sources. Hence, a RWHS should be designed according to the need of the household and a common size is not the best solution in most locations as rainfall varies over space.

There have been many studies demonstrating the benefit of having a RWHS in the house and also on design and performance criteria of RWHS. For example, Coombes et al. (2003) examined the performance of a RWHS in an old house in Maryville suburb of Newcastle in Australia. They considered three common water uses i.e. toilet, hot water and outdoor. Ghisi et al. (2009) evaluated the financial viability of installing a RWHS in five towns in Santa Catarina State in southern Brazil where they considered car washing at petrol stations in the City of Brasilia. The results showed that an increase in the tank size enhanced the reliability of the RWHS notably in meeting the desired demand.

Domènech and Saurí (2010) examined the efficiency of RWHS for the two main types of buildings prevalent in the Metropolitan area of Barcelona (Spain) by analysing users' practices and perceptions, drinking water savings and economic costs. They carried out the financial viability of the RWHS in single and multi-family buildings and found that in single-family households an expected payback period would be between 33 to 43 years depending on the tank size and for a multi-family building a payback period was 61 years for a 20 m^3 tank. In Australian studies by Van der Sterren et al. (2009, 2012 and 2013) it was found that although RWHS can be very useful to provide required water in peri-urban regions of Sydney, tank water quality may not always meet the drinking water standard in relation to heavy metals and pathogens. They also found that RWHS can enhance the stormwater runoff quality, which in turn would enhance the health of urban waterways. Kus et al. (2011) compared the water quality with the Australian Guidelines for Water Recycling (2009). They used eleven rainwater tanks located in the Sydney metropolitan area and five rainwater tanks located in peri-urban regions of Sydney. They demonstrated that simple yet effective treatments could bring the water quality to desired standards for non-potable uses.

Imteaz et al. (2011a) proposed a daily water balance model for optimisation of RWHS within the campus of Swinburne University of Technology in Melbourne, Australia. They demonstrated the usefulness of large rainwater tanks when these are connected with large roof areas. Furthermore, they found that total construction costs of RWHS can be recovered within 15 to 21 years depending on the tank size, climatic conditions and future water price increase rate. Campisano and Modica (2012) presented a dimensionless methodology for the optimal design of domestic RWHS in Sicily, Italy. Seventeen rainfall stations were used in the methodology which was based on the results of daily water balance simulations. The results showed that the economical convenience of large tanks would decrease as rainwater availability decreases. Rahman et al. (2012) examined the water savings potential, reliability of water supply, financial benefits, and the adequacy of the current government rebate for a RWHS in detached house at ten different locations in Greater Sydney, Australia. They suggested that government authorities in Sydney should maintain or possibly increase the rebate for the RWHS to enhance its acceptance. Ghisi and Schondermark (2013) presented an investment feasibility analysis of the RWHS for the residential sector for five towns in Santa Catarina State, southern Brazil. They observed that the ideal tank capacity can be conservative for high rainwater demands and in such cases; an investment feasibility analysis should be carried out in order to obtain a more appropriate tank capacity. It was noted that rainwater use would be economically feasible for most cases; and the higher the rainwater demand, the greater the feasibility. Mehrabadi et al. (2013) assessed the applicability and performance of a RWHS to supply daily non-potable water. They found that in humid climate, it is possible to supply about 75% of non-potable water demand by storing rainwater from larger roof areas.

This paper investigates the potential of a RWHS in peri-urban areas of Greater Sydney where semi-rural and rural properties depend on RWHS to meet most of their household water needs including drinking, washing and irrigation. Here, reliability of a RWHS is quite important as there is no mains water to supplement the RWHS. In this case, if a RWHS cannot meet the demand, water is to be bulk supplied into the tank, or an alternative groundwater well/bore needs to be built. The findings of this study would provide useful guidance in selecting the most appropriate RWHS in this region of Sydney.

2. Water balance model

In this study, to simulate the performance of a RWHS, a water balance simulation model (WBSM) on a daily time scale was built in Excel. The developed model accounted for various factors for a RWHS such as tank size, daily rainfall, losses, daily water demand, mains top up and tank spillage. The adopted approach was very similar to Su et al. (2009) and Rahman et al. (2012).

The rainfall was regarded as inflow and the release and possible spill as outflow. The release was estimated based on the following equations:

$$R_t = D_t \quad \text{if} \quad I_t + S_{t-1} \geq D_t \tag{1}$$

$$R_t = I_t + S_{t-1} \quad \text{if} \quad I_t + S_{t-1} < D_t \tag{2}$$

where D_t is the daily demand (m^3) on day t, S_{t-1} is the tank storage at the end of the previous day (m^3), R_t is release from rainwater tank (m^3) and I_t is inflow (m^3). Spill SP_t (m^3) is calculated from the following equations:

$$SP_t = I_t + S_{t-1} - D_t - S_{MAX} \quad \text{if } I_t + S_{t-1} - D_t > S_{MAX} \tag{3}$$

$$SP_t = 0 \quad \text{if } I_t + S_{t-1} - D_t \leq S_{MAX} \tag{4}$$

where S_{MAX} is the design storage capacity (m^3). The tank storage S_t at the end of day t was calculated using the following equations:

$$S_t = S_{MAX} \quad \text{if } SP_t > 0 \tag{5}$$

$$S_t = S_{t-1} + I_t - R_t \quad \text{if } SP_t \leq 0 \tag{6}$$

The reliability of RWHS was calculated as the ratio of the number of days when the intended demand was met fully by the available rainwater and the total number of simulated days.

3. Study area and data

In this paper, ten different locations in the Greater Sydney are considered as shown in Figure 1. Nine of these ten locations are situated in the peri-urban regions of Greater Sydney, which are Campbelltown, Hornsby, Penrith, Richmond, Castlereagh, Wallacia, West Pennant Hills, Moss Vale, and Cataract Dam. The other location (Parramatta) is situated in the approximate centre of the Greater Sydney, which is used for bench marking the water use in peri-urban and metropolitan Sydney regions. For each of these ten locations, a daily rainfall station was selected and the data was obtained from the Australian Bureau of Metrology (the list of stations is provided in Table 1). The data lengths were in the range of 31 years to 150 years, with an average of 73 years. The average monthly rainfall distribution in the Greater Sydney region is shown in Figure 2, which shows that July to Sep are the lowest rainfall months, which are also the winter season requiring very little irrigation due to minor gardening activity in this region during winter months.
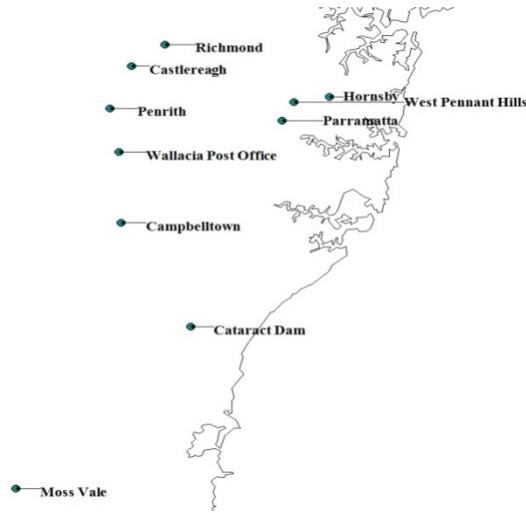

Figure 1 Ten different locations in Greater Sydney selected in this study

In this study, three different combinations of water use were considered: (i) toilet and laundry (ii) irrigation and (iii) a combination of toilet, laundry and irrigation (combined use). The feasibility of 8 different rainwater tank sizes, from 1 kL to 20 kL was examined. A hypothesized new development was considered at each of the study locations with a single household having 4 occupants. A total site area of 450 m^2 was considered with a roof, lawn and impervious areas of 200 m^2, 150 m^2 and 100 m^2, respectively.

The rainwater tank was considered to be located above ground. The water demand data for the toilet, laundry and irrigation use for residential properties were obtained from Sydney Water. The toilet considered in the study was a 6-litre AAA rated dual flush toilet, and a frequency of toilet use of three times per person per day was assumed, which was equivalent to 0.018 kL of water use per person per day. The washing machine considered in this study was rated AAAA. It was assumed that the washing machine had a volume of 50 ltires and it would be used 3 times per week, which was equivalent to 0.0215 kL/day of water use. The irrigation demand per square metre of lawn area was assumed to be 10mm per day as per Sydney Water recommended value in this region.
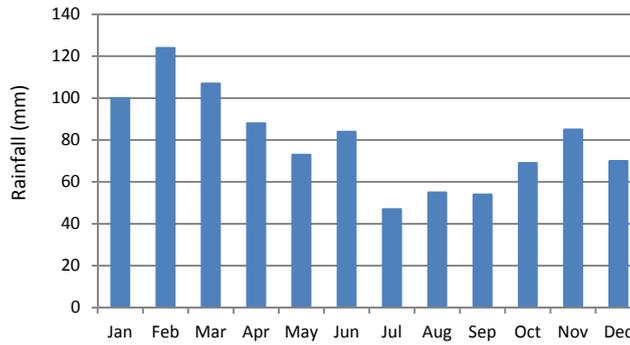
Figure 2 Average monthly rainfalls in Sydney region

Table 1 Study locations and details of selected daily rainfall data

Location	Rainfall station	Period of rainfall record	Average annual rainfall (mm)
Campbelltown	068007	1900 - 2009	743
Hornsby	066158	1936 - 2009	1,325
Parramatta	066124	1966 - 2009	963
Penrith	063185	1970 - 2009	971
Richmond	067021	1902 - 2003	800
Castlereagh	067002	1939 - 2011	685
Wallacia Post Office	067029	1943 - 2011	847
West Pennant Hills	067098	1943 - 2006	1,028
Moss Vale	068195	1971 - 2009	1,089
Cataract Dam	068016	1935 - 2011	1,080

4. Results

The reliability of rainwater tanks of different sizes and water use across all the ten locations are shown in Figures 3 to 5. Figure 3 shows that on average 1 kL rainwater tank can meet the demand for toilet and laundry use for 87% of the days in a year, which increases to 97% for a 5 kL tank size and 100% for a 20 kL tank size. Among the ten locations considered here, Hornsby has the highest reliability (99.26% for a 5 kL tank) and Castlereagh has the lowest one (79% for a 5 kL tank). This reliability is well related with the average annual rainfall values at these two locations (1,325 mm and 685 mm for Hornsby and Castlereagh, respectively).

Figure 3 also shows that the differences in reliability across different locations reduces as the tank size increases and a rainwater tank of 7.5 kL size can meet the demand for toilet and laundry use for about 100% at the nine locations; on the other hand, a rainwater tank of 7.5 kL size can meet the demand for toilet and laundry use for about 85% at Castlereagh. This suggests that in peri-urban areas of Sydney, a 7.5 kL rainwater tank should be adopted to meet toilet and laundry demands to ensure reliable supply and to maximize water conservation.

Figure 5 presents reliability values for the toilet, laundry and irrigation use (combined use). It is found that the reliability increases with the increasing rainwater tank size as expected. The highest and lowest reliability values for a 5 kL tank are found to be for Hornsby (69%) and Castlereagh (32%), respectively, which is similar to the toilet and laundry use (see Figure 3). The average reliability over the ten locations is very close to the reliability for West Pennant Hills as can be seen in Figure 4. The reliability for combined use does not reach 100% for any of the ten locations even for a 20 kL tank size. Furthermore, there is a notable difference in reliability across different locations in Sydney, which suggests that a common tank size is not appropriate for Greater Sydney as practiced currently.
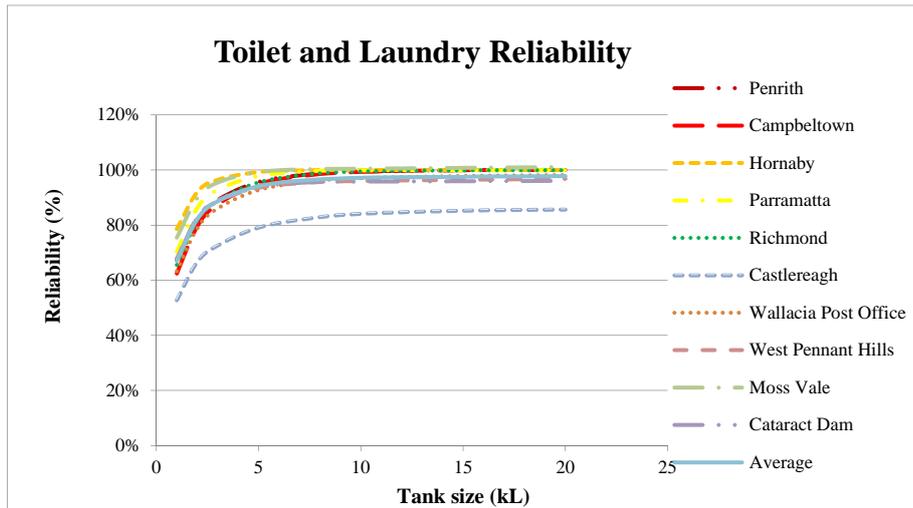
Figure 3 Reliability of rainwater tanks at ten selected locations for toilet and laundry use

As can be found in Figure 4, the reliability for irrigation use at all the ten locations is smaller than for toilet and laundry use (shown in Figure 3). For a 20 kL tank, the reliability values for Hornsby and Castlereagh are 82% and 41%, respectively. This result shows that reliability value varies significantly at these two locations, which is well related with the average annual rainfalls (mean annual rainfall of 1,325 mm and 685 mm for Hornsby and Castlereagh, respectively). The average reliability for the ten locations is very close to the reliability of West Pennant Hills. These results highlight that even with a 20 kL rainwater tank, the reliability of 100% cannot be achieved for irrigation use at any of the ten study locations. This is due to the fact of high irrigation demand in the Greater Sydney region, which is characterized by periods of drought spells lasting over weeks and even months in almost all the years on record.
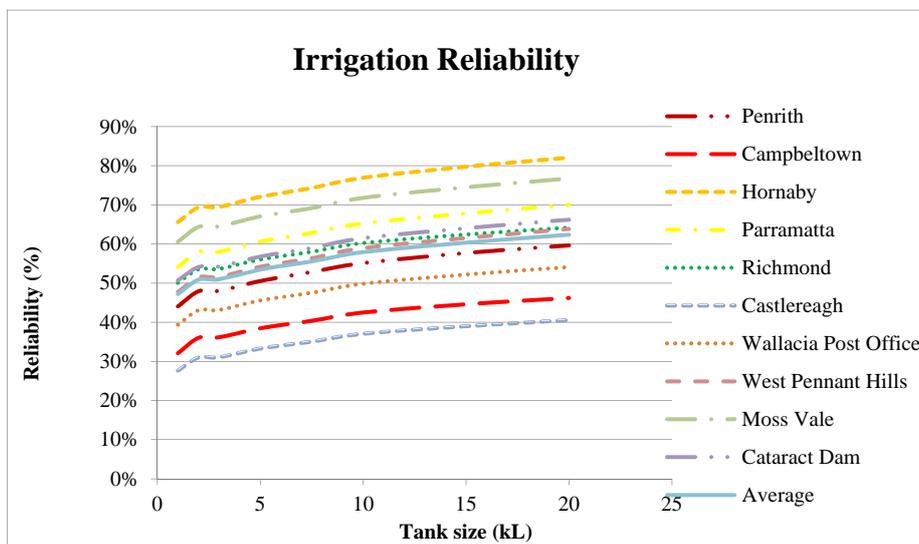

Figure 4 Reliability of rainwater tanks at ten selected locations for irrigation use

Figure 6 shows the water savings for toilet and laundry use from a 7.5kL rain water tank; after about 10 kL size, the water savings becomes nearly constant for all the ten locations. This is due to the fact that water utilization from the tank depends on the number of users in the house, and for a larger tank there would be much more unutilised water overflowing from the tank. For a 5 kL tank, average annual water savings range from 27 kL (Castlereagh) to 34 kL (Hornsby) with a mean value of 32 kL, which suggests a smaller variation across the ten locations in water savings for toilet and laundry use.
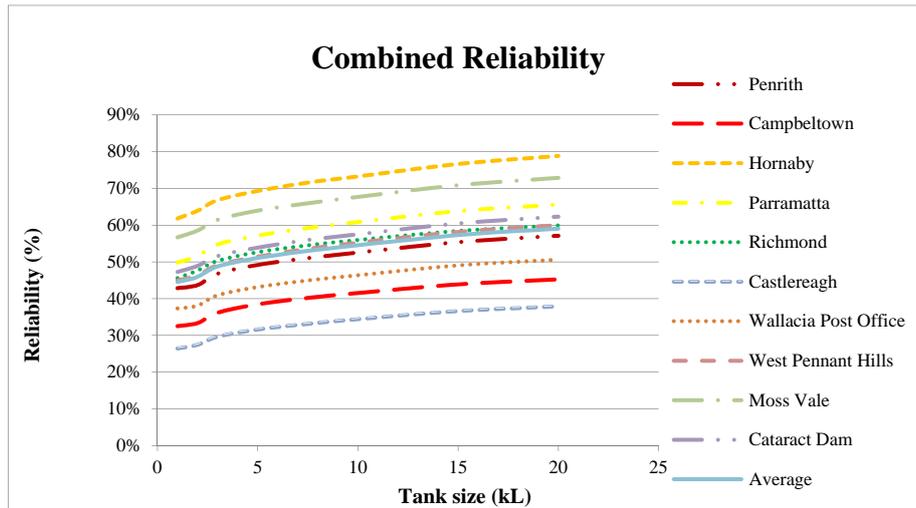
Figure 5 Reliability of rainwater tanks at the ten selected locations for combined use
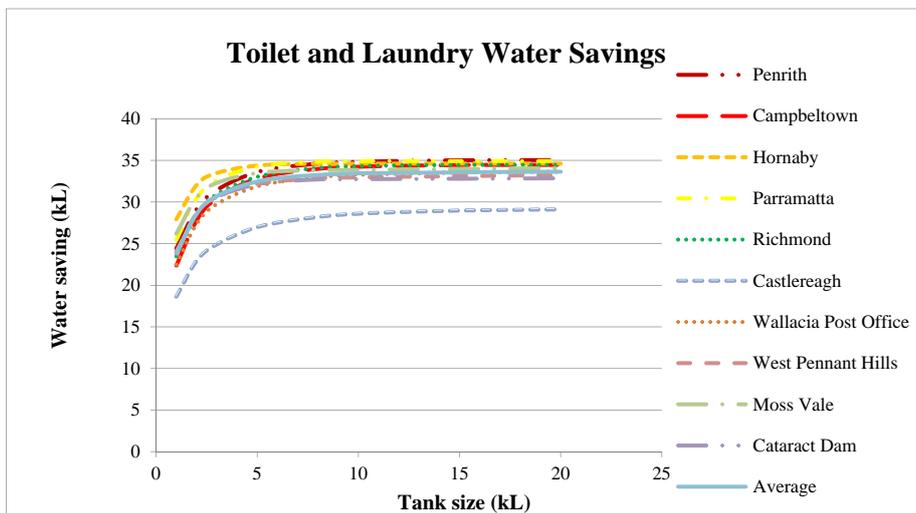

Figure 6 Water savings for toilet and laundry use

Figure 7 shows that water savings for irrigation use increases with increasing rainwater tank size as expected. For a 5 kL tank, the average annual water savings range from 58 kL (Penrith) to 45 kL (Castlereagh) with the mean value for the ten locations is 54 kL. Figure 8 shows that the differences in water savings for combined use for the ten different locations reduce as the size of rain water tanks reduces. The water saving increases with the increasing rain water tank size as expected. For a 5 kL tank, Penrith has the highest average annual water savings (62 kL), and Castlereagh has the lowest annual water savings (50 kL) and Wallacia corresponds very well to the average annual water savings over the ten locations (56 kL).

It should be noted here that the reliability reported in this study is based on the long-term daily rainfall data and represents the average reliability at a given location; the reliability will differ from year to year depending on the rainfall pattern of the location, e.g. for a wet year, reliability will be higher than a dry year, as found by Imteaz et al., 2011a, b; 2012; 2013).
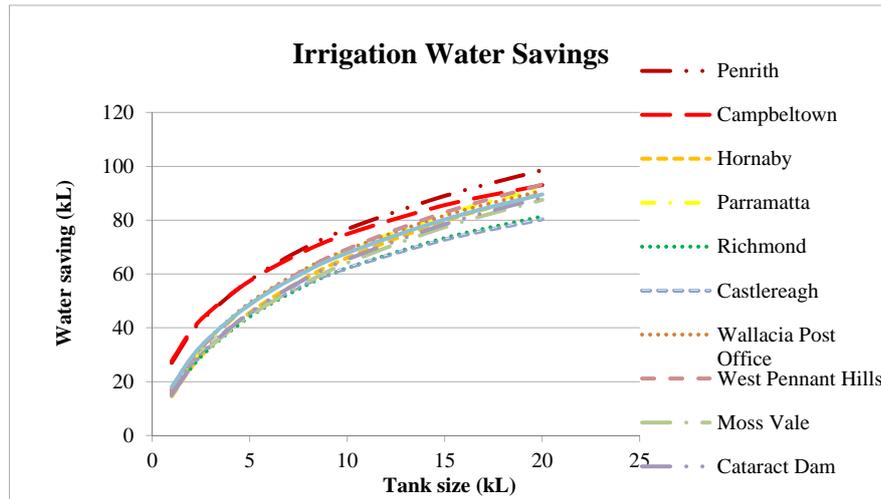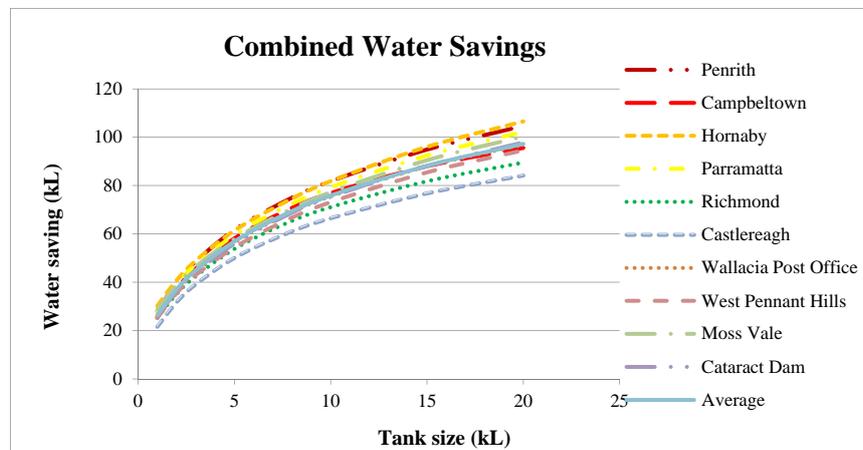
Figure 7 Water savings for irrigation use

Figure 8 Water savings for combined use

Table 2 shows the correlation coefficients of the relation between reliability, water saving and the size of rain water tanks for the ten different locations. Table 2 shows that Parramatta and Castlereagh have the lowest and highest correlation coefficients for toilet and laundry use. Also the combined and irrigation uses of the all ten locations exhibit strong correlation between the reliability, water saving and rainwater tanks size.

Table 2 Correlation coefficients between reliability, water saving and the size of rain water tanks

Locations	Toilet and laundry		Irrigation		Combined use	
	Reliability	Water saving	reliability	water saving	reliability	water saving
Penrith	0.890	0.892	0.986	0.992	0.987	0.993
Campbelltown	0.930	0.931	0.990	0.995	0.990	0.996
Hornsby	0.929	0.931	0.982	0.989	0.991	0.988
Parramatta	0.850	0.853	0.984	0.991	0.993	0.991
Richmond	0.926	0.927	0.987	0.993	0.996	0.993
Castlereagh	0.953	0.956	0.988	0.995	0.990	0.995
Wallacia Post Office	0.937	0.938	0.986	0.993	0.987	0.992
West Pennant Hills	0.910	0.913	0.983	0.990	0.989	0.990
Moss Vale	0.881	0.884	0.983	0.988	0.991	0.988
Cataract Dam	0.893	0.895	0.982	0.990	0.990	0.990

For 5 kL rain water tank in the ten selected locations in Greater Sydney, the average annual rainfall is strongly correlated with the reliability for the (a) toilet and laundry use than for (b) irrigation and (c) combined use as expressed by the following equations:

$$R1 = -0.394 + 0.195 \times \ln(AAR), \; r = 0.677 \tag{7}$$
$$R2 = -3.129 + 0.535 \times \ln(AAR), \; r = 0.891 \tag{8}$$
$$R3 = -2.974 + 0.509 \times \ln(AAR), \; r = 0.901 \tag{9}$$

Where R1, R2, R3 are reliabilities (%) for (a) toilet and laundry, (b) irrigation and (c) combined use respectively and AAR is average annual rainfall value (mm) and r is correlation coefficient. Indeed, it is found that the average annual water savings for 5 kL rainwater tank in case of (c) combined use has higher correlations with the average annual rainfall than for (a) toilet and laundry use and (b) irrigation use as shown by the following equations:

$$AWS1 = -13.69 + 6.747 \times \ln(AAR), \; r = 0.638 \tag{10}$$
$$AWS2 = 89.09 + 5.91 \times \ln(AAR), \; r = 0.235 \tag{11}$$
$$AWS3 = -18.65 + 11.04 \times \ln(AAR), \; r = 0.614 \tag{12}$$

Where AWS1, AWS2, AWS3 are average annual water savings (kL) for (a) toilet and laundry, (b) irrigation and (c) combined use, respectively.

5. Conclusion

This paper investigates the performance of a rainwater harvesting system (RWHS) in peri-urban regions of Greater Sydney, Australia. Ten locations are selected from the peri-urban regions of Greater Sydney. It has been found that reliability of water supply increases as tank size increases for all the three water use considered here. For toilet and laundry use, a 7.5 kL tank can meet almost 100% of the demand, and hence this is the recommended tank size in peri-urban regions of Sydney. However, irrigation demand cannot be met 100% of the days in a year even with a tank size of 20 kL. It has also been found that reliability of a RWHS is highly dependent on mean annual rainfall of the location. A set of regression equations are developed which can be used to estimate water savings and reliability using the mean annual rainfall data at any arbitrary location in the peri-urban regions of Greater Sydney. The method presented here can also be applied to other Australian states and countries to estimate water savings and reliabilities of RWHS.

6. Acknowledgements

References

Campisano A, Modica C (2012). Optimal sizing of storage tanks for domestic rainwater harvesting in Sicily. *Resources, Conservation & Recycling*, 63, 9-16.

Coombes PJ, Kuczera G, Kalma JD (2003). Economic water quantity and quality impacts from the use of a rainwater tank in the inner city. *Australian Journal of Water Resources*, 7(2), 25-36.

Domenech L, Sauri D (2010). A Comparative appraisal of the use of rainwater harvesting in single and multi-family buildings of the metropolitan area of Barcalona (Spain): social experience, drinking water savings and economic costs. *Journal Cleaner Production*, 11, 1-11.

Eroksuz E, Rahman, A (2010). Rainwater tanks in multi-unit buildings: A case study for three Australian cities. *Resources, Conservation & Recycling*, 54, 1449-1452.

Ghisi E, Fonseca DT, Rocha VL (2009). Rainwater harvesting in petrol stations in Brasilia: Potential for potable water savings and investment feasibility analysis. *Resources, Conservation & Recycling*, 54, 79-85.

Ghisi E, Schondermark PN (2013). Investment Feasibility Analysis of Rainwater Use in Residences, *Water Resources Management*, DOI 10.1007/s11269-013-0303-6.

Imteaz MA, Shanableh A, Rahman A, Ahsan A (2011a). Optimisation of rainwater tank design from large roofs: a case study in Melbourne, Australia. *Resources, Conservation & Recycling*, 55, 1022-29.

Imteaz MA, Ahsan A, Naser J, Rahman A (2011b). Reliability Analysis of Rainwater Tanks in Melbourne using Daily Water Balance Model. *Resources, Conservation & Recycling*, 56, 80-86.

Imteaz MA, Rahman A, Ahsan A (2012). Reliability analysis of rainwater tanks: A comparison between South East and Central Melbourne. *Resources, Conservation & Recycling*, 66, 1-7.

Imteaz MA, Ahsan A, Shanableh A (2013). Reliability analysis of rainwater tanks using daily water balance model: variations within a large city. *Resources, Conservation & Recycling*, 77, 37-43.

Kus B, Kandasamy J, Vigneswaran S, Shon HK (2011). Water quality in rainwater tanks in rural and metropolitan areas of New South Wales, Australia. *Journal of Water Sustainability*, 1(1), 33-43.

Mehrabadi MH, Saghafian B, Fashi FH (2013). Assessment of residential rainwater harvesting efficiency for meeting non-potable water demands in three climate conditions. *Resources, Conservation & Recycling*, 73, 86-93.

Rahman A, Keane J, Imteaz MA (2012). Rainwater Harvesting in Greater Sydney: Water savings, reliability and economic benefits. *Resources, Conservation & Recycling*, 61, 16-21.

Su M, Lin C, Chang L, Kang J, Lin M (2009). A probabilistic approach to rainwater harvesting systems design and evaluation. *Resources, Conservation & Recycling*, 53, 393-99.

Van der Sterren M, Rahman A, Dennis G (2013).Quality and quantity monitoring of five rainwater tanks in Western Sydney, Australia. *Journal of Environmental Engineering*, 139, 332-340.

Van der Sterren M, Rahman A, Dennis GR (2012). Implications to stormwater management as a result of lot scale rainwater tank systems: a case study in Western Sydney, Australia, *Water Science and Technology*, 65, 8, 1475-1482.

Van der Sterren M, Rahman A, Shrestha S, Barker G, Ryan G (2009). An overview of on-site retention and detention policies for urban stormwater management in the greater Western Sydney region in Australia, *Water International*, 34, 362-372.