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A Case Study on Reliability, Water Demand and Economic Analysis of Rainwater Harvesting in Australian Capital Cities

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Abstract: This paper presents reliability, water demand and economic analysis of rainwater harvesting (RWH) systems for eight Australian capital cities (Adelaide, Brisbane, Canberra, Darwin, Hobart, Melbourne, Perth and Sydney). A Python-based tool is developed based on a daily water balance modelling approach, which uses input data such as daily rainfall, roof area, overflow losses, daily water demand and first flush. Ten different tank volumes are considered (1, 3, 5, 10, 15, 20, 30, 50, 75 and 100 m^3). It is found that for a large roof area and tank size, the reliability of RWH systems for toilet and laundry use is high, in the range of 80–100%. However, the reliability for irrigation use is highly variable across all the locations. For combined use, Adelaide shows the smallest reliability (38–49%), while Hobart demonstrates the highest reliability (61–77%). Furthermore, economic analysis demonstrates that in a few cases, benefit–cost ratio values greater than one can be achieved for the RWH systems. The findings of this study will help the Australian Federal Government to enhance RWH policy, programs and subsidy levels considering climate-sensitive inputs in the respective cities.

Keywords: benefit–cost; reliability; water balance model; water conservation; water security

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1. Introduction

In the last few decades, water demand across the world has been increasing due to several factors, such as population growth, urbanisation, change in socio-economic condition and climate variability and change [1]. Australia is the second driest continent in the world with average annual rainfall below 600 mm over 80% of the continent, and below 300 mm over 50% [2]. Frequent water restrictions in Australia, including several capital cities and various rural centres, highlight the importance of water conservation measures [3]. On the other hand, higher water demand, frequent droughts and bushfire due to climate variability and change have put water supply systems under stress in Australia [4]. The scarcity of fresh water has led to the need to identify and make use of alternative fresh water sources that can meet the growing demand for water [5]. To enhance water security, alternative water sources are receiving much attention, such as RWH, grey water reuse and wastewater recycling. Among these, RWH is considered as an attractive option because of technological, economic and environmental benefits. RWH is not a new technology but it has been identified as one of the best means of promoting sustainable water supply in urban areas [6]. It is a viable technique that could be used as an alternative water supply for both potable and non-potable purposes, as well as to reduce flood risk [7]. Thirty-four percent of households have adopted RWH in Australia. It provides about 177 billion litres of water, accounting for about 9% of residential water use in urban areas, which is worth AUD 540 million [8]. State governments and local councils have been promoting RWH through campaigns, as well as offering cash rebates and grants to promote water saving ideas and innovations [9–11].

The reliability of an RWH system in Australia is highly variable from location to location due to high climate and rainfall variability across the continent. Moreover, the reliability also depends on the frequency of rainy days in a year which varies from high (near the north Queensland and southern Australian coast) to low (central Australia). Rainfall intensities and climate conditions play an important role in reliability analysis of an RWH system, for example, how many rainy days, rainfall per day and the annual total rainfall. Reliability and water saving of RWH systems are still the most important objectives in many studies [12,13]. Water saving and reliability of RWH systems are fundamentally related to site conditions such as climate and catchment, the storage size and water demand scenarios. As a result, the design of an RWH system must account for projected water demand that aligns well with local rainfall patterns and catchment conditions in order to significantly improve the system's overall multi-objective performances [14].

The performance and design of an RWH system are related to the size and characteristics of the contributing catchment, level of rainfall and demand of the system. A number of approaches can be used in RWH system design, optimisation and performance evaluation, for instance, the design storm approach [15], the analytical probabilistic or stochastics approach [16], mass curve analyses [17,18] and computer-based simulation or behavioural analysis [19,20]. Among these approaches, the most accurate method is a computer model designed to optimise the size of RWH systems and to analyse the water savings and/or stormwater management performance under different rainfall regimes [21]. This method is chosen in this study to estimate the optimum tank size since it does not overestimate the tank size as in a few other approaches.

Several studies have been carried out to assess the benefits and implementation of RWH systems in response to growing water demand around the world. These studies demonstrate a growing interest in RWH systems across the globe, such as Souza and Ghisi [22] for 12 countries; Africa (Ahiablame et al. [23] for Lomé, Togo; Imteaz et al. [24] for Nigeria; Kahinda et al. [25] for South Africa; and Ndomba and Wambura [26] for Tanzania); Asia (Ali et al. [27] for Pakistan; Abdulla and Al-Shareef [28] for Jordan; Bashar et al. [29] for Bangladesh; Hafizi et al. [30] for Malaysia; Cheng and Liao [31] for Taiwan; Jing et al. [32] for China; and Shokati at al. [17] for Iran); Australia (Alim et al. [33] for Werrington, NSW; Eroksuz and Rahman [34] for Sydney, Newcastle and Wollongong; Imteaz et al. [10] for Melbourne; Imteaz et al. [12] for Adelaide; and Zhang et al. [9] for Western Australia); Europe (Campisano and Modica [35] for Sicily; Farreny et al. [36] for Spain; Matos et al. [37] for Portugal; Notaro and Freni [38] for Southern Italy; Sazakli et al. [39] for Greece; Villarreal and Dixon [18] for Norrköping, Sweden; and Roebuck et al. [40] for the UK); America (Dallman et al. [41] for California; Ghisi and Martini [42] for Brazil; Jones and Hunt [43] for the southeastern United States; Lawrence and Lopes [44] for Texas; and Sample et al. [45] for Virginia).

Based on the several studies presented above, it can be easily argued that most of the studies previously conducted in Australia calculated reliability and water saving of a RWH system for major cities like Sydney and Melbourne. Australia is a big continent with highly variable rainfall over space; hence, different cities will have different optimum rainwater tank sizes for a given water demand, which has been largely disregarded. This research problem has been investigated here using latest rainfall data across eight capital cities in Australia. Consideration of local climatic conditions, as done in this study, will assist in a better planning of rainwater utilisation and other relevant water resources management issues in Australia at a national level.

2. Study Area and Data

Australia is the focus of this study. It is the sixth largest country in the world, which comprises a land area of 7.69 million km^2. Rainfall in Australia is highly variable with low average annual rainfall over most of the continent. The north, east and southwest coasts and ranges receive moderate to high rainfall while the rest of the continent is quite dry. Australian capital cities (Adelaide, Brisbane, Canberra, Darwin, Hobart, Perth, Melbourne and Sydney) were considered for this study. Spatial locations of the selected eight rainfall stations, one from each city, can be seen in Figure 1, while Table 1 provides the location, coordinates (latitude and longitude), station name, data time series length and average annual rainfall for the selected stations. Historical daily rainfall data from these locations were collected from the Australian Bureau of Meteorology covering 75 years. The daily rainfall data were checked in a number of ways such as for missing data and consistency and with visual inspections of plots.

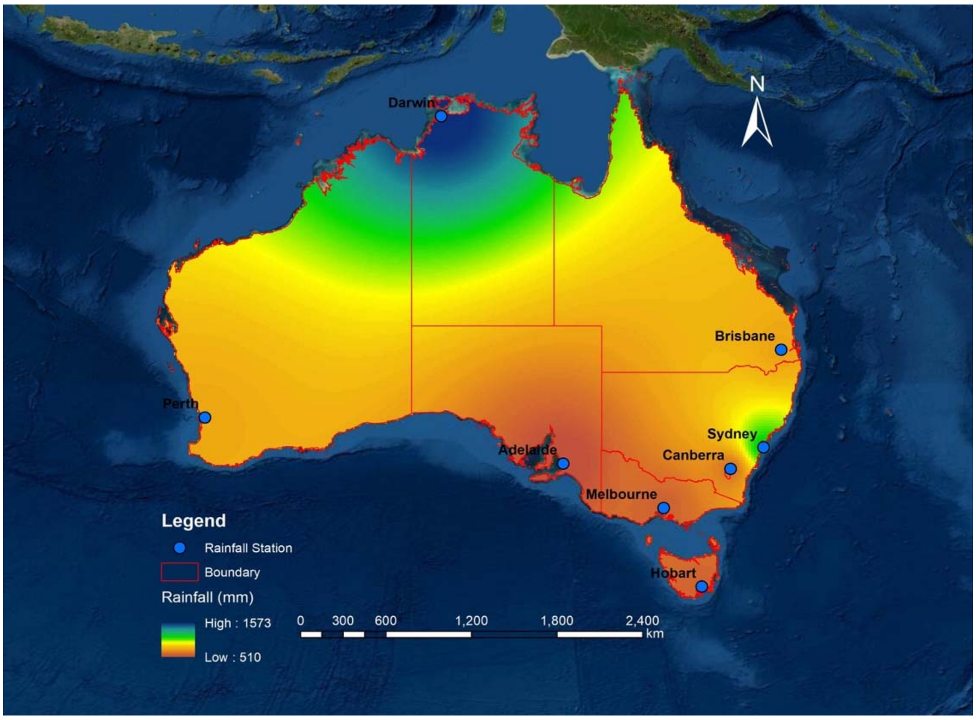

Figure 1. Location of the selected rainfall stations and spatial distribution of mean annual rainfall.

Table 1. Summary of selected daily rainfall data.

Location	Lat.	Long.	Station No.	Station Name	Duration	Data Length (years)	Average Annual Rainfall (mm)
Adelaide, SA	−34.92	138.59	023011	North Adelaide	1945–2019	75	510
Brisbane, QLD	−27.54	152.33	040082	University of Queensland Gatton	1945–2019	75	753
Canberra, ACT	−35.26	149.14	070000	Ainslie Tyson St	1945–2019	75	648
Darwin, NT	−12.42	130.89	014015	Darwin Airport	1945–2019	75	1574
Hobart, TAS	−42.89	147.33	094029	Hobart (Ellerslie Road)	1945–2019	75	598
Melbourne, VIC	−37.79	144.91	086039	Flemington Racecourse	1945–2019	75	592
Perth, WA	−31.93	115.98	009021	Perth Airport	1945–2019	75	761
Sydney, NSW	−33.87	151.22	066006	Sydney Botanic Gardens	1945–2019	75	1176

3. Methodology

A Python-based daily water balance model was developed to assess the reliability of an RWH system. The primary input data for the model were daily rainfall. The basic idea underlying the model is that the rainfall falling on a roof area initially discharges to a first flush device and then to the rainwater tank. Water is drawn from the rainwater tank for intended use. 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). All analysis was undertaken for ten different rainwater tank sizes (1, 3, 5, 10, 15, 20, 30, 50, 75 and 100 m^3) to enable selection of optimum rainwater tank size for all the eight locations. As shown in Figure 2, the methodology flowchart demonstrates the logical steps to calculate reliability, water saving and economic parameters of a rainwater harvesting system. A similar daily water balance approach was used in several previous studies, for example, by Eroksuz et al. [34]; Imteaz et al. [10]; Rahman et al. [11]; Amos et al. [46]; Bashar et al. [29]; Alim et al. [33]; Khan et al. [47].

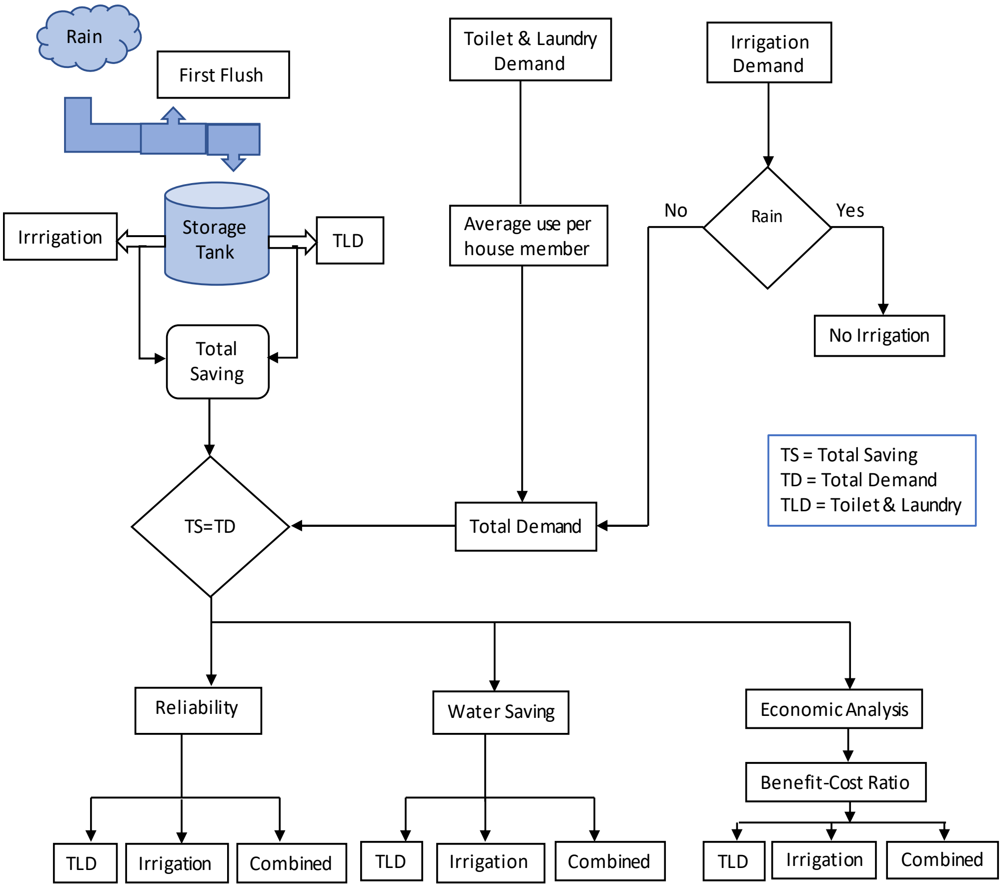

Figure 2. Flowchart showing the adopted methodology of daily water balance model.

3.1. Reliability and Water Saving Analysis

The reliability of an RWH system is defined as the percentage of days in a year when the rainwater tank is able to supply the intended water demand fully.

$$R = \frac{N - X}{N} \times 100 \tag{1}$$

where R is the reliability of the RWH system to be able to supply the intended demand (%), X is the total number of days in a year when intended water demand is not met, and N is the total number of days in that year. Therefore, $N - X$ provides the total number of days where intended water demand has been met.

3.2. Water Demand

In the past, only a few studies were carried out to estimate the daily water demand for these capital cities individually except for Sydney and Melbourne. A hypothesised 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 roof, irrigation and impervious areas of 200 m^2, 150 m^2 and 100 m^2, respectively. The following input data were used: first flush = 150 L and RC = 0.85, where RC = runoff coefficient.

Total demand consists of toilet flushing and laundry along with irrigation demand. The demand for toilet flushing and laundry is calculated based on the following information:

- Toilet: 6 L/flush, full flushed thrice a day per person, giving 18 L/person/day.
- Laundry: Washing machine 50 L/wash, at 0.43 washes/day, resulting in 21.5 L/day.

For an example, for 4 persons in a house visiting the toilet three times a day per person on average, total demand for toilet flushing and laundry will be: 4 × 3 × 6 + 0.43 × 50 = 0.0935 m^3/day.

- Irrigation: Outdoor use includes irrigation at 10 mm depth of irrigation multiplied by the irrigation area (150 × 10 mm = 1.5 m^3/session).

3.3. Dimensionless Design Parameters

Two non-dimensional parameters, the demand fraction and the storage fraction, are adopted in order to assess the optimum sizing of the system across different capital cities. The demand fraction (D/Q) is defined as the ratio between the annual water demand D (L^3) and the annual inflow Q (L^3). While the storage fraction (S/Q) is defined as the ratio between the storage capacity of the system S (L^3) and the annual inflow Q (L^3) [48].

3.4. Economic Analysis

To perform economic analysis, all the costs expressed here are in Australian dollars.

$$\text{Discount rate} = \frac{1}{(1+\mathrm{i})^{\mathrm{n}}}\ \mathrm{PV} = \frac{\mathrm{CF}}{(1+\mathrm{i})^{\mathrm{n}}} \tag{2}$$

where i is the interest rate and t is the year in which the cash flow occurs. Present values are then calculated by multiplying cash flows (CFs), or in this case, total costs for a given year by the discount rate or the PV of one dollar in that year. The net present value (NPV) is then the sum of present values (PVs) over the project life and is calculated as:

$$\mathrm{NPV}(\mathrm{i},\ \mathrm{N}) = \sum_{\mathrm{t}=0}^{\mathrm{N}} \frac{\mathrm{CF}_{\mathrm{t}}}{(1+\mathrm{i})^{\mathrm{t}}} \tag{3}$$

where N is number of years the life cycle is considered over (here 50 years).

The benefit–cost ratio (BCR) is calculated using discounted rates (i.e., present values). It is simply the sum of discounted costs (C)—NPV of costs, divided by the sum of discounted benefits (B)—NPV of benefits as they occur at time t over the lifetime of the project N, as shown in equation below [49]:

$$\mathrm{BCR} = \frac{\sum_{\mathrm{t}=0}^{\mathrm{N}} \frac{\mathrm{C}_{\mathrm{t}}}{(1+\mathrm{i})^{\mathrm{t}}}}{\sum_{\mathrm{t}=0}^{\mathrm{N}} \frac{\mathrm{B}_{\mathrm{t}}}{(1+\mathrm{i})^{\mathrm{t}}}} \tag{4}$$

4. Results and Discussion

4.1. Reliability

The reliability of rainwater tanks of different sizes and each water use type for these cases are shown in Figure 3a–c. It shows that, on an average, a 1 m^3 rainwater tank can meet the demand for toilet and laundry use for 71% of the days in a year, which increases to 88% for a 3 m^3 tank, 93% for 5 m^3, 97% for 10 m^3 and 99% for a 15 m^3 tank. Among all the eight locations, Darwin has the lowest reliability (88%) and Sydney has the highest (99%) for a 10 kL tank size. It is also found that throughout all the locations, an increase in tank size increases the reliability, and a 10 m^3 tank can meet the demand for toilet and laundry use with a reliability of greater than 97% at all the eight locations. Even for a larger tank size, it is not possible to achieve 100% reliability, except for Darwin which shows 100% reliability with a roof size of 200 m^2 and a tank size of 20 m^3. This is similar to the findings of Hazani et al. [21] who conducted an RWH case study over 10 peri-urban regions in Greater Sydney, Australia and found a reliability of 86% for toilet and laundry use using a 2 m^3 tank, which increased to 97.5% when a 5 m^3 tank was considered. Bashar et al. [29] showed the reliabilities of rainwater harvesting systems with different water demands and tank sizes vary widely across six major cities of Bangladesh. Imteaz et al. [12] developed a daily water balance model to assess the reliability of an RWH system. It was found that for a relatively small roof size (100 m^2), 100% reliability cannot be achieved even with a very large tank (10 kL). Similar to Imteaz et al. [12], we found that nearly 100% reliability is not possible to achieve for a small roof area, and even for a 200 m^2 roof size and 10 m^3 tank, up to 99% reliability is achieved.

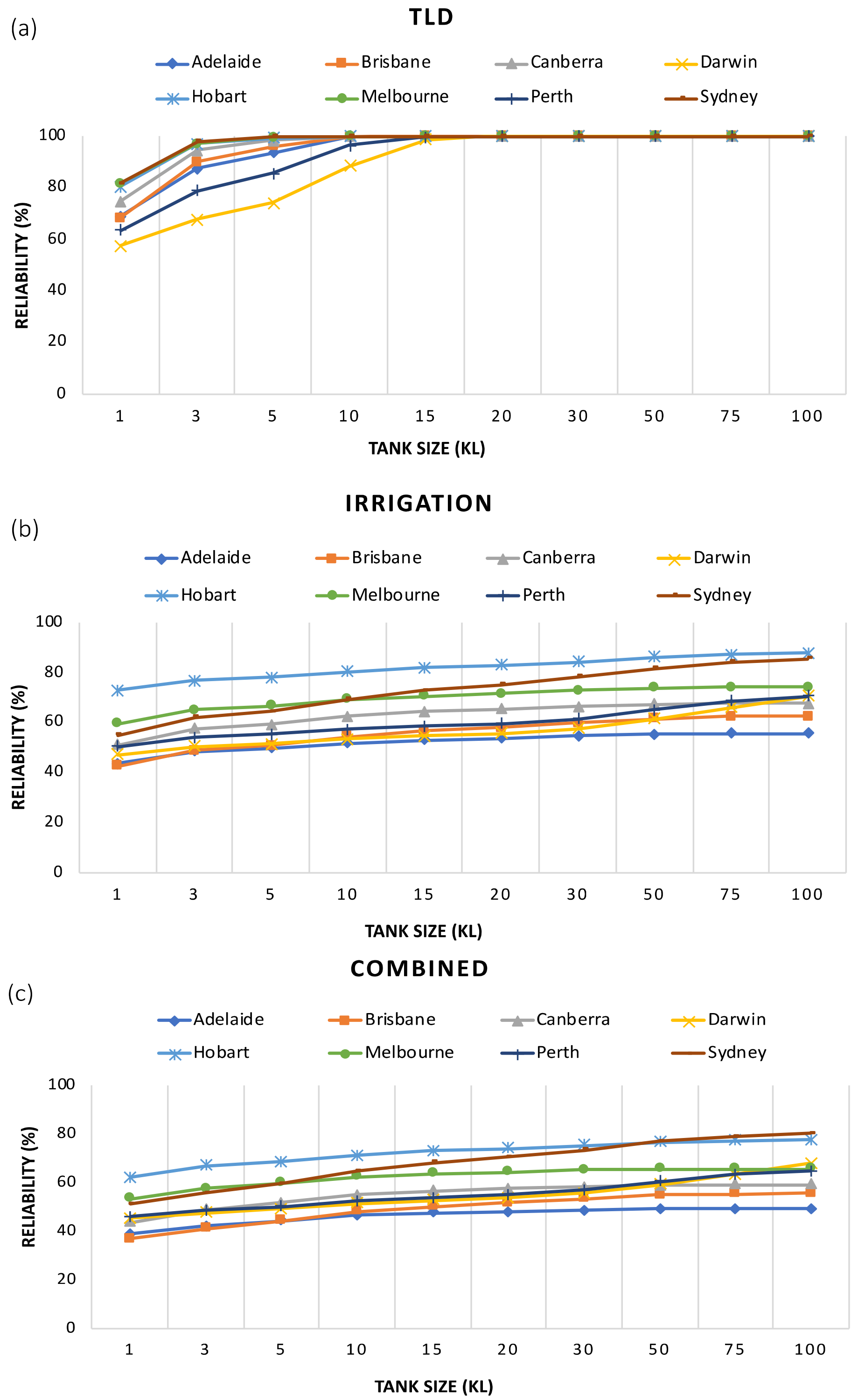

Figure 3. Reliability of rainwater tanks for TLD, irrigation and combined use (**a**) TLD use; (**b**) irrigation use; (**c**) combined use.

For irrigation use, the reliability for all the locations is less than TLD use. Figure 3 shows that, on average, a 1 m^3 rainwater tank can meet the demand for irrigation use for

52% of the days in a year, which increases to 57% for a 3 m^3 tank, 59% for 5 m^3, 62% for 10 m^3 and 64% for a 15 m^3 tank. It is found that Adelaide shows the lowest reliability in the range of 43–55% for all the ten tank sizes, while Hobart shows the highest system reliability in the range 72–87%. It is noted that even for a 100 m^3 tank size, system reliability is below 85% at all of the locations. The main reason for less reliability in most of Australia is higher irrigation demand, which is 1.5 m^3/session. For example, for a 3 m^3 tank size, the demand is exactly half of the tank size.

Similarly, for combined use (toilet, laundry and irrigation use), the demand is quite high, which results in less system reliability all over Australia. It is found that Adelaide shows the lowest reliability in the range of 38–49% for all the ten tank sizes, while Hobart shows the highest system reliability in the range 61–77%. Moreover, the reliability for irrigation and combined use is highly variable across all the locations since irrigation demand depends on number of rain days in a year which varies from location to location. Rainfall plays a very important role in reliability analysis, for example, how many rainy days, rainfall per day and the annual total rainfall. Therefore, it is found that for a large roof area and good tank size, it is possible to achieve 97% reliability for TLD use. Reliability is also impacted by higher rainfall variability from location to location across Australia.

Figure 4 shows the relationships of reliability, roof area and tank volume for a four-person household scenario for Sydney. It is clear from the figure that the reliability is significantly dependent on roof size and the reliability keeps on increasing with the increase in roof size.

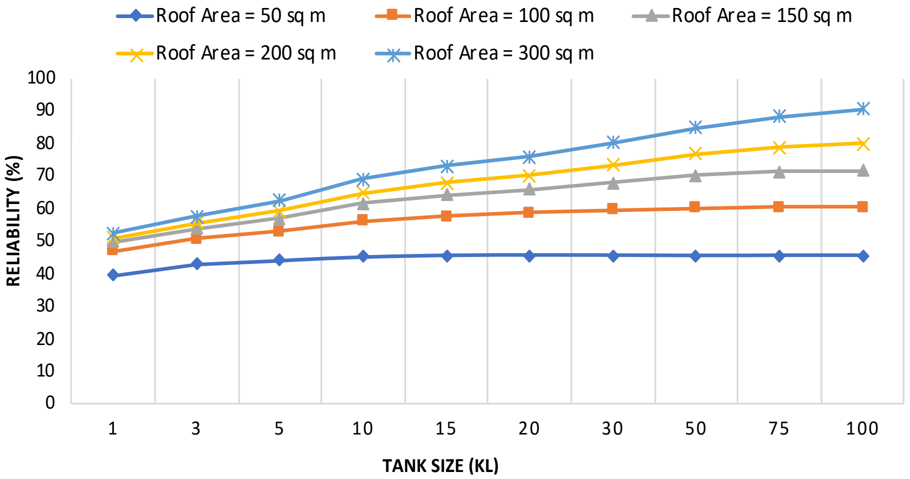

Figure 4. Reliability–roof area–tank size relationships for Sydney (combined use).

4.2. Water Savings

Figure 5 shows mean annual water saving curves for different tank sizes for all three water uses. For a 5 m^3 tank, the mean annual water savings range from 25 m^3 (Darwin) to 34 m^3 (Sydney), with the mean value for all locations being 31 m^3. For toilet and laundry use, it can be seen that after a 10 m^3 tank size, the water savings nearly become constant for all the eight locations. This is due to the fact that water utilisation from a tank largely depends on the number of users in the house; for a larger tank, if the number of users is not increased, the water savings would not increase as the harvested water remains mostly unutilised.

For irrigation use, water savings increase with size for all the locations as shown in Figure 5b. This is because the irrigation demand is quite high compared to toilet and laundry demand. For a 5 m^3 tank size, Darwin shows the lowest mean annual water savings, i.e., 27 m^3, while Sydney has the highest value, 65 m^3. Similar trends can be seen for combined use as well. This is similar to the findings of Mehrabadi et al. [50], who examined RWH efficiency for non-potable water demand in three climate conditions of

Iran. It was found that it is possible to supply at least 75% of non-potable water demand by storing rainwater from larger roof areas for a maximum of 70% of the time.

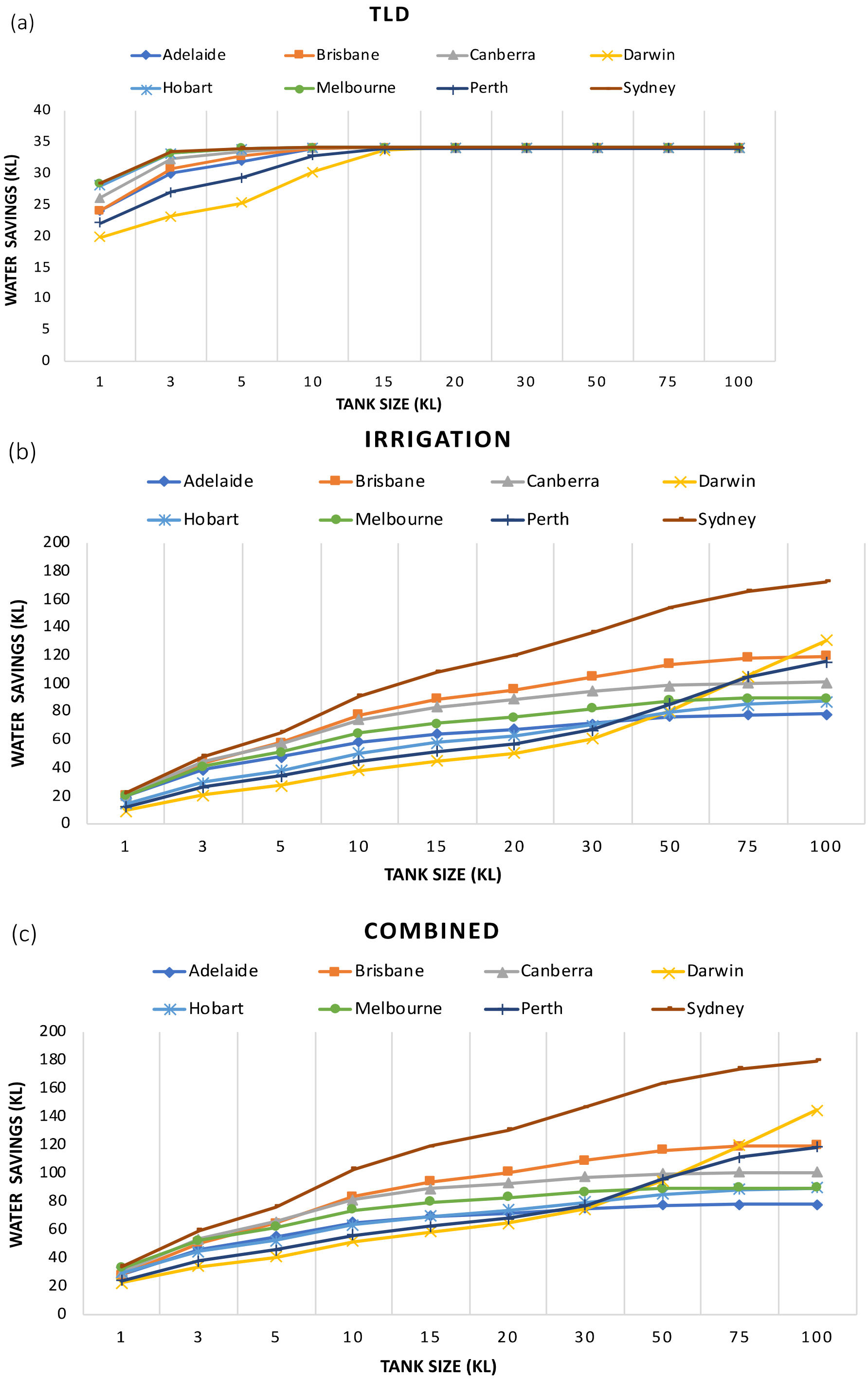

Figure 5. Average annual water savings for TLD, irrigation and combined use (**a**) TLD use; (**b**) irrigation use; (**c**) combined use.

Figure 6 shows the relationships of water savings, first flush and tank volume for a four-person household scenario for Sydney. It is clear from the figure that the water saving is significantly dependent on first flush, and water savings decrease as the first flush volume increases.

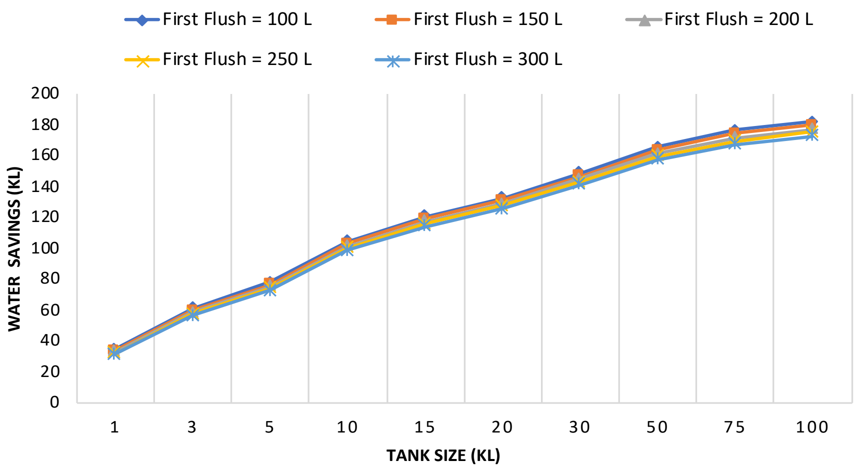

Figure 6. Water savings–first flush–tank size relationships for Sydney (combined use).

Figure 7 shows variability in annual water savings across the eight different cities. Red boxplots show variability in TLD use, green shows irrigation use and blue shows combined use. A large size box represents high variability between water savings for a particular location, while a smaller box shows less variability. As shown in Figure 7, beyond the 10 m^3 tank, water saving becomes almost constant for most of the locations except Darwin and Perth.

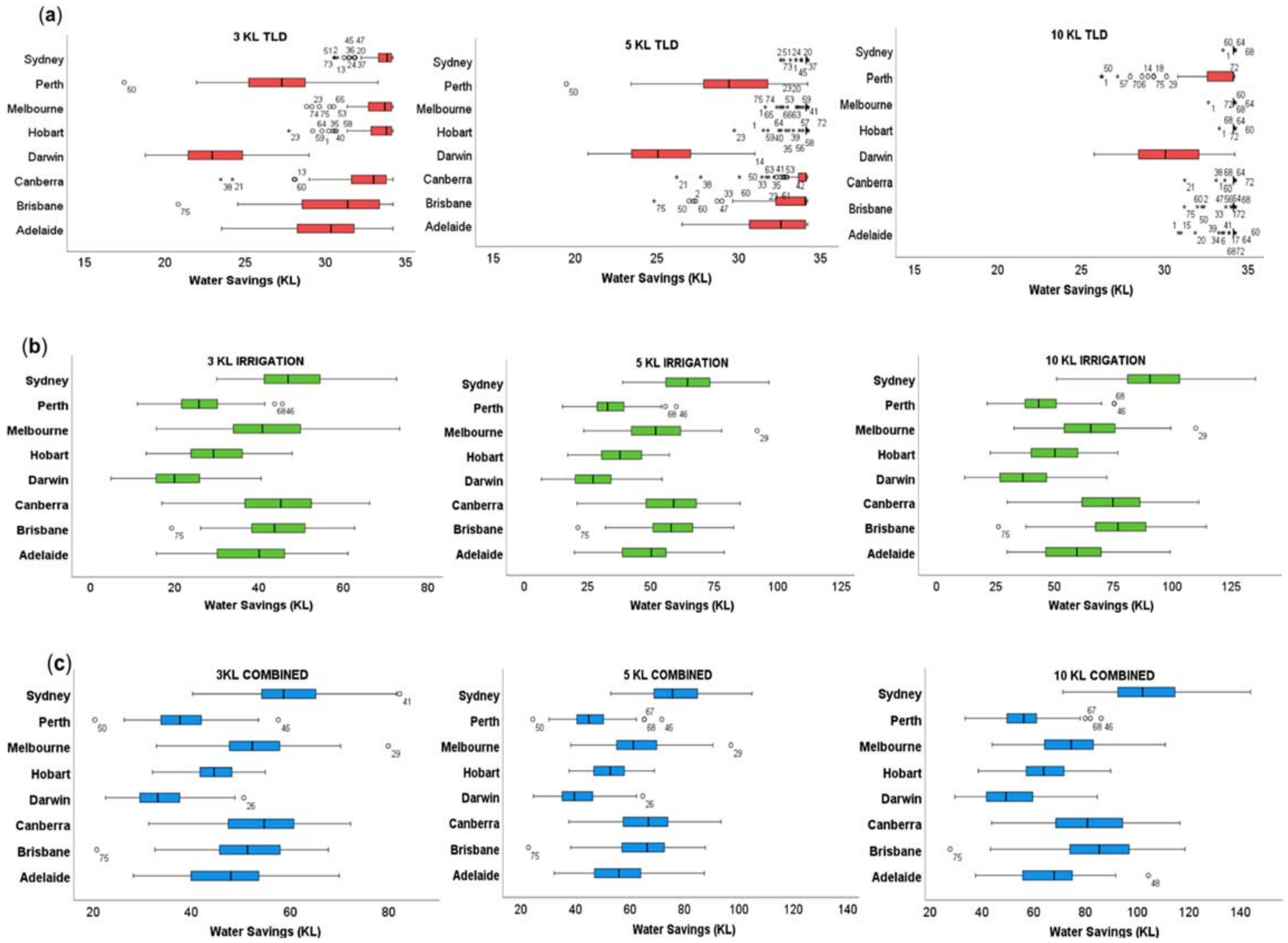

Figure 7. Boxplot showing distribution of annual water savings for: (**a**) TLD use; (**b**) irrigation use; (**c**) combined use for eight different cities for 3, 5 and 10 m^3 rainwater tanks.

4.3. Dimensionless Design Parameters

The demand fraction (D/Q) values for combined and irrigation uses are shown in Figure 8, while the storage fraction (S/Q) vs. tank are shown in Figure 9. The demand fraction varies in the range of 2.04–11.45, with the highest values for Darwin, while the smallest values are found for Sydney and Hobart. As seen in Figure 8, as tank size increases, D/Q decreases for all the locations. The storage capacity of the RWH system is an important design parameter, and is considered in the range from 1 to 100 m^3 for this study. The storage fraction (S/Q) is found to vary in the range of 0.03–1.28. From Figure 9, it is found that Perth shows the highest storage fraction value, while Sydney shows the lowest one. It can be seen that as the storage capacity increases, S/Q ratio also increases for all the locations. Palla et al. [48] found the storage capacity to be in the range of 0.01 to 3.98 for Italy, and our storage fraction falls within their range.

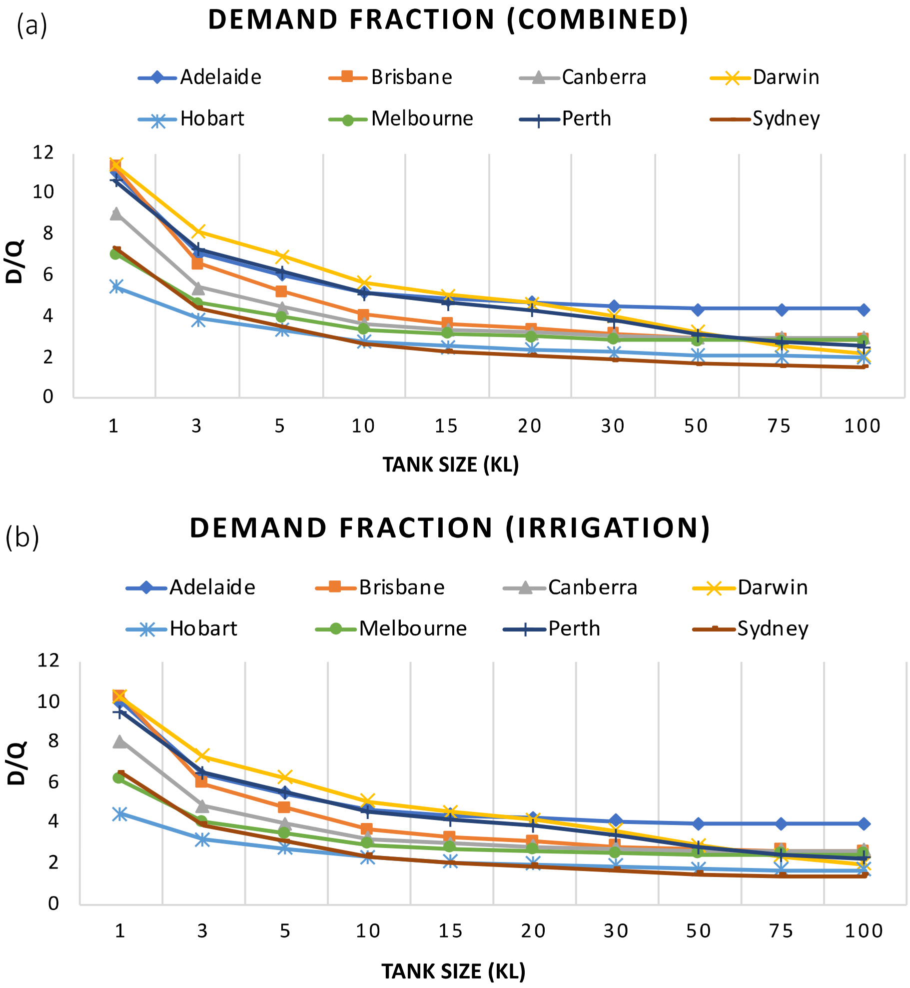

Figure 8. Demand fraction (D/Q) vs. tank size for all eight locations with respect to two water demand types: (**a**) combined use; (**b**) irrigation use.

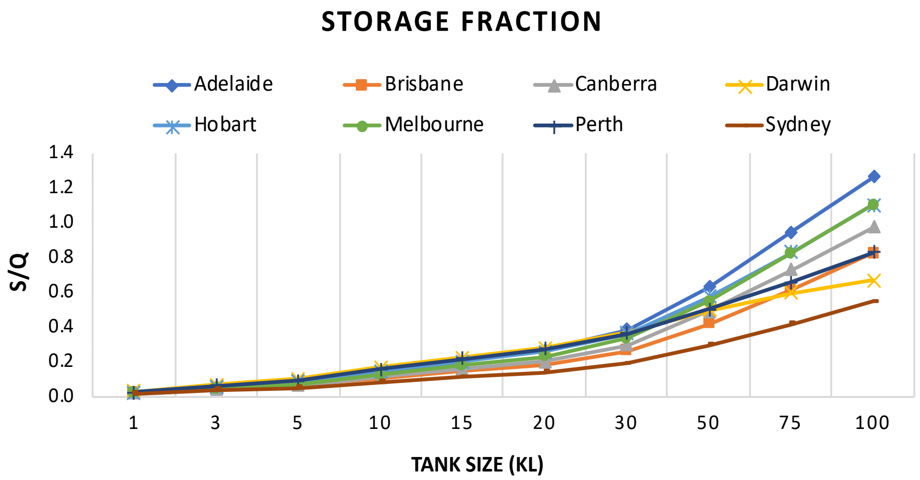

Figure 9. Storage fraction (S/Q) vs. tank size for all eight locations.

4.4. Monthly Water Demand Analysis

Figure 10 shows number of days in a month when most of the water demand was met for different cities. Water demand for Darwin is hardly met for the months of June to August (winter season) for TLD use for all three tank sizes. This is due to very low monthly average rainfall from June to September for Darwin. For irrigation and combined use, water demand is not fully met, like TLD, due to a higher requirement. For Brisbane and Darwin, water demand is hardly met in the winter months, i.e., June to August.

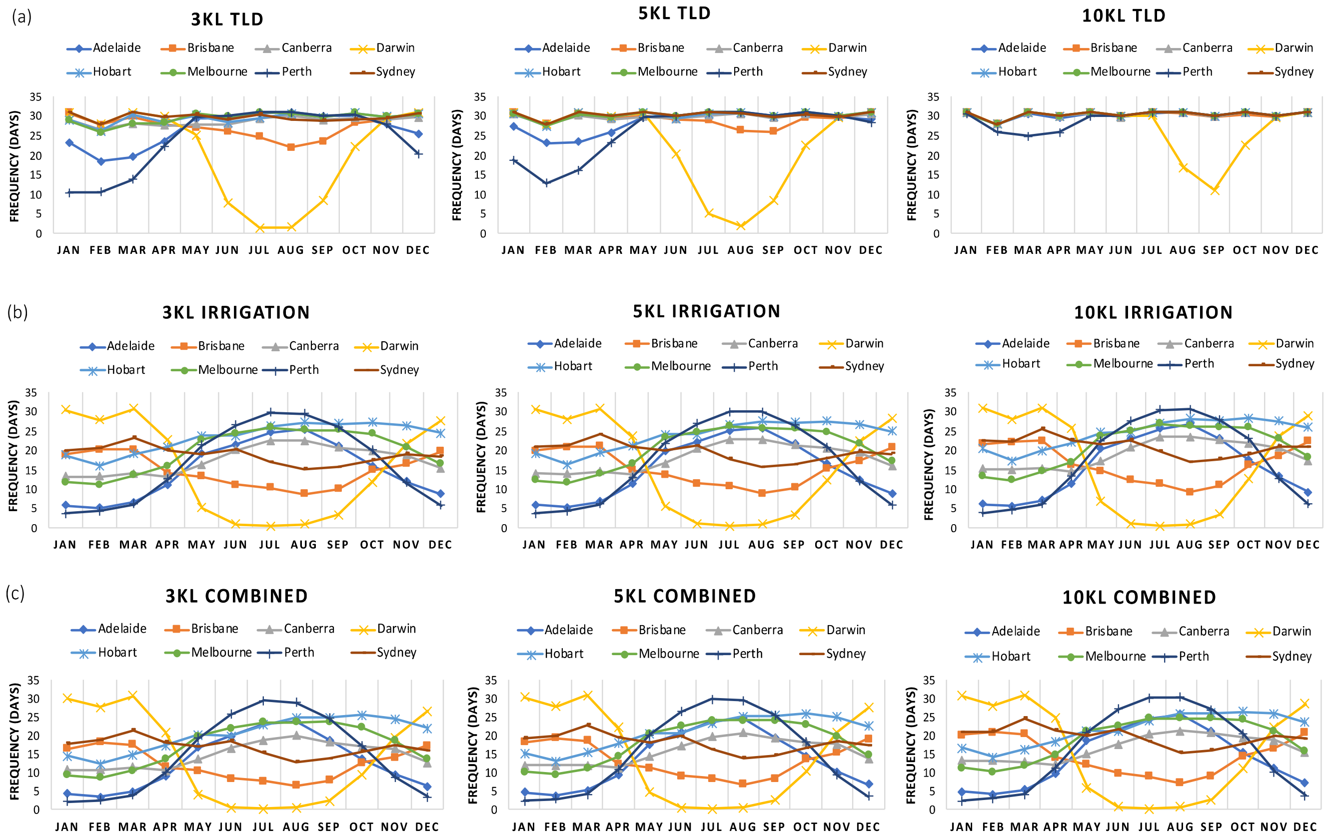

Figure 10. Charts showing number of days when monthly water demand is met for 3, 5 and 10 m^3 rainwater tanks for three different water demands: (**a**) TLD use; (**b**) irrigation use; (**c**) combined use.

The average monthly rainfall trend for all the eight cities is shown in Figure 11. When compared to other cities, Darwin and Perth have the highest variation over the year. Based on the daily rainfall data of the identified driest, wettest and average years on record, the rainfall, reliability and water savings of the RWH system at all the locations for a 10 m^3 tank and combined use were determined as shown in Table 2. For combined use, reliability ranges from 22 to 55% for the driest years, 34 to 76% for average years and 54 to 91% for the wettest years. Among all the locations, Brisbane has the lowest reliability (22%), while Hobart has the highest reliability (91%). Although water demand changes from year to year, in particular, the demand in earlier years (e.g., in the 1950s and 1960s) was smaller than in recent years; however, for simplicity, we have assumed a constant water demand throughout the whole study period.

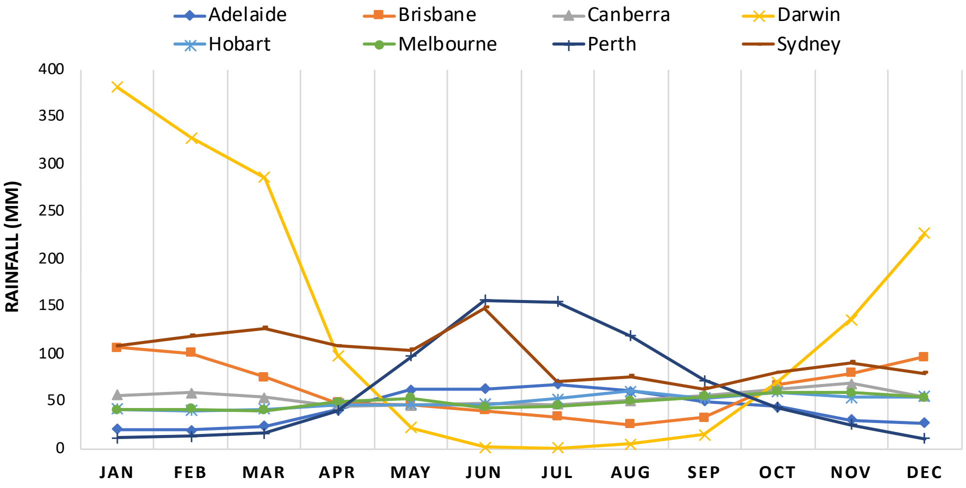

Figure 11. Average monthly rainfall for the selected eight cities.

Table 2. Summary of dry, average and wet year rainfall, reliability and water savings for different cities (10 m^3 combined use).

City	Dry				Average				Wet			
	Year	Rainfall (mm)	Reliability (%)	Water Savings (m^3)	Year	Rainfall (mm)	Reliability (%)	Water Savings (m^3)	Year	Rainfall (mm)	Reliability (%)	Water Savings (m^3)
Adelaide	2006	270	28	39	1987	510	34	78	1992	832	54	104
Brisbane	2019	230	22	28	1966	753	41	106	1950	1241	67	99
Canberra	1957	295	25	44	1988	648	55	80	1950	1066	64	105
Darwin	1985	934	43	67	1947	1574	51	84	1974	2244	60	57
Hobart	2006	347	55	55	1983	598	51	75	1946	1004	91	57
Melbourne	1997	308	28	44	2004	592	76	63	1992	871	84	67
Perth	2006	480	43	53	1962	761	54	36	1955	1165	63	52
Sydney	1957	620	42	76	1985	1176	55	133	1950	1944	87	120

4.5. Economic Analysis

Figure 12 shows the summary of the benefit–cost ratios (BCRs) of RWH systems for all three water uses for eight different locations. It shows whether the intended RWH system is economically viable or not. If the BCR value is less than one, it means the RWH system is not financially viable. The benefit comes from water saving, which counteracts the capital and operating costs of the RWH system. The BCR indicates the most financially viable tank size for a particular water use in a particular city. To maximise the viability of the RWH system, the maximum amount of water needs to be saved. The point when the BCR crosses one is known as the payback period. For TLD use, the BCR value decreases as tank size increases from 1 to 100 m^3. From Figure 12a, it is found that Hobart shows the lowest BCR values for all the tank sizes in the range from 0.1–0.22, while Canberra shows the highest BCR values in the range 0.35–0.76. Similarly, for irrigation and combined use, Hobart shows the lowest BCR values while Canberra shows the highest BCR values.

Figure 12b shows that the BCR exceeds 1 for only four locations: Brisbane, Canberra, Perth and Sydney. Melbourne and Adelaide also show BCR values over 0.6 for all the tank sizes, except 1 kL, which is less than 0.6. By examining the three tables below it is found that for all the three water uses, BCR values are much lower than 1 for Darwin and Hobart for all tank sizes from 1–100 kL, which is due to the lower water price for these locations. Therefore, it is not financially feasible to implement RWH systems in these cities.

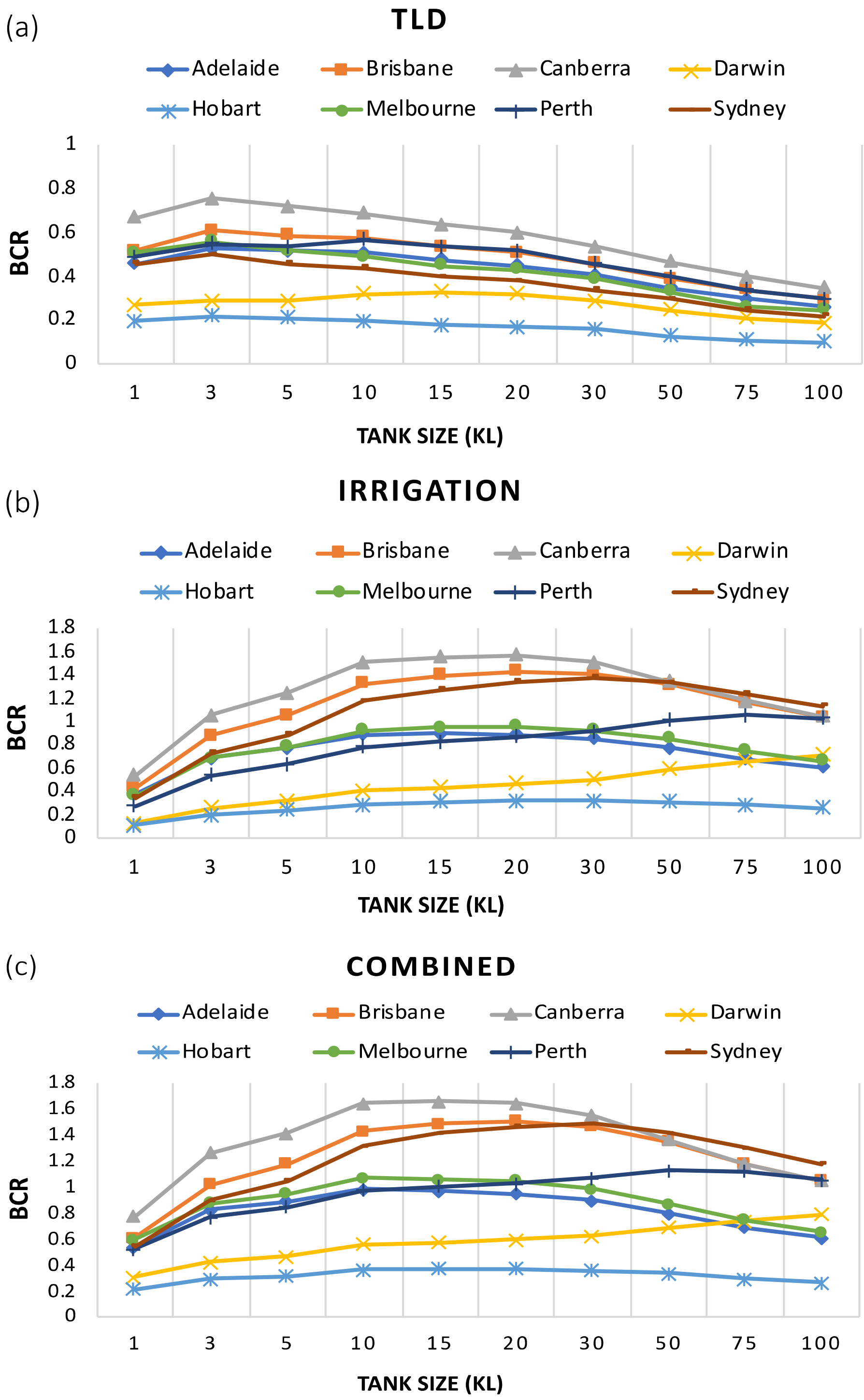

Figure 12. Plots showing BCR values of rainwater harvesting system for three water uses: (**a**) TLD use; (**b**) irrigation use; (**c**) combined use.

The financial effectiveness of an RWH system is also affected by various factors such as water requirements, climate condition and rainfall variability. For example, Ali et al. [27] conducted a study to assess the financial feasibility of an RWH system under five climate conditions in eight cities in Pakistan. It was found that RWH systems with a large tank size was not able to generate higher benefit–cost ratio values due to higher capital cost and functional investment. Similar to Ali et al. [27], we found that BCR values are generally small for bigger tanks. Hazani and Rahman [49] carried out financial analysis for peri-urban regions of Greater Sydney, Australia and found that the benefit–cost ratio decreases with increased tank size for toilet and laundry use. Our findings agree with Hajani and Rahman [49], i.e., the bigger the tank size, the smaller the BCR values. Khan et al. [47] examined the financial viability of an RWH system for the whole of Australia considering data from 601 rainfall stations. Results showed that the benefit–cost ratio of the RWH system exceeded one for only four sites in southeast Australia. BCR values were found to be smaller than 0.25 for most of the sites in the middle of Australia (arid region). The water price needs to be increased three times to make an RWH system feasible for eastern Australia, the coastal part of south Australia and the southwest of Western Australia. Similar to Khan et al. [37], our study also finds that BCR values are smaller than 1 in most of the cases. It should be noted that water demand plays a great role in financial analysis. The main reason for much lower BCR values for TLD use is due to lower water demand, for example, in Brisbane, the BCR for a 10 m3 rainwater tank is 0.58 when rainwater is used for toilets, whereas it will increase to 1.33 when used for irrigation. The lower BCR value for TLD use is due to the lower water demand which means collected rainwater is not fully utilised and therefore reduces the profits attained by the RWH system. Furthermore, BCR is much less than 1 for Hobart for all the three water uses, which is due to the low water price for Hobart. Therefore, to make the RWH system economically viable for Hobart, the water price needs to be at least doubled.

The breakdown of the different cost components is shown in Figure 13. It can be seen that the replacement cost represents the main component with 50%, whereas the rainwater tank cost is the second component (20%). It should be noted that for this analysis, the lifespan of an RWH system is considered to be 40 years, with a 2.5% inflation rate and a 5% interest rate.

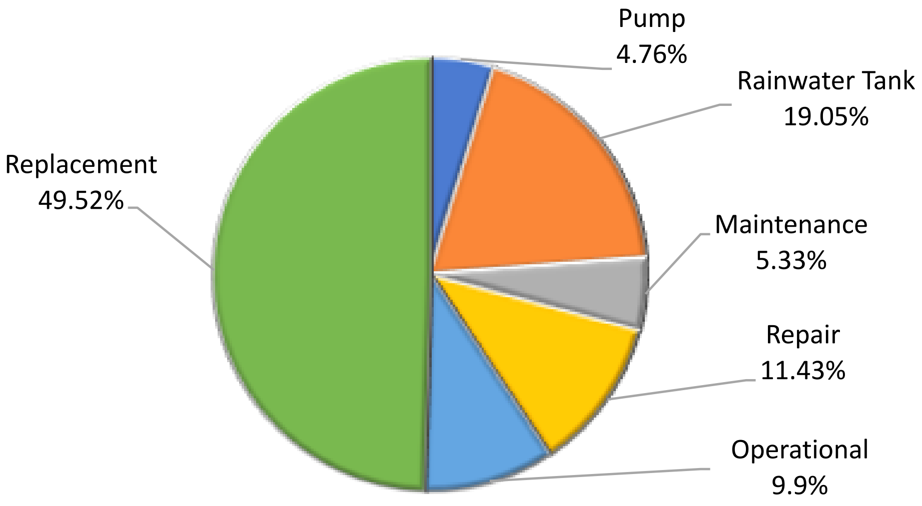

Figure 13. Breakdown of life cycle cost.

5. Conclusions

The results show that for toilet and laundry use, reliability is quite high (88–99%) for each city if the tank size is in the range of 10–100 m^3. Among all eight locations, Darwin has the lowest reliability (88%) and Sydney has the highest (99%) for a 10 kL tank size. It is also found that for all the locations, an increase in tank size increases the reliability for up to a 10 m^3 tank size and, beyond that, reliability tended to reach a constant value. Usage of tank volumes larger than this constant volume will not be economical, while for combined use (toilet, laundry and irrigation use), the demand is quite high, which results in less system reliability for all the locations across Australia. It is found that Adelaide shows the lowest reliability in the range of 38–49% for all the ten tank sizes while Hobart shows the highest system reliability in the range 61–77%.

Economic analysis showed that BCR values decrease as tank size increases for toilet and laundry use. For all the three water uses, Hobart shows the lowest BCR values for all the tank sizes while Canberra shows the highest value. It is found that for all the three water uses, BCR values are much lower than 1 for Darwin and Hobart for all tank sizes, which is due to the lower water price for these locations. Therefore, it is not financially feasible to implement an RWH system in these cities with the current water price. It should also be noted that water demand plays a great role in financial analysis. The lower BCR value for TLD use is due to the lower water demand, which means collected rainwater is not fully utilised and therefore lowers the financial return from an RWH system. For a sustainable and viable RWH system, the economic analysis highlighted that choosing the right tank size is critical for achieving high water saving efficiency and maximising the initial investment's return.

Furthermore, this research has also illustrated significant water savings from town water supplies which can be achieved from an RWH system even in dry periods for Australia. Some cities such as Darwin with higher annual rainfall, but with well-defined months of low rainfall, do not achieve a high potential for water savings and end up requiring larger rainwater storage tanks. It was also noted that the sizing of the rainwater tanks is influenced by a number of factors, including catchment area, number of households, water demand and rainfall.

Future research should focus on using hourly rainfall data instead of daily rainfall data. Monte Carlo simulation should also be adopted to account for the inherent variability in the input variables such as rainfall, water demand and loss characteristics. Additionally, smaller cities in Australian arid regions, which cover about 75% of the continent, should be considered in future studies to evaluate the feasibility of an RWH system.

Author Contributions: P.P. wrote Python code to carry out the formal data analysis, conducted all the data analysis and prepared the first draft of the paper. A.R. proposed the conceptual framework of the study, checked results and enhanced the writing of the paper. All authors have read and agreed to the published version of the manuscript.

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