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The influence of irrigation area and roof size on the economics of rainwater harvesting use in urban agriculture: A case study in Sydney, Australia

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Abstract: *Urban agriculture and Rainwater Harvesting (RWH) have grown in popularity in recent years. The economic viability of RWH systems has been reported with various outcomes. The water demand profile is complex and of all domestic demands, outdoor irrigation use is the most variable and potentially the largest domestic use of potable water. Water for gardening, toilet and laundry does not need the high level of treatment that drinking and cooking water requires. The amount of water a RWH system can supply for these uses is influenced by the rainfall pattern, tank size and roof area. A versatile economic evaluation tool named ERain has been developed to analyse the economics of various RWH system arrangements. ERain combines performance analysis using daily rainfall data with life cycle cost analysis. Here ERain has been used to assess the effects of varying roof size or irrigation area on the economic viability of RWH systems for tank sizes ranging from 1-7kL. Results show that excluding outdoor use, the benefit cost ratio (BCR) increases with roof size along with reliability, while efficiency decreases. Interestingly, the larger roof area has the most significant effect in terms of reliability on the smaller tanks. Including outdoor use reduced reliability overall but increases both the efficiency and BCR indicating that it is better financially to use the RWH system for outdoor use when reliability is not a concern. The larger NPVs and BCRs occur with the larger irrigation areas as this increases water use and hence monetary water savings. Within the 1-7kL tank range, the 7kL tank is the most favourable when outdoor irrigation use is connected.*

***Keywords**: Rainwater harvesting, Economic analysis, Rainwater tank, Tank size, Roof area.*

1. Introduction

Rainwater harvesting (RWH) from roof tops as a result of the millennium drought has become a significant feature in Australia (van Dijk et al., 2013). About 34% of households in Australia have adopted RWH systems which is the highest adoption rate in the world (Beatty and McLindin, 2012). With this has come a significant amount of research and installation guidelines from various sectors including universities, government and other research organisations such as Commonwealth scientific and industrial research organisation (CSIRO). For example, in 2008 the Master Plumbers and Mechanical Services Association of Australia (2008) developed and published a Rainwater Tank Design and Installation Handbook (HB 230-2008) for regulatory authorities, installation professionals and homeowners. In 2010 the Environmental Health Committee produced a timely revision of the 2004 Guidance on use of rainwater tanks (EnHealth, 2010) in response to the ongoing interest in using RWH systems. Various rebate schemes were introduced which have now been reviewed by several authors and government departments (Gato-Trinidad and Gan, 2014; Hall, 2013). RWH reports were prepared for the prime minster and cabinet. In many cases, RWH systems have been mandated for new constructions. In NSW, for example, they were included in Building Sustainability Index (BASIX) requirements. Now we are starting to see reviews of RWH system used globally (Amos et al., 2016; Campisano et al., 2017; Sharma et al., 2016). Since the drought has eased in Australia, and in Sydney particularly, there appears to be a reduced interest in RWH systems, and the desalination plant has also lost its spotlight. BASIX compliance records from 2005 to 2015 (BASIX, 2016) reveal this current trend. However, internationally there is heightened interest in RWH systems and Australia has been criticized for its weak water security (Beatty et al., 2009; Burton et al., 2015), so it is likely that RWH systems will continue to grow across Australia.

Urban agriculture is also on the increase in Australia due to the increasing cost of food and other social trends (Russ Grayson, 2017). Local councils are encouraging the practice and providing guidelines on how to do practice forms urban agriculture in various ways (Sydney, 2017) and gardens along roadsides are becoming popular in the inner city (Marshall, 2017). Urban agriculture may be defined as "agriculture within an urban or peri-urban setting" (Hamilton et al., 2014). As well as vegetables and fruit trees, it can also encompass bees and animal production, such as chickens, and fish in Aquaponics (Orsini et al., 2013). Various countries have already been quite successful in urban agriculture. Cuba has become a world leader in urban agriculture and has developed a system called "organoponics" (Eigenbrod and Gruda, 2015; Orsini et al., 2013), Mexico City produces 20% of its own food (Dieleman, 2016). In many developing countries, home gardens supply family their food, and important nutrition (Gallaher et al., 2013), and to some extent - income (Jayasuriya et al., 2014). There are growing demands to increase urban agriculture (Corbould, 2013; Eigenbrod and Gruda, 2015; Orsini et al., 2013; Suparwoko and Taufani, 2017) to avoid the "food deserts" present in some American cities (Beaulac et al., 2009; Horst et al., 2017; Walker et al., 2010) where fresh vegetables simply aren't available locally (Eigenbrod and Gruda, 2015; Smith et al., 2013). Measuring up against Goal 11 of the United Nations' sustainable development goals (SDGs), cleaner and sustainable cities, most - if not all countries - will come short. Australia, although a developed country, does not meet Goal 3 (health and well-being) due particularly to increased diabetes. Urban agriculture as a healthy pursuit can help alleviate this by increased activity, healthier foods and building awareness. Concurrently, in recognition of water shortages, there is a trend in Australia towards using native plants that naturally have a lower water use than many imported ornamentals (Josh Byrne & Associates, 2013). Urbanisation, population increase and changing climates are increasing competition over water resources and arable land worldwide (Corbould, 2013). Urban Agriculture can alleviate the food demand to some degree, but as with the concept of greening cities, this will also increase the water demand. Roof RWH in urban areas may then be able to meet some of this increased water demand. An important question is to what extent roof RWH can provide this water and what are the economic implications of using it to do so.

The economic viability of RWH systems has been reported with various different outcomes, predominantly at a cost, however some report a positive financial evaluation. Assessing the viability of RWH systems faces a number of challenges. Firstly, proper evaluation of the lifecycle costs particularly of the maintenance and replacements costs which are often neglected. Secondly modelling the systems performance is difficult and often based on various assumptions about water consumption, and a standardised site (roof area and tank size particularly). Irrigation and outdoor use is potentially the most variable household water use, with some owners using virtually no water outdoors, to others using large amounts, especially when there are no restrictions in place. The quantity of water available for harvest is influenced especially by roof area supplying the RWH system (its catchment). Roof area can vary considerably with the size of the house, or because parts of the roof are unsuitable for harvesting (e.g. due to overhanging trees or the practicality and/or cost of the guttering arrangement). The rainfall pattern, tank size and water demand profile will also affect how much water can be harvested. Irrigation use particularly will be influenced by the rainfall and the season.

Most studies use a standard roof size and quantity of water used for irrigation. The Australian Bureau of Statistics (2013) reported that in NSW approximately 48% of people use mains water to irrigate. Here we have developed a versatile economic evaluation tool named ERain to investigate the effect of varying roof size and irrigation water use on RWH system performance and the economic viability. ERain combines performance analysis using daily rainfall data and various water demand profile data with a detailed life cycle cost analysis based on AS/NZ Standard AS4536 "Life Cycle Costing – an Application Guide" (Standards Australia, 2014). Model outputs include both performance and economic indicators which can be compared. Economic measures reported include the benefit cost ratio (BCR) and net present value (NPV) and performance indicators include reliability (% of days the demand is met) and efficiency (% of available water used – i.e. not lost to overflow). ERain is designed to be flexible and to be able to account for all the aspects of costs involved, anticipating that innovation will be an ongoing feature of RWH system design and urban agricultural methods for some time to come (Kongo and Jewitt, 2006). System configurations will be greatly affected by Innovation and this will have a direct impact on economics (Gabrielsson et al., 2018; Getnet and MacAlister, 2012; Melville-Shreeve et al., 2014). One of today's challenges is to make RWH economically viable. It is hoped that developments in Australia can contribute towards meeting SDG goal 2 zero hunger, and goal 6, clean water and sanitation, in developing countries. The technological achievement of putting man on the moon 50 years ago in 1969, should be matched with providing the basic needs of man.

In this study ERain has been used to assess the economic implications of varying the roof size, and the irrigation area of RWH systems with tank sizes ranging from 1-7kL. Parramatta, the geographical centre of Sydney, Australia, has been used as the study site.

2. MATERIALS AND METHOD

2.1. Scenarios

This study considers a single occupancy house in Parramatta with 4 occupants. Site dimensions are similar to those used in previous studies (Hajani et al., 2013; Rahman et al., 2012). In order to reflect the tendency towards smaller lot sizes, the overall site area is reduced from 450 m^2 to 400 m^2 and the nominal landscaped area from 150 to 120 m^2. However, a variety of landscape areas, namely 40, 80, 120, 160 and 200m^2, are modelled to account for variation in water use. In Sydney currently, while plot sizes are decreasing, house sizes are increasing and so an average roof area of 200 m^2 was chosen and a variety of roof areas, namely 100, 150, 200, 250 and 300m^2 were modelled to account for variation in the roof sizes and connection.

The RWH system is commonly used for the toilet and Laundry, with and without irrigation, and outdoor use. Tank sizes ranging from 1-7 kL were considered for toilet and laundry type connections and tanks sizes up to 15kL when irrigation use is included. This size range reflects the tank sizes commonly installed to fulfil or exceed the BASIX legislation requirements. The majority of tanks are in the 0-2kL, and 2-3kL range, with a few being larger than 10kL in the Parramatta area. For cost analysis, “Slimline” tanks have been assumed as these are the most common in urban areas where space is limited. Losses of 1mm per square meter of roof area, a first flush volume equivalent to the first 0.5mm of rain and a mains top up level of 5% of the tanks volume are adopted.

2.2. Rainfall Data

The Rainfall data from 1965 – 2015 for Parramatta (Station No. 066124), was used in this study (Table 1).

Table 1 Summary of daily rainfall data

Country	Location	Type	Rainfall station	Period of rainfall record	Average annual rainfall (mm)	5^{th} Percentile (mm)
Australia	Parramatta	Urban	066124	1965 - 2015	964	612

2.3. Water Demand Profile

The profile chosen in this research was designed around looking at each specific water use and calculating estimates for each starting with quantities obtained from the Reece Sustainable Bathroom Guide and the distribution of water use between uses reported by Kuczera et al. (2003). The overall usages that these specific values yielded were then compared with the averages given by Sydney water, 297 L/p/d (litres per person per day). This resulted in an average consumption of 172 L/p/d excluding outdoor use (which varies and is ultimately shared between the occupants) and a maximum outdoor use of 1233 L/household. Toilet use is based on two full flushes and one half flush of a 3 star toilet per person/day, resulting in 23.5L/p/d. Laundry use is based on 3 loads for every 2 people each week in a 3 star washing machine, resulting in 150 L/p/week or approximately 10.7L/p/d. Outdoor uses include washing one car per household every 2 weeks, at 180L/wash, and a low estimate for washing hard surfaces of 8min per week (at 18L/min), resulting in 20L/day, assuming that some people may also water the garden or wash the car at the same time. Irrigation use is calculated at 10mm depth of irrigation per household per day multiplied by the irrigation area assumed for the property (generally 120m^2) giving 120m^2*10mm = 1200L/household/day, which is comparable with assumptions used in other studies (Hajani et al., 2013; Rahman et al., 2012). A sprinkler may use 1000L/hr so it is not unreasonable to think that a property may have 2 sprinklers running for 30-40 min per day which would result in approximately the 1200L of water as assumed in this study. Irrigation is assumed to stop when there are consecutive days of rain. Variation in irrigation use between users is modelled by changing the area of irrigation considering 40, 80, 120, 160 and 200m^2.

2.4. Economic Inputs

Interest and inflation (other than water) were considered as 4.6% and 2.5% respectively from the WACC biannual update report for the water industry produced by Independent Pricing and Regulatory Tribunal (IPART).The primary benefit of the RWH system is the monetary value of the water saved. This is calculated using the annual average amount of water saved, found by the daily analysis and summary modules, multiplied by the current water price of $2.28/kL (including a service charge of $114.04). Prices were obtained from Sydney water's prices for customers 2015 and compared with a recent water bill. The water inflation rate was taken from prices for customers between 2016-2020. Costs have been categorised according to AS/NZ 4536:1999 Life cycle costing - An application guide (Australian Standard, 2014). Predominantly the Acquisition and Use and Maintenance Support categories were considered while renewal and adaption and disposal were not.

Table 1 Acquisition costs

Cost Code	Details	units	per unit	Total
	Catchment and Drainage System			
1104	Roof Treatment to adequate standard		-	
1104	Downpipes to tank	1	$43	$43
1104	Guttering		-	
	Tank			
	Tank volume (kl)=(m^3)	3		
	Tank slab area	2.2		
3101	Cost of land /m^2	2.2		
3102	Levelling ground (m^2)	2.2	$13.87	$32.89
3103	Concrete base for tank (exc.labour) (m^2)	2.2	$104.22	$247.16
3104	Tank Cost	1	$910	$0.00
	Water Treatment			
1104	Gutter and downpipe screening	1	$15.00	$15.00
1104	Tank and inlet screening, passive treatment, outlet height			
1104	First Flush device	1	$17.00	$17.00

2.4.1. Life Cycle Phase A – Acquisition

The variety in types of RWH installation leads to a number of complex issues when it comes to costing. For example, the level of advice that may be used to design the system is a costing issue that is often neglected. In this analysis the focus has been the effect of tank size on the economic viability of the system. For this reason, an average price was adopted for most aspects of the system while special attention was given to costs that vary with different size tanks. Prices were obtained from various suppliers and compared with Cordell and Rawlinsons (Rawlinsons, 2015; Solutions, 2015) where they had comparative pricing. The hourly rates for the various trades were taken as the average values given in "Payscale" - an online guide for trade rates. An example of some of the capital costs are shown in Table 1, labour costs are included elsewhere. The red highlighted section shows the values that vary with tank size.

2.4.2. Life Cycle Phase B – Use and Maintenance Support

Dividing the RWH system into separate sections helps identify the various maintenance issues. These costs occur on a scheduled basis rather than at acquisition. Repair and replacements are considered to carry more cost to the owner than general maintenance which the owner is assumed to do himself. The pump is assumed to run for 2 hrs/day using 0.9KW/h at $0.2122 per kWh.

2.5 Method: "ERain" Analysis Tool

ERain combines performance analysis with economic analysis using daily rainfall data, economic data and scenario inputs. It was originally developed as a spread sheet model and has been upgraded using FORTRAN and RScript programming in conjunction, with information from extensive literature reviews on both RWH (Amos et al., 2016) and Urban Agriculture (Amos et al., 2018). The basic model parameters are shown in Figure 1. ERain uses the yield after spillage model (YAS) which Fewkes et al. (2000) deem to be more conservative than a yield before spillage model.

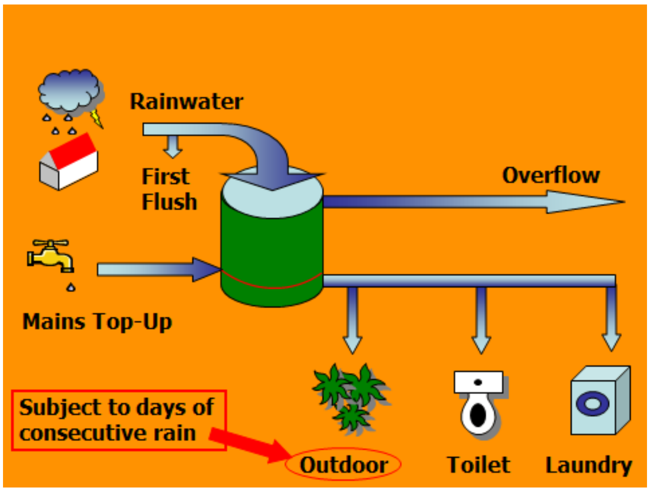

Figure 1. ERain basic parameters model

Following the guidelines in AS/NZ 4536:1999 Life cycle costing - An application guide (Australian Standard, 2014) ERain includes all aspects of a product's life cycle and presents the benefit cost ratio (BCR), and net present value (NPV) standardised to Australian Dollars (AU$), using the concept of Present Value (PV).The PV is calculated as shown in equation 1:

$$\text{Discount rate} = \frac{1}{(1+i)^t} \quad PV = \frac{CF}{(1+i)^t} \tag{1}$$

Where, CF is the cash flow, i the interest rate, and t the year in which it occurred. The NPV is defined as the sum of PVs over the project and is calculated as shown in equation 2:

$$NPV(i, N) = \sum_{t=0}^{N} \frac{CF_t}{(1+i)^t} \tag{2}$$

Here CF is the difference between cash inflow and outflow reduced by the discount rate appropriate to the time (t) of transaction. N is life cycle length (years). Equation 3 shows how the benefit-cost ratio (BCR) is the sum of discounted costs (C) divided by the sum of discounted benefits (B) as they occur at time (t) over the project lifecycle length N:

$$BCR = \frac{\sum_{t=0}^{N} \frac{C_t}{(1+i)^t}}{\sum_{t=0}^{N} \frac{B_t}{(1+i)^t}} \tag{3}$$

In summary the NPV is the sum of benefits minus the sum of costs over the project's lifecycle. BCR is a ratio of the benefits and costs. The BCR being a ratio is sometimes considered by analysts to be inaccurate (Cbabuilder, 2016). A basic understanding of basic economics is required to understand the implications of BCR and NPV.

The two main measures of system performance reported by ERain are reliability and efficiency. Reliability is defined as the percentage of days that the demand was met. Efficiency is defined as the percentage of available water used. Among other things, the Efficiency indicates if a greater tank size could help yield more water from the given roof area.

3. RESULTS AND DISCUSSION

3.1. BCR of roof size for a toilet and laundry only installation

Results from varying roof areas for the various tank sizes are shown in Figure 2. For the 3kL tank, the reliability and BCR increase with roof size while the efficiency decreases. Even with a small roof area, only 30% of the available water is being used with this type of installation. With larger roof areas the efficiency decreases to only 10%, however the system is quite reliable at over 70%. The increase in roof area has the largest effect on efficiency when the tank is small. For example a 1.1kL tank's reliability increases by10.6% from a minimum of 61.4% to max of 72%, while for a 7kL tank the equivalent increase is only 4.5% from 95.1% to 99.6%. This influences the NPV and BCR results. For example, the NPV of a smaller tank (1.1kL) with a large roof (300m^2) has a less negative NPV than a larger tank (3kL) with a smaller roof (100 m^2).

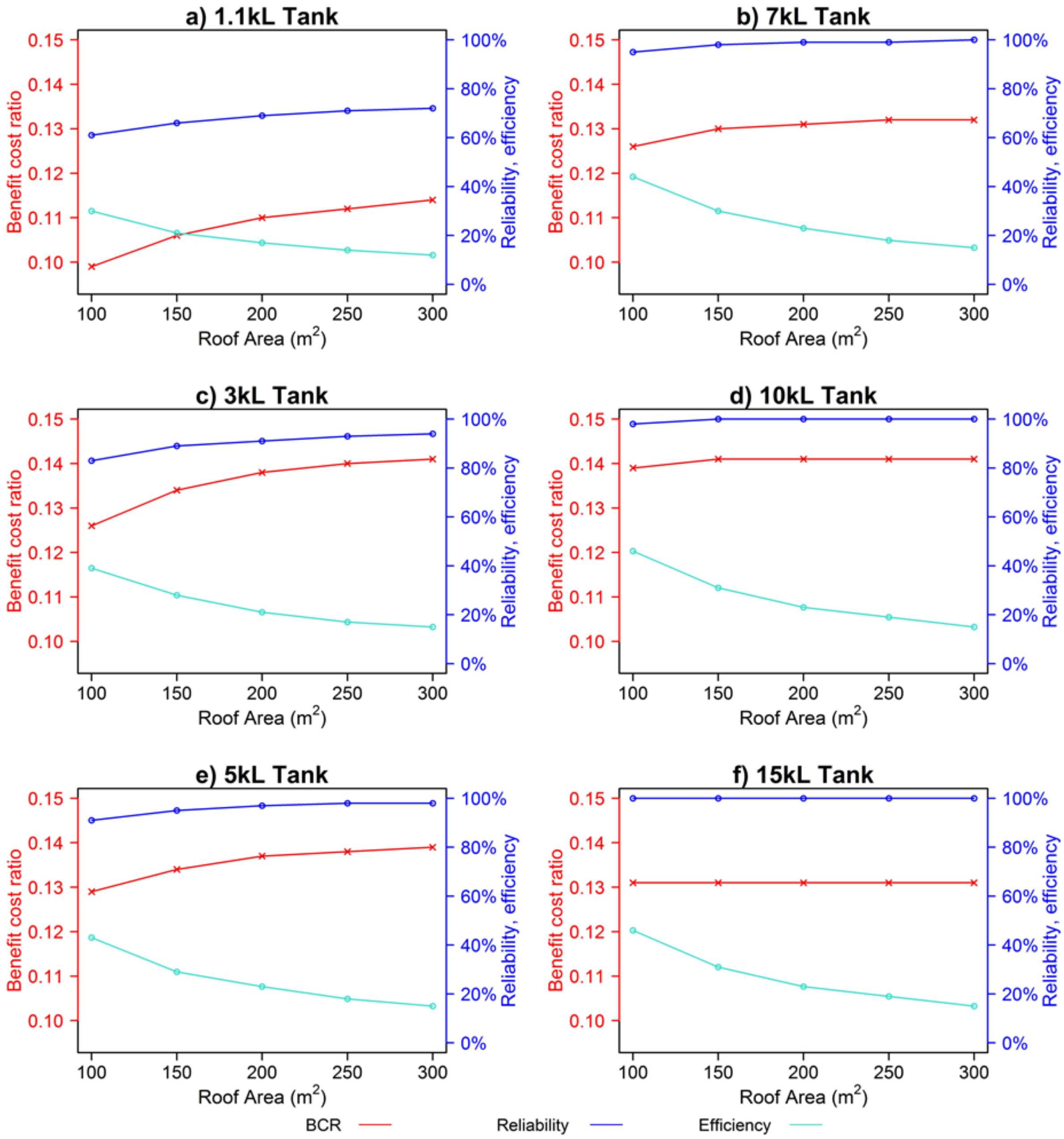

Figure 2 Roof area vs. BCR, reliability and efficiency for toilet and laundry use

3.2. BCR of roof size for a toilet, laundry and outdoor installation

As expected, system reliability is reduced by connecting irrigation while the efficiency increases and so does the BCR, as seen in Figure 3. Therefore, financially, it is an advantage to use the harvested rainwater for irrigation, particularly when mains water is connected as a backup, as it usually is in the urban environment, and where reliability is not an issue. The larger roof catchment means that the smaller rainfall events harvest a more substantial quantity of water and help refill the tank, increasing reliability. The efficiency decreases mainly due to increased overflows, and particularly with the larger rainfall events. If we again compare the results for the 1.1kL tank and 300m^2 roof with a 3kL tank and 100m^2 installation, we find that NPV is now more negative where for the toilet and laundry only installation above the opposite was true. For a toilet and laundry only installation, reliability is quite high even with a smaller tank, and so a larger tank does not increase reliability much. Once outdoor use is connected however, reliability reduces, leaving room for greater increases in reliability with a larger tank size. The highest NPV is still negative ($16657) and the BCR less than 1. Interestingly the highest (least negative) NPV occurs with a 10kL tank, while the highest BCR is 0.355 with a 15kL tank. It appears that compared to the NPV, the BCR will generally imply that a larger tank size is more economically viable.

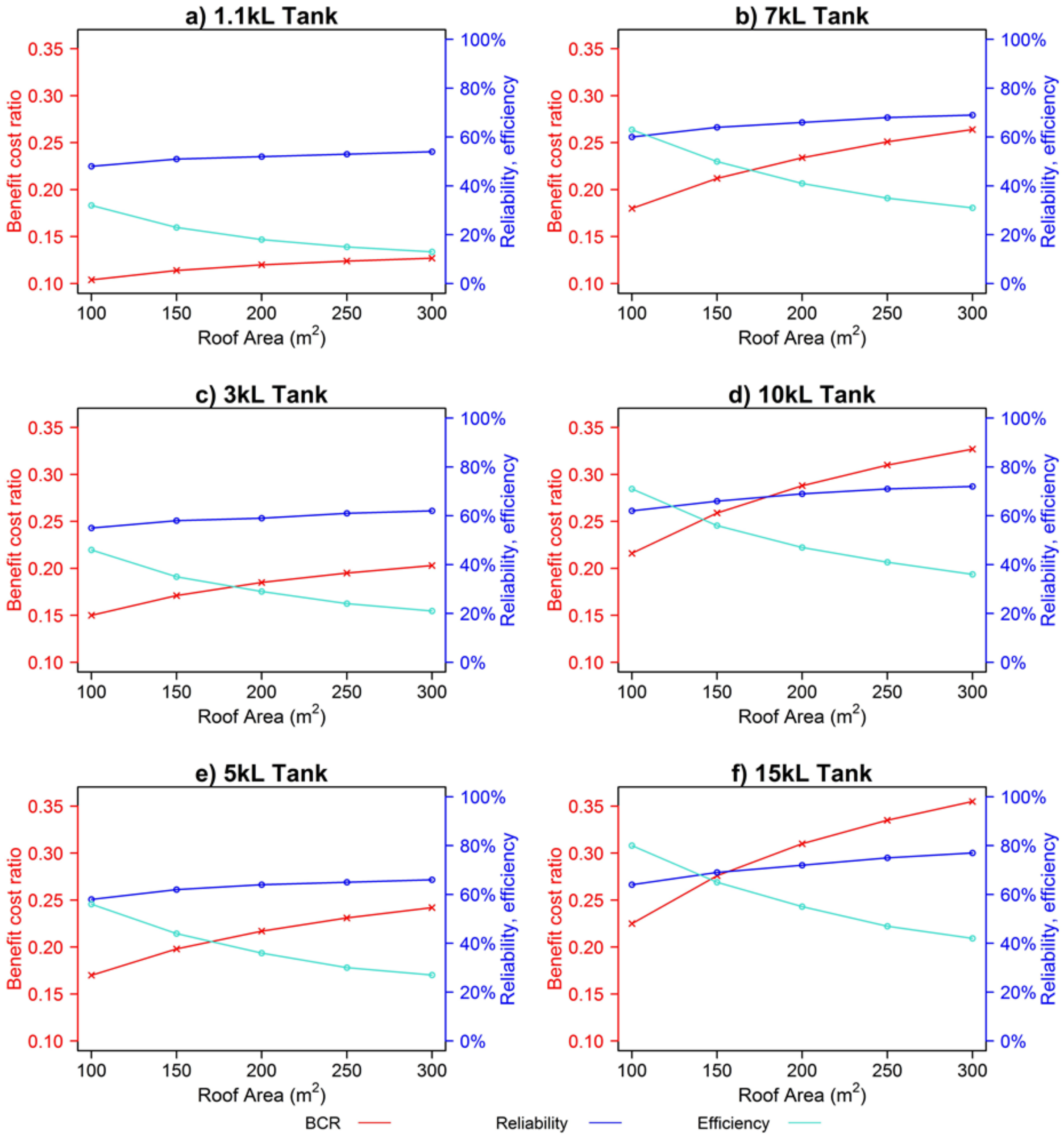

Figure 3 Roof area vs. BCR, reliability and efficiency for toilet, laundry and outdoor use

3.3. Various irrigation areas for a toilet and laundry and outdoor installation

Results for varying irrigation area with a set a roof area of 200m^2 are shown in Figure 4. For the smallest tank, there is a slight increase in the BCR when increasing the irrigation area from 40 to 80 m^2, but for larger irrigation areas there is no significant increase. The efficiency and reliability are virtually unchanged implying that the RWH system has already reached its capacity to supply water with a small area being irrigated. The larger 3kL tank has a higher BCR for any irrigation area, and also shows a greater increase in BCR with irrigation area. Efficiency increases only slightly to a maximum of 30%, again implying that the system is already at its capacity to supply water at the lower irrigation areas, while reliability declines to 60% with the larger irrigation areas. The low efficiency means that lots of water is being lost to overflow. The 5kL tank has

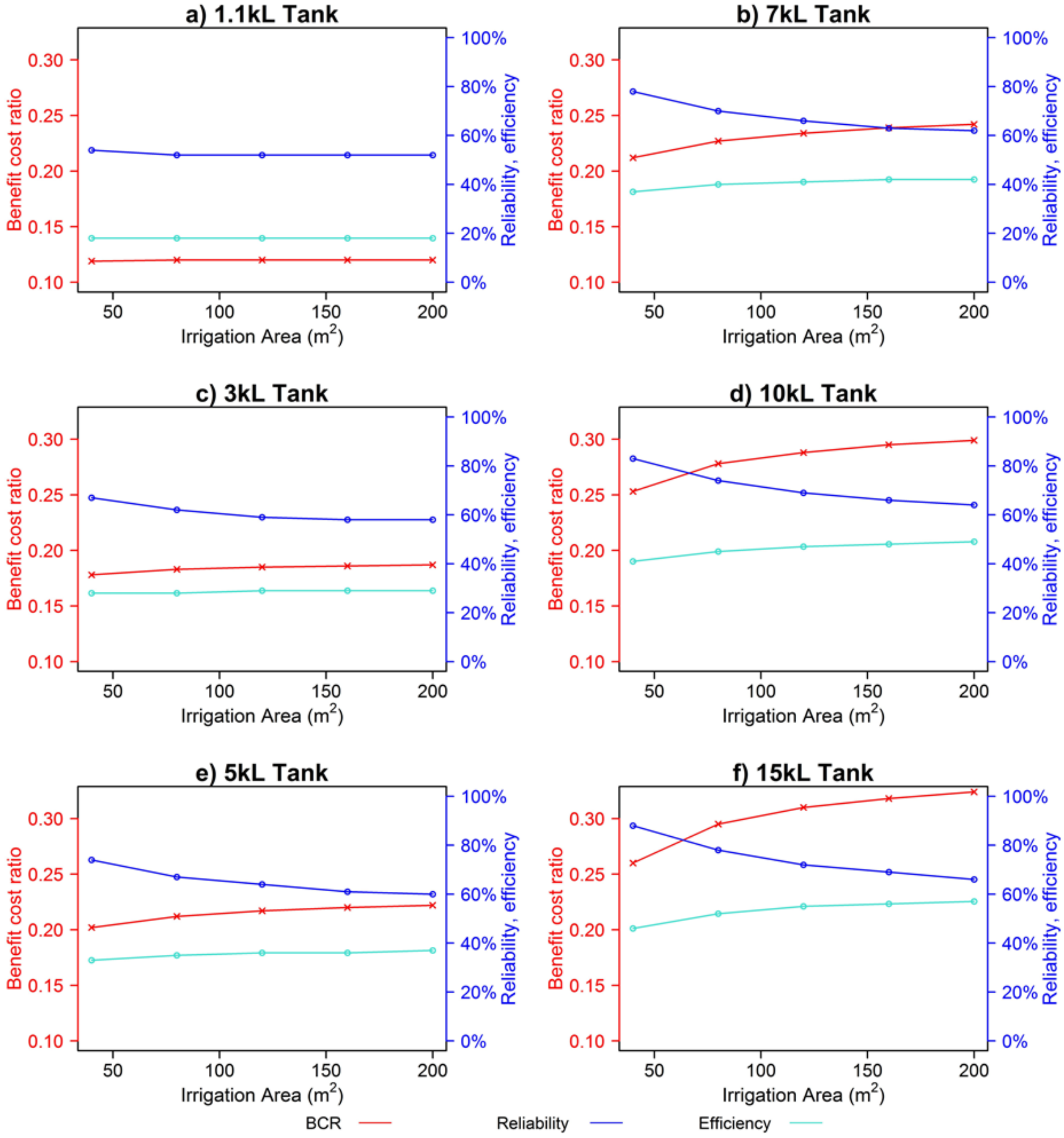

Figure 4 Irrigation area vs. BCR, reliability and efficiency for toilet, laundry and outdoor use

higher BCR than both the 1.1 and 3kL tanks for all areas of irrigation and corresponding higher efficiencies and reliabilities. The relatively small increase in efficiency, and low reliability, implies that the 5kL tank system is again close to capacity to supply water. Exploring larger tank sizes' results showed that larger NPVs and BCRs occur with the larger irrigation areas as this increases water use and hence monetary water savings. The highest BCR was found with a 15kL tank; while the highest (least negative) NPV occurs with a 10kL tank. These results could be affected if future rainfall patterns do not reflect the historical data that is available for, only, the last 100 years or less (Haque et al., 2016).

4. CONCLUSION

Increase in roof area for a toilet and laundry only installation increases both the reliability and BCR while efficiency decreases. For a 3kL tank only 30% of the available water is used with the smallest roof area (100 m^2). This decreases to

10% with the largest roof area (300 m^2) while reliability increases to over 70%. Interestingly it is with smaller tanks that the increased roof area has the biggest effect in increasing the reliability. This implies that if there is a larger catchment available the tank size can be reduced.
Increase in roof area has a greater effect for an installation that includes outdoor usage. The decreased reliability means that there is greater potential for increasing reliability with a larger tank or roof area. This changes the pattern of BCR and NPV. Without outdoor use, attached reliability is already high with a small tank and so a larger tank offers little increases in reliability. The lower efficiency at larger roof areas compounds the increase in reliability with increasing tank sizes. Without outdoor uses attached, the NPV of a 1.1kL tank with a roof area of 300m^2 is more favourable than the 3kL tank with a roof area of only 100m^2. When outdoor uses are attached, this is no longer the case and the 3kL becomes more favourable than the 1.1 kL tank.

Including outdoor use considerably reduces the reliability overall while the efficiency and BCR increase. This indicates that it is financially advantageous to use the RWH system for outdoor use where reliability is not a concern. Increasing the irrigation use increases the NPVs and BCRs as this increases water use and hence monetary water savings. The highest BCR occurs with a 15kL tank; while the highest (least negative) NPV occurs with a 10kL tank. The BCR of smaller tanks do not increase much with larger irrigation areas because the RWH system has already reached its capacity to supply water even with a small area of irrigation. Crop failure due to decreased reliability however may still be an issue if the water supply is not supplemented with mains water.

This study highlighted a number of areas for further research. This study only presented a simplistic method of modelling irrigation use and a more in-depth study focusing on irrigation use would be useful. Some say that, with respect for gardening, a rainwater tank is empty when it is needed most. To address this, the reliability and efficiency of RWH systems in relation to irrigation use could be explored in more depth. Particular attention should be paid to evapotranspiration, water requirements, and yield. Relationships between monthly and seasonal variation in rainfall, rainfall categories, total water available in the various regions of Australia and their influence on reliability and efficiency of RWH systems should also be explored to deepen the understanding of roof RWH's potential use in urban agriculture and the contribution it can make to greener cities and the SDGs.

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