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Evaluation of climate change impacts on rainwater harvesting

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ABSTRACT

Water management is an important issue in urban design due to the growing concern of water scarcity. As a result, rainwater harvesting system has received notable attention as an alternative water source. Rainwater is one of purest form of waters and can easily be accessed via a rainwater harvesting system. In general, performance of a rainwater harvesting system is estimated based on historical rainfall data without the possible impacts of climate change on rainfall. However, rainfall pattern is likely to change in the future as a consequence of climate change that may affect the performance of a rainwater harvesting system. But research on climate change impacts on rainwater harvesting is limited. The objective of this study is to understand the plausible impacts of climate change on the performances (i.e. water savings, reliability and water security) of a residential rainwater harvesting system, based on the projected future rainfall conditions. A continuous daily simulation water balance model is developed based on behavioural analysis and yield-after-spillage criteria to simulate the performances of a rainwater harvesting system. The analysis is conducted at five locations in the Greater Sydney region, Australia.

The results indicate that performances of a rainwater harvesting system will be impacted negatively due to climate change conditions in the future. It is found that a given tank size at the selected locations would not be able to supply expected volume of water under changing climate conditions in future. Water savings is going to be reduced from a rainwater harvesting system in future (e.g. 2%–14% reduction for 3 kL tank for indoor water demand). Moreover, number of days in a year to meet the water demand by a rainwater harvesting system (i.e. reliability) is likely to be reduced (e.g. 3%–16% reduction for 3 kL tank for indoor water demand). Also, the percentage of days a rainwater tank would remain completely empty is likely to increase in future (e.g. 12% in future climate conditions in comparison to 8% in historical conditions for indoor water demand). Furthermore, it is found that the performance of a rainwater harvesting system will be more affected in dry season than the wet season. The findings of the study will help water authorities and policy makers, as well the home owners to improve their understanding of climate change impact on residential rainwater harvesting system, and will assist them in selecting appropriate rainwater tank size in the context of climate change.

1. Introduction

Water supply security has become a major concern worldwide due to ever-increasing water demand resulting from population growth, rapid urbanisation and industrial development. Moreover, availability of water resources is decreasing due to water pollution around the world as a consequence of increasing urbanisation and industrialisation (Simeonov et al., 2003). Currently, it is estimated that approximately 2.4 billion people in the world (i.e. 36% of global population) are facing water shortages (IFPRI, 2012), and water scarcity is more critical in developing countries. United Nation (2013) reported that by 2050 the world population will reach 9.6 billion; about 70% of those populations would be living in urban areas (FAO, 2009). To serve this huge population, water demand in domestic, irrigation and industrial sectors will be amplified across the world (Pohle et al., 2012; Jakimavičius and Kriaučiūnienė, 2013; Price et al., 2014). Several studies (e.g. OECD, 2012; Haque et al., 2014; Wang et al., 2015) predicated that by 2050 global water demand would increase by about 55%, and this growing water demand would make the naturally limited water resources scarcer.

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Moreover, it has been predicted that about 52% of the global population would be exposed to severe water shortages by 2050 if no appropriate adaption and mitigation actions are taken to source new water supplies (IFPRI, 2012).

Besides growing population, rapid urbanisation and industrialisation, changes in the climatic condition is considered to be another major factor in water demand and supply (Chen and Xu, 2005; Elmahdi et al., 2009). For example, in an Australian study, Haque et al. (2013a, b, 2015) found that climate change was one of the influencing factor that impacted catchment water yield negatively (i.e. reduction in volume) and affected water demand pattern. Consequently, water resource availability could be severely impacted due to climate change conditions resulting from global warming. As a result of global warming, evapotranspiration and atmospheric water storages are likely to be affected which in turn would change the magnitudes, frequencies and intensities of future rainfall (Arnell, 1999; Middelkoop et al., 2001; Wang et al., 2015). Moreover, climate change would affect the seasonal and interannual variability of rainfall as well as geographical distributions. These plausible variations in rainfall and increase in temperature are likely to aggravate the water shortage conditions around the world in the future. For example, Ma et al. (2008) found the decreasing trend in annual streamflow 5 catchments out of 8 in Northwest China due to decreased precipitation and increased evapotranspiration.

Evidence of climate change has already been perceived in many parts of the world (Ren et al., 2002; Fang et al., 2007; Shahid et al., 2012). Moreover, confirmation of global warming due to the raised greenhouse gases is accumulating (IPCC, 2013). Intergovernmental Panel on Climate Change (IPCC) has reported based on the prediction from global climate models that global mean air temperature could increase by 1.5 °C–4.5 °C in high greenhouse gas emission scenarios (IPCC, 2013). Hence, climate change issues need to be considered in the planning and management of water resources to ensure adequate water supply in the context of changing environment.

In general, risk of water inadequacy is lesser in developed countries than developing countries (Silva et al., 2015). But supplying adequate water to the cities requires a notable amount of other resources such as energy and infrastructure. Hence, even countries with good water balance conditions between demand and available water resources are continuously evaluating alternatives (e.g. reduction in water consumption and identification of new sources to supply water) to optimise water management. One of the most common and adaptable alternative sources is the rainwater for use in the buildings, in particular residential buildings (Eroksuz and Rahman, 2010; Imteaz et al., 2012; 2013). The centuries old practice of using rainwater has been revived and the world has seen a greater attention in the past decade to harvest rainwater to lessen the pressure on main water supplies and to provide water for living in many regions. For example, installation of rainwater tanks in residential houses has become popular in many Australian cities as a result of greater environmental awareness and employment of mandatory water restrictions (Rahman et al., 2010). Rainwater utilisation is also perceived as a sustainable design approach for water resources management (Devkota et al., 2015; Morales-Pinzón et al., 2015).

Rainwater is used as either the principal or a supplementary source of water to the main water supply system in a residential building, which is generated from rainwater harvesting (RWH) system. However, use of RWHS is not limited to residential buildings only; it has been implemented to some other types of buildings such as commercial buildings and collective houses in countries such as Japan, UK, Australia and Germany (http://www.sciencedirect.com/science/article/pii/S0921344914002365, Zaizen et al., 2000, http://www.sciencedirect.com/science/article/pii/S0921344914002365, UNEP, 2002). RWHS, in general, contains three modules: collection, storage and treatment, and the generated rainwater are used for both potable and non-potable applications depending on water demand and supply conditions at the location (Fewkes, 2006). RWHS is mainly used to manage shortages in water supply in the developing countries for both the potable and not potable uses such as Bangladesh, Botswana, China, India, Kenya and other countries in Africa (http://www.sciencedirect.com/science/article/pii/S0921344914002365, UN-HABITAT, 2005, http://www.sciencedirect.com/science/article/pii/S0921344914002365; Meera and Ahammed, 2006). On the other hand, in the developed countries such as Germany, France, Japan, Singapore and United States, it is mainly used to supplement main supply for non-potable use e.g. toilet and laundry use, and garden irrigation (http://www.sciencedirect.com/science/article/pii/S0921344914002365, Kloss, 2008, http://www.sciencedirect.com/science/article/pii/S0921344914002365, Schets et al., 2010). However, rainwater is also used for potable use in some developed countries; for example, in Australia rainwater is used for drinking in some rural and peri-urban areas where mains water is not available (http://www.sciencedirect.com/science/article/pii/S0921344914002365, MPMSAA, 2008, Hajani and Rahman, 2014).

Rainfall is the main variable of interest for a RWHS system (Silva et al., 2015), especially temporal variability of rainfall is the critical governing factor in its performance. Design of RWHS is generally concerned with determining the optimum tank size to ensure water supply for the anticipated use. An oversized tank is a loss of resources (e.g. energy, time and money); on the other hand an undersized tank will not be able to fulfil the required water demand. Therefore, needs of households and the characteristics of the geographical locations should be considered when designing a RWHS. Many studies are available in literature on the benefits, design, performance and feasibility analysis of a RWHS, for example in Germany (Herrmann and Schmida, 2000), in China (Fengtai and Xiaochao, 2012), in Brazil (Ghisi and Ferreira, 2007), in USA (Aladenola and Adeboye, 2010; Steffen et al., 2013), in Italy (Palla et al., 2012), in Virginia (Sample and Liu, 2014), in Mexico (García-Montoya et al., 2015) and in Australia (Imteaz et al., 2011a, 2011b; Rahman et al., 2012).

Most of these studies are based on the historical climate conditions in the study location to perform such analysis. Only a few studies incorporated future uncertain rainfall event in estimating reliability of a RWHS. For example, Basinger et al. (2010) generated ensembles of synthetic rainfall time series adopting a Markov Chain algorithm to incorporate rainfall uncertainty in a RWHS. Wallace et al. (2015) used daily rainfall data which was statistically downscaled from Global Climate Models (GCMs) in estimating required catchment area and tank size for a given reliability. Lo and Koralegedara (2015) also incorporated statistically downscaled rainfall data from GCMs along with historical rainfall conditions to incorporate variability in rainfall in a RWHS. However, as mentioned earlier that rainfall pattern and variability are likely to be altered in future in the context of climate change, which can introduce uncertainty in designing a RWHS if the plausible changes in rainfall are not taken into consideration. Understanding how performance of a rainwater tank changes in response to variation in the climate conditions is a vital component in the planning, management and development of RWHS as an alternative water sources to supply water. However, research on climate change impacts on rainwater harvesting is still very limited.

The objective of the present study is to understand the plausible impacts of climate change on the performance of a residential RWHS. The study attempts to answer the following questions: (i) Will a given tank size at a given location be adequate in changing climate conditions in future to supply expected volume of water, (ii) How much variation in water savings is expected to happen, (iii) Will the proportion of days when a RWHS is likely to meet the required demand be increased or decreased, and (iv) Will the percentage of time a rainwater tank would remain completely empty be increased or decreased? The findings of the study will help water authorities and policy makers, as well the home owners to improve their understanding of climate change impact on residential RWHS, and will assist them in adopting proper rainwater tank size in the context of climate change.

2. Methods

The performance of a RWHS has been estimated herein from the balance between non-potable water demand and harvested rainwater on a daily time step in a residential building. A water-balance simulation model has been built in MATLAB to simulate the performance considering various factors associated with a RWHS (e.g. rainwater tank size, daily rainfall, losses, daily water demand, water supply top up from mains and tank spillage). The water balance model has been built based on a behavioural type model (yield-after-spillage) (Fewkes and Butler, 2000; Liaw and Tsai, 2004; Mitchell, 2007).

Behavioural analysis uses a mass balance equation through continuous simulation in order to track the changes in inputs, outputs and storage volume. In the behavioural model, change in the storage volume of a fixed rainwater tank size is estimated as below:

$$V_i = V_{i-1} + R_i + DR_i - E_i - SP_i - SW_i \tag{1}$$

where, V_i is the storage volume of the rainwater tank at the end of time step i ($i = 1$ for first day of simulation, and $i = n$ for the last day of simulation), V_{i-1} is the storage volume of the rainwater tank at the end of pervious time step, R_i is the runoff from the roof catchment, DR_i is the daily rainfall to the rainwater tank, E_i is the evaporation from the rainwater tank, SP_i is the spillage amount due to overflow and SW_i is the supplied rainwater volume. Spillage occurs when harvested rainwater amount exceeds the rainwater tank capacity which may happen during a heavy rain event. In the case of covered rainwater tank, the daily rainfall component becomes zero and evaporation amount can be neglected. In this study, covered type rainwater tank is considered and also, the tank is assumed to be placed on ground over concrete base, which is the common practice in Australia.

The adopted methodology to estimate the performance of a RWHS is presented schematically in Fig. 1. The algorithm starts by setting the initial volume of a rainwater tank to 20% of tank size from the mains supply, that is considered as storage level after main (SLAM). The available runoff (R) during time period i is then estimated from the daily rainfall (DR), the roof catchment area (CA) and the runoff coefficient (RC); the equation is presented as below:

$$R_i = DR_i \times CA \times RC \tag{2}$$

If the available runoff/harvested rainwater exceeds the rainwater tank capacity, the storage level before use (SLBU) becomes the volume of the tank size otherwise it is the summation of runoff at the time step and the storage level after main in the previous time step. Then the required water demand is supplied from the SLBU. If the amount of required water demand is greater than the SLBU, main water supply (MWS) is needed to provide the extra amount otherwise the required amount is delivered from the SLBU. Afterwards, storage level after main (SLAM) is calculated; if MWS is needed then SLAM at the end of the time step would be the same as initial volume as it is required to have at least an amount of water equal to initial volume if there is no rain or shortages. If no MWS is needed, then the SLAM at the end of time step would be equal to tank size less the supplied water from the tank. The procedure is repeated for each day of the year, and each year is dealt with separately.

A number of commonly adopted tank sizes (3, 5, 7 and 10 kL) are selected for a typical lot size in Sydney (450 m^2), with 4 occupants as detailed in Section 3. A total of five different locations are considered since Sydney is a large city with high areal rainfall variability. For each of the four tank sizes, water savings are calculated for two different types of water uses (i.e. indoor and outdoor) for the historical and future daily rainfall.

Reliability of a RWHS is calculated for each of the scenarios as the ratio of total number of days when demand is fulfilled by the harvested rainwater and the total number of simulated days. The equation to estimate reliability is presented in the following.

$$Reliability\ (\%) = \frac{Total\ no.\ of\ days\ when\ main\ water\ supply\ is\ not\ needed}{Total\ no.\ of\ simulated\ days} \times 100 \tag{3}$$

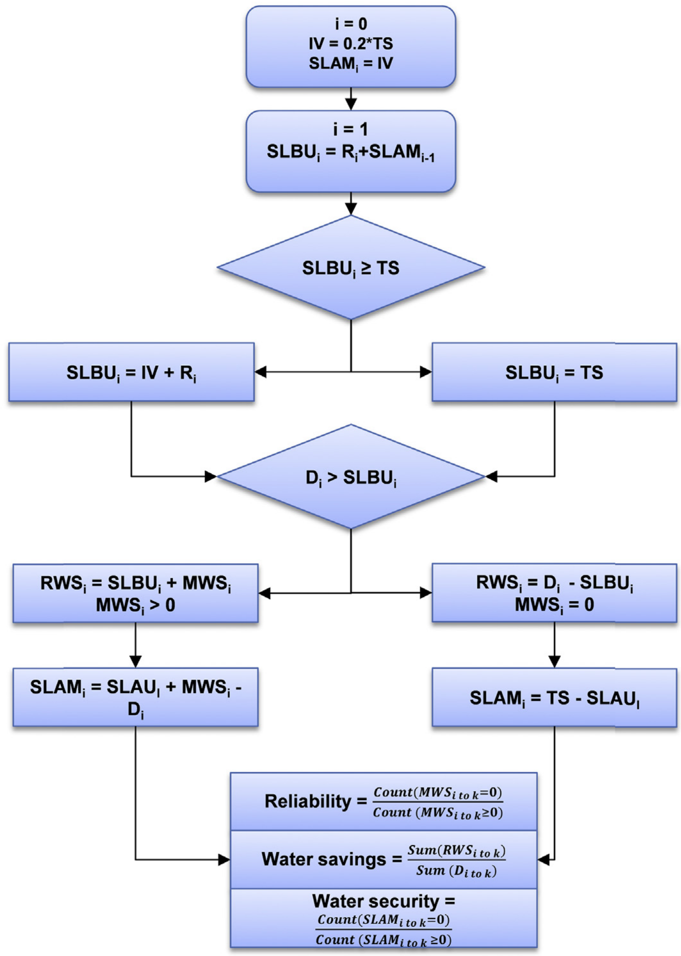
Water savings of RWHS is calculated as the ratio of the total amount of water supplied from the rainwater tank and the total amount of water demand. The equation to estimate water savings is presented in the following.

$$Water\ savings\ (\%) = \frac{Total\ amount\ of\ water\ supplied\ by\ RWHS}{Total\ amount\ of\ water\ demand} \times 100 \tag{4}$$

Water security of a RWHS is calculated as the ratio of the total number of days when rainwater tank volume remains zero after the initial volume and the total number of simulated days.

$$Water\ security\ (\%) = \frac{Total\ no.\ of\ days\ when\ the\ tanks\ remains\ empty}{Total\ no.\ of\ simulated\ days} \times 100 \tag{5}$$

Reliability, water savings and water security have been



Note: i = time step, IV = initial volume of water in a rainwater tank, $SLAM$ = storage level after mains supply, $SLBU$ = storage level before use, R = effective runoff from roof catchment, TS = rainwater tank size, D = daily water demand, RWS = rainwater supply, MWS = main water supply

Fig. 1. Approach to estimate the performances of a rainwater harvesting system.

Table 1
Changes in annual average rainfall at the 5 stations in NSW, Australia for the period of 2020–2039 in comparison to the historical rainfall average.

ID	Station	Historical period	Future period	Historical rainfall avg./year (mm)	Future rainfall avg./yearly (mm)	% Changes/yearly
066124	Parramatta	1966–2014	2020–2039	957.09	818.77	−14.45
066037	Sydney	1930–2014	2020–2039	1086.83	895.14	−17.64
067019	Blacktown	1987–2014	2020–2039	868.735	703.97	−18.97
067021	Richmond	1940–2003	2020–2039	853.74	658.936	−22.82
063039	Katoomba	1986–2014	2020–2039	1391.03	916.84	−34.09

calculated for monthly and yearly time steps as well as for all the simulation periods and reported in percentage.

3. Study area and data

In this study, 5 different locations in the Greater Sydney regions of Australia were considered. The daily rainfall data for the historical period at the selected locations were obtained from the Australian Bureau of Meteorology (Table 1). The data lengths were in the range of 28–84 years, with an average of 50 years. The mean annual rainfall across the selected locations ranges from 853 to 1391 mm/year, with an average of 1031 mm/year. The projected future rainfall data at the selected location were obtained from NARCliM project (Evans et al., 2014). The duration of the projected rainfall data was taken as 20 years in this study covering 2020–2039. The downscaled future rainfall data were generated from a global climate model, Commonwealth Scientific and Industrial Research Organisation (CSIRO Mk.3). Detailed description on the NARCliM project can be found on the website, http://www.environment.nsw.gov.au/research/Regionalclimate.

Both indoor and outdoor non potable water demand were considered in this study. Toilet and laundry demand was considered as indoor, and garden watering was considered as outdoor demand. The analysis was also done based on combined water demand (i.e. indoor + outdoor). Four different rainwater tank sizes were considered: 3 kL, 5 kL, 7 kL and 10 kL. It is to be noted here that in practice a 3 kL tank is commonly adopted in Sydney for a detached residential building. It was assumed in this study that a residential building will have 4 occupants at each of the selected locations. A total site area of 450 m^2 consisting of a roof, lawn and impervious areas of 200 m^2, 150 m^2 and 100 m^2, respectively was chosen based on the commonly adopted choices in building design in Sydney.

The water demand data for indoor and outdoor use for residential buildings were obtained from Sydney Water. The toilet demand was calculated as 0.018 kL/person/day by considering a 6 L AAA rated dual lush toilet and 3 times use of the toilet by a person per day. The laundry demand was calculated by assuming that it would be used 3 times in a week (i.e. 7 days) and had a volume of 50 L and 4A rated. The equivalent value of laundry demand was estimated as 0.0215 kL/day (i.e. (3/7)*50/1000). The garden watering demand (i.e. outdoor demand) was assumed to be 10 mm per day per square meter of lawn areas based on Sydney Water recommended value in the region. In the water balance model, outdoor demand was kept zero if the daily rainfall exceeded 10 mm. Moreover, in an event of heavy rainfall, outdoor demand was kept zero for a number of subsequent days (one day for each 25 mm of rainfall).

It should be noted that with time, water demand, average number of occupants and water use patterns are expected to change, which however is difficult to predict, and hence kept fixed in this study.

The runoff coefficient to consider the losses due to first flash and gutter overflow was assumed to be 0.85, which is within the range found by van der Sterren et al. (2012), and within the typical ranges of 0.8 and 0.95 for roof catchments (Ghisi et al., 2009; Khastagir and Jayasuriya, 2010).

4. Results and discussion

4.1. Changes in future rainfall

Annual average rainfall is expected to reduce by around 14%–34% at the 5 selected stations in the NSW, Australia for the future period, projected by the CSIRO Mk.3 GCM (Table 1). Among the 5 stations, Katoomba station would face the highest reduction (around 34%) in rainfall where the historical annual average rainfall is the highest. As can be seen in Fig. 2, average rainfall in dry season would reduce by around 42–65%, whereas average rainfall in wet season is expected to increase by around 0.45–10% at 4 stations, only Katoomba station shows decrease in rainfall in wet season by 5%. The findings indicate that dry season rainfall would be more impacted by climate change which is expected to be drier; on the other hand the wet season would be less impacted which is expected to be wetter.

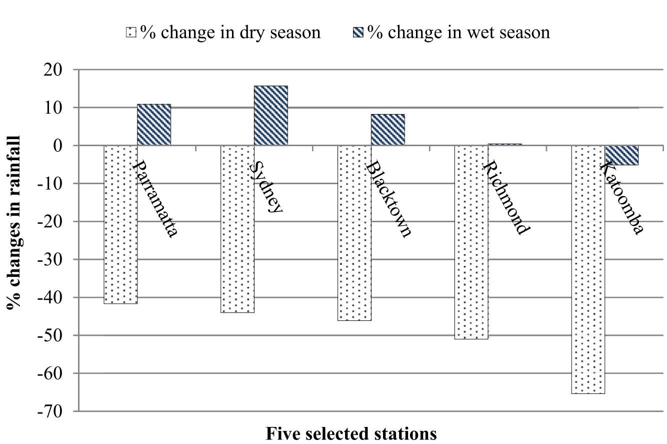


Fig. 2. Seasonal rainfall changes in the forecasted period at 5 selected stations in NSW, Australia.

Monthly rainfall changes in the future period indicate that January and December months would be wetter (Table 2) as all the 5 rainfall stations show higher rainfall in these two months than the historical period. All other months demonstrate lesser rainfall than the historical average for most of the stations. Average rainfall changes across all the stations show that January and December rainfall would increase by about 15% and 41%, respectively; November rainfall would not change, and rainfall in all other months would decrease by about 2%–81%. Rainfall in the months of April to September are likely to be notably affected by climate change conditions as these months show greater reduction in rainfall compared to the historical rainfall.

4.2. Impacts on water savings from a RWHS

Water savings for indoor water demand under 3 kL rainwater tank is likely to be reduced by around 2%–14% (Table 3) at 5 stations for the 2020–2039 period in comparison to the historical period. Among the 5 stations, Katoomba station is going to be impacted more as the estimated reduction in water savings is highest in the station. The reduction in water savings at the stations is likely to be interrelated with the reduction in rainfall of those stations. As calculated earlier, the reduction in rainfall is estimated to be 14%–34% of the five stations, which resulted in reduction in water savings by 2%–14%. The highest amount of water savings is estimated at Katoomba station whereas the lowest amount of water savings is estimated at Richmond stations for all tank sizes. These results also indicate the correlation of rainfall amount with the water savings as annual average rainfall is found to be highest in Katoomba station and lowest in Richmond station. As can be seen in Table 3, to achieve the similar water savings of 3 kL rainwater tanks, the tank size needs to be increased to different sizes in the future period for the stations. For example, at Parramatta, Sydney and Blacktown the tank size need to be increased to 5 kL, at Richmond the tank size does not require a change as there is not much difference in water savings for 3 kL tank between historical and future period, and at Katoomba the tank size needs to be increased to 10 kL tank to achieve the similar water savings of 3 kL tank at the historical period.

As can be seen in Table 3, water savings for outdoor demand for all the tank sizes is much less than that of indoor demand as outdoor demand is approximately 16 times [i.e. outdoor demand (1.5 kL)/indoor demand (0.0935 kL)] higher than the indoor demand. Water savings for outdoor demand is also likely to reduce under future rainfall conditions. The estimated reduction varies from 0.21% to 15.92% under 3 kL tanks for the five stations. Katoomba stations would face the highest reduction (15.92%) in waters savings as the predicted rainfall reduction is highest in the station among all the stations. Results in water savings under future conditions for combined demand follows the pattern of outdoor demand conditions as outdoor demand governs the water demand amount in combined demand.

Estimated water savings for dry season and wet season under 3 kL tank for the historical and future period are presented in Table 4. The results indicate that water savings become less in dry season than wet season for all stations, for example, in Parramatta estimated water savings is found to be 88.65% in dry season whereas the savings in wet season is found to be 97.71% during the historical period which is 9% higher than the savings in dry season. In terms of changes in water savings between historical and future period it is found that water savings would reduce in dry season

Table 2
Changes in monthly average rainfall at the 5 stations in NSW, Australia for the period of 2020–2039 in comparison to the historical rainfall average.

	Parramatta	Sydney	Blacktown	Richmond	Katoomba	Average
Jan	22.61	25.19	16.36	1.79	11.48	15.49
Feb	-18.70	-5.83	-8.55	-14.23	-19.78	-13.42
Mar	8.85	6.51	-0.03	-3.75	-21.58	-2.00
Apr	-11.37	-14.92	-13.55	-25.89	-46.55	-22.46
May	-43.41	-42.56	-54.12	-62.79	-73.96	-55.37
Jun	-78.74	-81.45	-78.71	-81.11	-87.12	-81.42
Jul	-47.45	-58.04	-67.43	-64.86	-83.03	-64.16
Aug	-58.45	-56.28	-58.48	-62.68	-72.68	-61.71
Sep	-41.19	-42.73	-38.13	-38.58	-64.64	-45.05
Oct	-12.59	2.78	-11.64	-24.93	-30.38	-15.35
Nov	-2.75	10.15	4.43	-6.18	-3.51	0.43
Dec	67.89	56.82	34.44	33.64	15.68	41.69

Note: The blue colour indicates increase in rainfall and the green colour indicates decrease in rainfall

Table 3
Changes in water savings for future rainfall conditions for 3 kL, 5 kL, 7 kL and 10 kL rainwater tanks.

Station	3 kL		5 kL		7 kL		10 kL	
	Historical	Future	Historical	Future	Historical	Future	Historical	Future
Indoor demand								
Parramatta	92.46	88.47 (**-4.32**)	97.66	94.26 (**-4.51**)	99.23	97.23 (**-2.02**)	99.70	98.90 (**-0.79**)
Sydney	94.61	92.24 (**-2.50**)	98.43	96.13 (**-2.33**)	99.29	97.83 (**-1.47**)	99.49	99.48 (**-0.02**)
Blacktown	90.30	85.01 (**-5.86**)	96.45	91.59 (**-5.04**)	98.45	93.90 (**-4.62**)	99.39	97.25 (**-2.15**)
Richmond	83.85	82.06 (**-2.13**)	89.95	88.50 (**-1.62**)	92.24	91.94 (**-0.33**)	98.87	96.75 (**-0.13**)
Katoomba	95.24	81.53 (**-14.39**)	98.17	87.29 (**-11.07**)	98.65	91.28 (**-7.46**)	98.76	96.38 (**-2.41**)
Outdoor demand								
Parramatta	14.12	14.09 (**-0.21**)	17.10	16.94 (**-0.97**)	19.49	18.82 (**-3.45**)	22.10	20.63 (**-6.65**)
Sydney	15.95	15.85 (**-0.63**)	19.16	18.98 (**-0.90**)	21.61	21.01 (**-2.76**)	24.56	22.99 (**-6.37**)
Blacktown	12.89	12.69 (**-1.55**)	15.55	15.11 (**-2.84**)	17.69	16.62 (**-6.02**)	19.98	18.2 (**-8.91**)
Richmond	12.26	11.96 (**-2.45**)	14.86	14.17 (**-4.64**)	16.82	15.62 (**-7.14**)	19.75	16.98 (**-14.01**)
Katoomba	17.40	14.63 (**-15.92**)	22.13	17.73 (**-19.86**)	25.40	19.78 (**-22.10**)	28.95	21.88 (**-24.43**)
Combined demand								
Parramatta	13.55	13.43 (**-0.89**)	16.28	16.05 (**-1.45**)	18.56	17.79 (**-4.35**)	20.96	19.48 (**-7.56**)
Sydney	15.25	15.13 (**-0.79**)	18.24	18.01 (**-1.30**)	20.58	19.86 (**-3.61**)	23.31	21.67 (**-7.57**)
Blacktown	12.35	12.1 (**-2.06**)	14.87	14.31 (**-3.89**)	16.84	15.72 (**-7.14**)	18.95	17.17 (**-10.35**)
Richmond	11.65	11.41 (**-2.10**)	14.18	13.44 (**-5.49**)	15.98	14.76 (**-8.29**)	18.73	16 (**-17.02**)
Katoomba	16.88	14.11 (**-19.68**)	21.27	16.99 (**-25.23**)	24.30	18.89 (**-28.66**)	27.59	20.79 (**-32.67**)

Note: All the values in the table are in %.
The bold marked values represent the changes in % between the future and historical values.

and would increase in wet season in the future period. For indoor demand, water savings are expected to reduce by 10%–36% for the stations in dry season whereas water savings are expected to increase by 2%–5% in wet season in the future period. Similar pattern changes are found for both the outdoor and combined demand scenarios. It is mentioned earlier that the future rainfall is expected to be wetter in wet season and drier in dry season which is likely to be the reason for increase and decrease in water savings from a RWHS in the wet and dry seasons, respectively, in the future period. From Table 4, it can be found that effect of seasonal changes is higher for outdoor demand than the indoor demand as water savings are expected to reduce by 26%–93% in dry season, and increase by 18%–37% which are much higher values than that of indoor demand scenarios.

Monthly pattern of estimated water saving for indoor water demand for both the historical and future period is presented in Fig. 3; the results are calculated by taking the average across the five stations. The results demonstrate that water savings is the lowest in the month of July for both periods, and the months where water savings are less than the other months are found to be May to October. Similar patterns have been found for outdoor and combined water demand. The results also demonstrate that water savings would be significantly impacted (reduction) during the months of June to September in the future period due to climate change conditions.

4.3. Impacts on reliability

Reliability is likely to reduce in the future period in comparison to the historical period for all the rainwater tank sizes and all the stations, as can be seen in Table 5. For indoor water demand, the reliability is expected to reduce by 3%–16%; for outdoor water demand the reliability is expected to reduce by 19%–30% and for combined water demand the reliability is expected to reduce by 19%–31% for the 3 kL rainwater tanks across all the five stations. Similar to the estimated changes in water savings for the future

Table 4
Water savings for dry and wet seasons in 3 kL tank for historical and future period.

	Dry season		Wet season	
	Historical	Future	Historical	Future
Indoor demand				
Parramatta	88.65	80.57 (−10.02)	97.71	99.71 (2.05)
Sydney	93.25	87 (−7.180)	96.65	99.69 (3.15)
Blacktown	86.99	74.79 (−16.31)	94.76	99.54 (5.04)
Richmond	82.47	69.75 (−18.22)	94.86	99.59 (4.98)
Katoomba	93.40	68.77 (−35.81)	97.82	99.65 (1.86)
Outdoor demand				
Parramatta	11.96	9.46 (−26.45)	17.89	23.3 (30.21)
Sydney	14.69	11.76 (−24.87)	17.84	24.59 (37.81)
Blacktown	10.98	8.32 (−31.91)	16.29	21.09 (29.43)
Richmond	9.86	6.88 (43.33)	17.49	21.54 (23.13)
Katoomba	15.09	7.78 (93.94)	24.48	28.97 (18.34)
Combined demand				
Parramatta	11.49	8.96 (−28.17)	17.23	22.12 (28.36)
Sydney	14.11	11.17 (26.40)	17.07	23.38 (36.97)
Blacktown	10.56	7.89 (−33.79)	15.61	20.05 (28.45)
Richmond	9.48	6.52 (−45.25)	16.81	20.47 (21.80)
Katoomba	14.53	7.39 (−96.46)	23.62	27.81 (17.70)

Note: All the values in the table are in % and for 3 kL tank.
The values in the parenthesis represent the changes in % between the future and historical values.

Table 6
Reliability for dry and wet seasons in 3 kL tank for historical and future period.

	Dry season		Wet season	
	Historical	Future	Historical	Future
Indoor demand				
Parramatta	87.83	79.71 (−9.25)	97.44	99.7 (2.32)
Sydney	93.01	86.29 (−7.23)	96.52	99.66 (3.25)
Blacktown	86.00	72.93 (−15.20)	94.57	99.5 (5.21)
Richmond	81.29	67.97 (−16.39)	94.73	99.5 (5.04)
Katoomba	93.57	67.08 (−28.31)	98.36	99.53 (1.19)
Outdoor demand				
Parramatta	15.21	7.99 (−47.47)	23.13	22.97 (−0.69)
Sydney	19.21	11.01 (−42.69)	22.41	24.64 (9.95)
Blacktown	14.02	7.46 (−46.79)	20.64	21.82 (5.72)
Richmond	12.27	6.14 (−49.96)	22.06	22.16 (0.45)
Katoomba	20.13	7.28 (−63.84)	31.42	31.31 (−0.35)
Combined demand				
Parramatta	14.39	7.33 (−49.06)	21.96	22.05 (0.41)
Sydney	18.18	10.17 (−44.06)	20.93	23.28 (11.23)
Blacktown	13.30	6.8 (−48.87)	19.62	20.04 (2.14)
Richmond	11.75	5.6 (−52.34)	21.03	20.81 (−1.05)
Katoomba	19.07	6.64 (−65.18)	29.99	29.66 (−1.10)

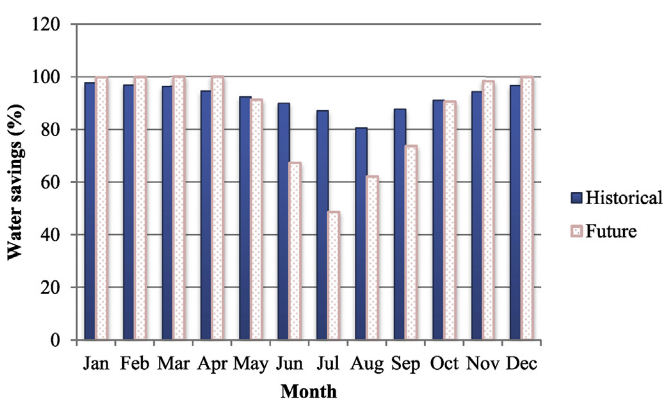


Fig. 3. Monthly water savings pattern for indoor water demand for both the historical and future period from 3 kL rainwater tank.

period, Katoomba station will face the highest amount of reduction in reliability among all the stations as the rainfall reduction is estimated to be the highest in the Katoomba station. In order to achieve the same amount of reliability for all the water demand scenarios from a particular rainwater tank size at the present conditions, the tank size needs to be increased in the future period, as can be seen in Table 5. The results in reliability changes indicate that the increase in tank size would be required for all the stations. For example, to achieve the same reliability from a 3 kL rainwater tank, the tank size needs to be increased to 5 kL at Parramatta, Sydney, Blacktown and Richmond. At Katoomba station, the tank size needs to be increased to 10 kL in order to achieve the same reliability of 3 kL tank as the reduction in reliability is found to be the highest for this station.

Estimated reliability of a 3 kL rainwater tank, and changes between the historical and future conditions for all the stations are presented in Table 6 for dry and wet seasons. The reliability is found to be less in dry season than that of wet season as the rainfall is smaller in the dry season compared to wet season. For indoor water

Table 5
Estimated changes in reliability for future rainfall conditions for 3 kL, 5 kL, 7 kL and 10 kL rainwater tanks.

Station	3 kL		5 kL		7 kL		10 kL	
	Historical	Future	Historical	Future	Historical	Future	Historical	Future
Indoor demand								
Parramatta	91.86	87.95 (−4.26)	97.50	92.99 (−4.63)	99.23	95.97 (−3.29)	99.73	98.83 (−0.90)
Sydney	94.41	91.81 (−2.75)	98.62	95.94 (−2.72)	99.54	97.71 (−1.84)	99.77	99.41 (−0.36)
Blacktown	89.64	83.9 (−6.40)	96.31	89.54 (−7.03)	98.48	93.37 (−5.19)	99.50	97.01 (−2.50)
Richmond	86.19	80.98 (−6.04)	93.04	86.77 (−6.74)	95.56	91.44 (−4.31)	98.97	96.45 (−2.55)
Katoomba	95.57	80.49 (−15.78)	98.79	86.58 (−12.36)	99.33	90.7 (−8.69)	99.45	96.11 (−3.36)
Outdoor demand								
Parramatta	18.43	14.22 (−22.84)	21.97	17.2 (−21.71)	24.40	19.41 (−20.45)	27.00	21.39 (−20.78)
Sydney	20.53	16.67 (−18.80)	24.27	20.02 (−17.51)	26.87	22.25 (−17.19)	29.88	24.33 (−18.57)
Blacktown	16.82	13.42 (−20.21)	19.94	15.96 (19.56)	22.04	17.71 (−19.65)	24.37	19.34 (−20.64)
Richmond	15.98	12.79 (−19.96)	18.96	15.23 (−19.67)	20.92	16.64 (−20.46)	23.85	18.13 (−23.98)
Katoomba	24.75	17.23 (−30.38)	29.23	20.71 (−29.15)	32.30	23.02 (−28.73)	35.84	25.18 (−29.74)
Combined demand								
Parramatta	17.47	13.45 (−23.01)	20.61	16.12 (−21.79)	22.80	18.01 (−21.01)	25.00	19.78 (−20.88)
Sydney	19.30	15.61 (−19.12)	22.76	18.69 (−17.88)	25.20	20.68 (−17.94)	27.69	22.42 (−19.03)
Blacktown	15.97	12.3 (−22.98)	18.83	14.71 (−21.88)	20.73	16.16 (22.05)	22.75	17.85 (21.54)
Richmond	15.17	11.92 (−21.42)	17.88	14.12 (21.03)	19.63	15.49 (21.09)	22.23	16.98 (23.62)
Katoomba	23.54	16.18 (−31.27)	27.70	19.31 (−30.29)	30.56	21.51 (29.61)	33.54	23.4 (30.23)

Note: All the values in the table are in %.
The values in the parenthesis represent the changes in % between the future and historical values.

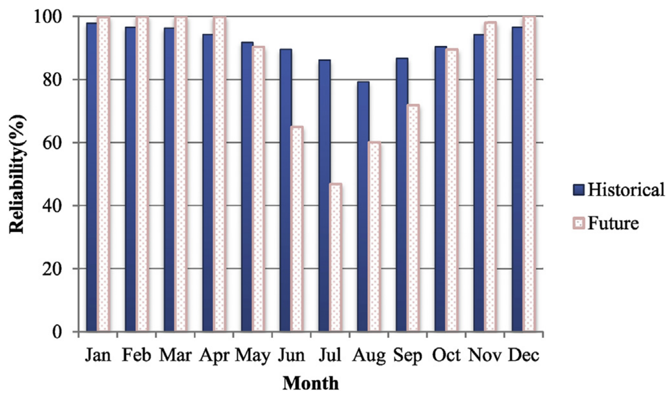


Fig. 4. Monthly pattern of reliability of a 3 kL rainwater tank for indoor water demand for both the historical and future climatic conditions.

demand, the reliability is likely to be reduced by 7%–28% in the dry season, whereas the reliability is likely to be increased by a small amount of 1%–5% in the wet season in the future period. The results indicate the dry seasons would be impacted more by the climate change conditions in the future. For outdoor and combined water demand scenarios, the estimated reduction in reliability is found to be in the range of 43%–65% in the dry seasons in the future period across the stations. In wet seasons, the estimated changes in reliability in the wet season period are not significant compared to dry season period in the future. The results indicate that reliability of a rainwater tank to meet outdoor water demand would be significantly impacted by the climate change conditions.

Monthly pattern of reliability of a 3 kL rainwater tank is presented in Fig. 4 for both the historical and future climatic conditions. It is found that reliability is generally lower in the months of June to October than the other months for both the historical and future climatic conditions. As can be seen in Fig. 4, the reliability of a rainwater tank would be significantly affected in the months of June to September similar to the water saving scenarios in the future period due to climate change conditions. The more likely reason for much reduction in reliability in those months is the higher percentage of rainfall reduction in those months in the future period as projected by the GCM.A similar pattern has been found for both the outdoor and combined water demands, as well as for other tank sizes.

4.4. Impacts on water security

Estimated percentage of time (i.e. security) the rainwater tank would be completely empty is presented for both the historical and future climate conditions in Table 7. It can be seen that for indoor demand only 8%–14% of days in a year the 3 kL rainwater tank would be completely empty in the historical period across the stations. It can also be seen that with the increase of tank size, the percentage of days the tank would become empty reduces, for example only 0.6%–4% days the tank would be completely empty in the historical period, which is a smaller percentage of the days than that of 3 kL rainwater tank. For outdoor and combined water demand scenarios, all tanks would be empty for most of the days, for example, 75%–84% of days the 3 kL tank would be empty for outdoor water demand in the historical period.

As can be seen in Table 7, changes in rainfall conditions in the future period would produce negative impact on the water security of a rainwater tank size as it increases the number of days that the rainwater tank would be empty in a year, for example the

Table 8
Estimated percentage of time the tanks would be completely empty in dry and wet seasons for both the historical and future climate conditions.

	Dry season		Wet season	
	Historical	Future	Historical	Future
Indoor demand				
Parramatta	12.16	20.28	2.55	0.30
Sydney	6.98	13.70	3.47	0.33
Blacktown	13.99	27.06	5.42	0.49
Richmond	18.70	32.02	5.26	0.49
Katoomba	6.42	32.91	1.63	0.46
Outdoor demand				
Parramatta	84.78	92.00	76.86	77.02
Sydney	80.78	88.98	77.58	75.35
Blacktown	85.97	92.53	79.35	78.17
Richmond	87.72	93.85	77.93	77.83
Katoomba	79.86	92.71	68.57	68.68
Combined demand				
Parramatta	85.60	92.66	78.03	77.94
Sydney	81.81	89.82	79.06	76.71
Blacktown	86.69	93.19	80.37	79.95
Richmond	88.24	94.39	78.96	79.18
Katoomba	80.92	93.35	70.00	70.33

Table 7
Estimated percentage of time (i.e. security) the rainwater tank would be completely empty for both the historical and future rainfall conditions for 3 kL, 5 kL, 7 kL and 10 kL rainwater tanks.

Station	3 kL		5 kL		7 kL		10 kL	
	Historical	Future	Historical	Future	Historical	Future	Historical	Future
Indoor demand								
Parramatta	8.13	12.04	2.49	7.00	0.76	4.02	0.26	1.16
Sydney	5.58	8.18	1.37	4.05	0.45	2.28	0.22	0.58
Blacktown	10.35	16.09	3.68	10.45	1.51	6.62	0.49	2.98
Richmond	13.80	19.01	6.95	13.22	4.43	8.55	1.02	3.54
Katoomba	4.42	19.50	1.20	13.41	0.66	9.29	0.54	3.88
Outdoor demand								
Parramatta	81.56	85.77	78.02	82.79	75.59	80.58	72.99	78.60
Sydney	79.46	83.32	75.72	79.97	73.12	77.74	70.11	75.66
Blacktown	83.17	86.57	80.05	84.03	77.95	82.28	75.62	80.65
Richmond	84.01	87.20	81.03	84.76	79.07	83.35	76.14	81.86
Katoomba	75.24	82.76	70.76	79.28	67.69	76.97	64.15	74.81
Combined demand								
Parramatta	82.52	86.54	79.38	83.87	77.19	81.98	75.00	80.21
Sydney	80.69	84.38	77.23	81.30	74.79	79.31	72.30	77.57
Blacktown	84.02	87.69	81.16	85.28	79.26	83.83	77.24	82.14
Richmond	84.82	88.07	82.11	85.87	80.36	84.50	77.76	83.01
Katoomba	76.45	83.81	72.29	80.68	69.43	78.48	66.45	76.59

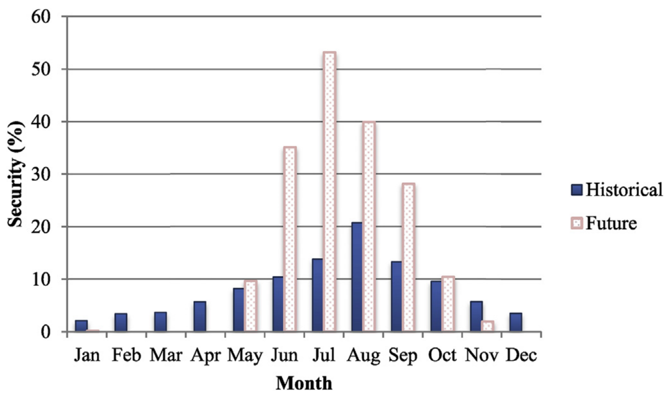


Fig. 5. Monthly pattern of water security of a 3 kL rainwater tank for indoor water demand for both the historical and future climatic conditions.

percentage of days a 3 kL rainwater tank would be completely empty would increase to 12% in future climate conditions in comparison to 8% in historical conditions for indoor water demand.

Seasonal changes on water security from a 3 kL rainwater tank for both the historical and future climate conditions are presented in Table 8. It can be seen that the number of days the 3 kL tank would remain empty is likely to increase notably in the dry season whereas in wet season there would not be any significant changes for all demand scenarios. For example, at Parramatta the number of days the tank would remain empty is likely to increase to 92% (future climate conditions) from 85% (historical climate conditions) for outdoor water demand in dry season, whereas the percentage of days would increase to 77.02% from 76.86% in the wet season, which is not significant. Similar results have been obtained for the 5 kL, 7 kL and 10 kL rainwater tanks.

Monthly pattern on water security of a 3 kL rainwater tank for both the historical and future climate conditions is presented in Fig. 5 for indoor water demand scenarios. It can be seen that the tank would provide less security during the months of May to October as the percentage of time the tank would be empty is higher in these months than the other months for both the historical and future climatic conditions. It can also be seen that climate change would impact on water security notably in the months of June to September as the tank would be empty by higher percentage of time in these months in the future period.

The three performance parameters of a rainwater tank that have been considered in this study are found to be directly related with the rainfall amount for both the historical and future climate conditions. For example, reliability of a 3 kL rainwater tank for combined water demand vs. average rainfall graph is presented in Fig. 6. Average yearly historical and future rainfalls are found to be the highest in Katoomba station, then Sydney, Parramatta, Blacktown and Richmond. Reliability of the 3 kL tank is also found to be in the same order of Katoomba > Sydney > Parramatta > Blacktown > Richmond. Rainfall reduction is found to be the highest in the Katoomba station in the future period, similarly the highest reduction in reliability is found to be in Katoomba station. Similar results have been obtained for water savings and security parameters.

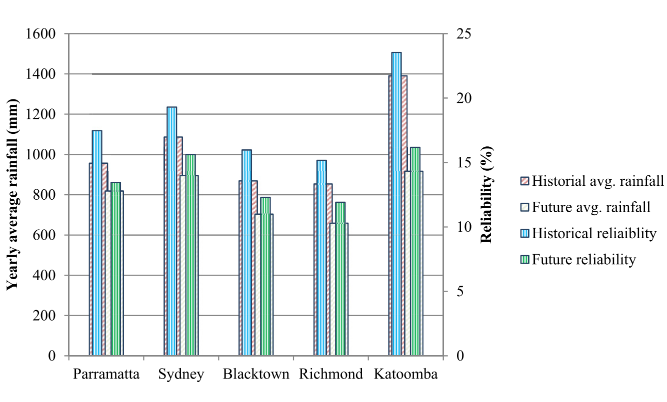


Fig. 6. Reliability vs yearly average rainfall of a 3 kL rainwater tank for both the historical and future period for combined water demand scenario.

5. Conclusion

In this study, the performance of a rainwater harvesting system under changing climatic condition in the future has been investigated at five locations in Greater Sydney region in Australia. The results indicate that performance of a RWHS would be negatively affected as a result of reduction in future rainfall. Water savings from a 3 kL rainwater tank is likely to be reduced by 2%–14% for indoor demand, 0.21%–15.92% for outdoor demand and 0.79%–19.68% for combined demand in the future period in comparison to the water savings in the historical period. Number of days to meet the water demand by a 3 kL rainwater tank (i.e. reliability) is likely to be reduced by 3%–16% for indoor demand, 19%–30% for outdoor demand and 19%–31% for combined demand. Moreover, the frequency a rainwater tank would remain completely empty is likely to be increased.

It is found that the performance of a RWHS would be significantly affected in the months of June to September (dry season in Sydney); the more likely reason is the higher percentage of rainfall reduction in those months in the future period as indicated by the global climate model. The results of the study demonstrate that the performance of a RWHS would be impacted more in the dry season than wet season. Seasonal changes in rainfall would put higher impact on the performance of a RWHS for outdoor demand than indoor demand.

One of the major findings of the study is that a 3 kL rainwater tank would not be able to provide the same volume of water (as in the current condition) in the future. The results indicate that higher storage capacity of a rainwater tank will be needed for all the stations to get the same performance of a 3 kL tank. These findings signify the incorporation of climate change conditions in designing an effective RWHS to select the optimum tank size to cater for future needs. This study is based on the rainfall projection from a single global climate model, which needs to be extended by including projections from several global climate models that will be done in future. However, the findings and the methodology adopted in this study would help the policy makers and the house owners to get an understanding of the impact of climate change conditions on the performances of a RWHS.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.07.038.

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