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Research article

Optimal storage sizing for indoor arena rainwater harvesting: Hydraulic simulation and economic assessment

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ABSTRACT

This study demonstrates a large roof (30,000 m^2) rainwater harvesting (RWH) system in an indoor arena by considering three water demand scenarios (toilet flushing, irrigation and combined demand) via hydraulic and economic assessments. The water saving efficiency (WSE) of the RWH system for each scenario was estimated by a simulation model using historical daily rainfall data (1968–2018). Depending on the water demand, the WSE was found to be independent of tank size when the tank size exceeded 1000 m^3. The results suggest that the WSE of the RWH system is highly influenced by water demand scenarios, and a storage capacity of 400–1000 m^3 would be enough for the applications considered in this study. The economic analysis results further showed that depending on the water demand, the RWH system with a rainwater storage capacity of between 100 and 600 m^3 was more economically beneficial due to its positive cost saving values. The results also showed that depending on the water scenarios, the unit water cost between 0.37 and 0.40 £/m^3 was lower than the mains water cost (0.40 £/m^3). As a result, the use of the RWH system with a tank between 400 and 600 m^3 can be the most favourable range under the conditions considered in this study. Given the variations in water price, rainfall patterns and discount rates, the sensitivity analysis showed that water tariffs and discount rates play a significant role in reducing the unit water cost of the system, maintaining it lower than the mains water cost. A payback period analysis of the RWH system with a 600 m^3 tank revealed that a 5% discount rate and a water price of 3 £/m^3 would be enough to make the RWH system cost effective and that the capital cost could be returned within 10–11 years. This study highlights the need for preliminary sizing of a rainwater tank and an economic analysis of a large rooftop RWH system to maximise the benefits.

1. Introduction

Rainwater harvesting (RWH) has been recognised as an effective management method. RWH can provide benefits, including a supply of non-drinking water for end uses such as toilet flushing, washing machines, washing cars and watering gardens. This can reduce a building's clean water demand and water bills (Campisano et al., 2017). Rainwater collected from roof runoff is the most common type of RWH system as it requires minimum treatment and only consists of a collection area, a conveyance system and a storage tank (Ward, 2007). Imteaz et al. (2013) conducted the reliability analysis of rainwater tanks for the residential sector in four different regions of Melbourne, Australia, using the daily water balance model. They found that the RWH system was significantly correlated with annual rainfall amounts. Fulton (2018) presented results obtained from continuous simulations of RWH systems for large hospitals in the United States and found that mains water consumption can be reduced by about 20–30%, depending on the design parameters and demand behaviour. Lani et al. (2018) assessed the hydraulic and economic performances of small- and large-scale RWH systems in commercial buildings in Malaysia for non-potable water use. The results showed that depending on the rainwater tank size, the maximum achievable reliabilities of RWH systems for the small and large commercial buildings were 93% and 100%, respectively. In addition, their economic analysis showed that depending on the water price scenarios, the optimum payback period (PBP) for larger systems was shorter (3.0–4.5 years) than that of smaller systems (6.5–10.0 years). They concluded that large commercial RWH systems can be more beneficial than small systems. A similar conclusion has been drawn elsewhere

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(Hofman-Caris et al., 2019).

Several scales of RWH systems operate in the UK, ranging from individual houses to commercial buildings for different non-potable water purposes (Fewkes, 2012). Chilton et al. (2000) investigated a prototype RWH system installed in a supermarket with a large roof of 2000 m^2. The results showed that the system's PBP was 12 years, with a collection efficiency of 57.4%. The results also illustrated the significant effects of rainfall trend and tank size on the capital PBP. Hills et al. (2002) demonstrated the use of reclaimed water at London's Millennium Dome, which is one of the largest in-building recycling schemes in Europe. The designed usage for toilets and urinal flushing was up to 500 m^3 per day using a combination of greywater, rainwater and groundwater treated on site. The contribution of rainwater to the total water demand was 19%, with groundwater as the major water source contributing 71%. The low contribution of rainwater was due to a problem concerning storage facilities' utilisation of rainwater collected from a huge roof area of the Dome (100,000 m^2). Although such a huge roof surface area can generate vast quantities of rainwater runoff during raining seasons, the area required for storage units is a constraining factor mainly due to its high capital cost. Thus, the RWH system was designed to utilise a maximum flow of 100 m^3/day by estimating a rainfall of 1 mm/day. In addition to the RWH system, the technical feasibility of the recycling processes utilised at the Dome was evaluated which showed potential water savings. However, detailed information on the RWH system performance at the Dome was unavailable, hindering an evaluation of its economic viability. Concerning the water saving efficiency (WSE) and capital PBP, Ward et al. (2012) investigated the techno-economic viability of a commercial-scale RWH system installed in an office building. The analysis was conducted using empirical monitoring data for an actual building occupied by111 people. The WSE of the RWH system was up to 87%, depending on the tank size, the system's PBP was 6–11 years. The results revealed that a commercial-scale RWH system in a large commercial building can yield more promising results.

The existing studies on the simulation-based optimization of a rainwater harvesting system and cases implemented in the UK (summarised in Tables S1 and S2) have offered some solutions to determine the optimum storage capacity for rainwater harvesting at residential or commercial buildings by taking into account optimizing variables, including cost, reliability, water saving efficiency, green roofs irrigation and runoff capture (An et al., 2015; Bocanegra-Martínez et al., 2014; Okoye et al., 2015; Ruso et al., 2019; Sample and Liu, 2014; Ward et al., 2012). However, it is often difficult to validate a global optimum for any conclusions and any applications as identifying an optimal storage size for a RWH system is highly depends on water demands, seasonal conditions, economics and infrastructure at a given geographic area (Alim et al., 2019; Semaan et al., 2020). Besides, in the UK, there has been a wider implementation of rainwater harvesting at commercial scales due to their financial benefit (Campisano et al., 2017), there is limited information for closing the implementation and investment gap in the rainwater reuse. Therefore, there is still a need to demonstrate practical ways to increase the applicability and cost-benefit of a large-scale rainwater harvesting system. This study will provide significant step towards local and water circular solutions for further study on the impact of urban densification and climate change strategies on water resource management. This study, therefore, investigates an optimal size of the rainwater storage capacity of a RWH system in an indoor arena via daily water balance simulations and economic analysis approaches.

2. Methodology

2.1. Study area description

Filton Airfield is a suburban town and civil parish in South Gloucestershire, Bristol, South West England, United Kingdom (Fig. 1). This former airfield site, which hosted the development of the Concorde airplane in the 1960s and 1970s, will be a new urban development comprising more than 2600 new houses and 24 ha of commercial space, as well as new schools, nurseries and green spaces. There exists the three-bay Brabazon Hangar, which was built in 1946. This will be transformed into a premier live entertainment venue with a capacity about 20,000 visitors, named as YTL Arena (YTL, 2020). The total roof area of the arena is about 30,000 m^2: 8500 m^2 (East), 13,000 m^2 (Centre) and 8500 m^2 (West).

2.2. Rainfall data collection and trend analysis

Historical daily rainfall records from 1968 to 2018 of the Filton Airfield site were obtained from the UK Centre for Ecology & Hydrology and Weather Underground, which is an online platform where local weather information is available (Tanguy et al., 2019; Underground, 2020). The rainfall data were collected using the nearest meteorological station to the Filton Airfield site (approx. 3 km).

The average annual rainfall and annual rainy days (i.e. >1 mm) are illustrated in Fig. 2. The annual average rainfall amount is 811 mm, and the annual average rainy days is 128 days. Two years (2000 and 2012) received significant precipitation of 1112 and 1125 mm, respectively, while in 1973 and 2010 the average annual rainfall was 569 and 584 mm, respectively. These results correspond to the annual rainy days. The years 2000 and 2012 counted 159 and 162 rainy days, respectively, while for 1973 and 2010 there were 97 and 113 rainy days, respectively. The seasonal variability of precipitation in Filton Airfield is presented in Supplementary Information (Figure S1).

The precipitation concentration index (PCI) and standard precipitation index (SPI) values were further analysed to confirm the climatic regimes (dry, normal and wet years). The PCI proposed Oliver (1980) was used to evaluate the fluctuation in rainfall amounts based on the monthly precipitation of 50 years. The SPI can provide a better understanding of qualifying rainfall variability over the selected period. From historical rainfall data and the analysed PCI and SPI values, three different years were selected to represent dry year, average year and wet year. Detail information, including equations employed for PCI and SPI calculations can be found in Supplementary Material.

Fig. 1. (a) Location of Filton Airfield and rainfall catchment and (b) Filton Airfield's development master plan and water reuse applications (YTL, 2020).

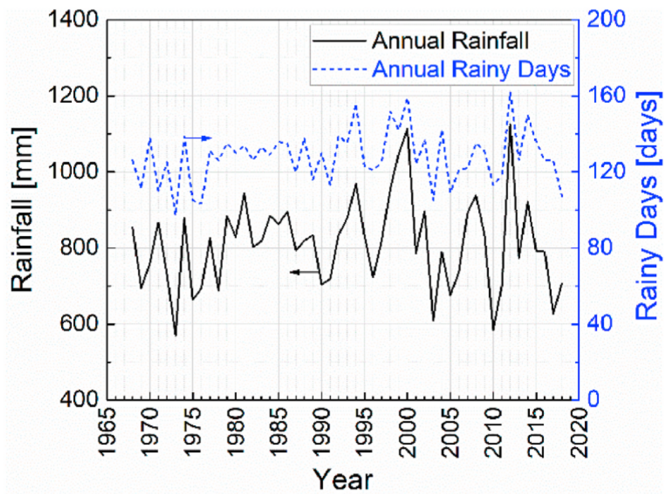

Fig. 2. Variations of annual average rainfall and annual rainy days (1968–2018).

2.3. End-use profile

It is well known that the most common applications of rainwater harvested from rooftops of non–residential buildings include toilet flushing and garden irrigation (Matos et al., 2015; Wang and Zimmerman, 2015). This study assumed four different water use scenarios: (a) toilet flushing within the YTL Arena (YA), (b) irrigation for the Brabazon Park (BP), (c) the Filton Golf Course (FG) and (d) a combination of toilet flushing and irrigation. Equations to determine the water demand for each application are presented in Table S3.

For toilet flushing demand within the YA, four different capacities were assumed to be met every functional day. An equal proportion of males and females was considered. For toilet use, half the males used urinals and the other half used toilet bowls. Toilet bowls were assumed to use 6 L per flush, while the urinals used 3.6 L per flush (Hills et al., 2002; Zadeh et al., 2013). The annual operation days was assumed to be 365 (Hills et al., 2001). An irrigation plan was assumed to be in operation when there is no rain from May to October for BP and FG (Fig. 1 and Table 1). The volume of irrigation water was assumed to be 5 L per square meter per day (Matos et al., 2013; Roebuck et al., 2011). Table 1 presents the values used for water demand estimation for each scenario.

Table 1
Water demand scenarios and values used for each scenario (baseline).

Scenario			Unit	Value
Single use	YTL Arena (YA) toilet flushing (TF_{YA})	Visitors (TF_{YA1}, TF_{YA2}, TF_{YA3}, TF_{YA4})	Person/day	2,000, 5,000, 10,000, 20,000
		Toilet	L/flush	6
		Urinal	L/flush	3.6
		Frequency	Flush/capita/day	2
	Irrigation (IR_{BP} & IR_{FG})	Brabazon Park (BP) (IR_{BP1} & IR_{BP2})	ha	6 and 12
		Filton Golf Course (FG) (IR_{FG1} & IR_{FG2})	ha	23 and 46
		Frequency (May–October)	Irrigation/week	1
		Water use	L/m^2/day	5
Combined use	50%TF + 50%IR and 70%TF + 30%IR			

2.4. Water balance simulation

In this study, a spreadsheet-based daily water balance model was developed based on the yield after spillage (YAS) concept (Figure S2) developed by Jenkins and Pearson (1978) due to its highly accurate and conservative analysis results (Campisano and Modica, 2012; Wang and Zimmerman, 2015; Ward et al., 2010b). It was assumed that a RWH system for the YA has a general configuration (Figure S2), which consists of the basic functions of treatment of collected rainwater (i.e. first flush and filter), conveyance to a storage tank and distribution for end-uses. The water balance models used in this study are presented in Table S3.

Fig. 3 shows the steps computed and the statement taken at each time step for developing the tank volume model. It determines the performance of the RWH system in terms of water saving efficiency under various water demand scenarios and tank sizes. Thus, the result indicates an optimal storage size for a given water application in this study. It was assumed that the storage tank was connected to the mains supply and located underground; therefore, the loss of water by evaporation from the tank was not considered in this study. In addition, a mains top-up volume of 1/3 of the tank capacity was adopted in this study (Amos et al., 2018). This study considered a roof runoff coefficient of 0.85 for metal sloping/curved roof (Farreny et al., 2011b). In the calculation of the harvested rainwater, if the rainfall was less than or equal to the first flush volume, the volume of the harvested rainwater was considered to be 0. However, if it was higher than the first flush volume, the volume of the harvested rainwater was calculated using Eq. (S6). Meanwhile, if there was no rain in the previous day, the first 1 mm of rainfall was taken out from the rainfall in the current day and then calculated using Eq. (S6) (Martinson and Thomas, 2009; Meera and Ahammed, 2018). Nevertheless, it has to be acknowledged that the first flush volume is highly dependent on the antecedent dry period, meaning that the long dry period causes the pollution build-up on the roof, and hence a more detailed approach is needed to control the water quality, indicating that the effect of antecedent dry days (i.e. climate change) on the first flush volume and quality needs to be considered. However, since the scope of this study is to demonstrate the quantity and storage capacity of a RWH system for the YA at Filton Airfield for selected water uses, in the current study, the first flush behaviour was simplified by setting a fixed first flush volume regardless of the total load. The filter coefficient (FC) was considered to be 0.9 (Ward et al., 2010a), with the tank size varying from 100 to 2000 m^3.

The WSE (%) is defined as the average percentage of water demand satisfied by rainwater yield for each year of the rain data series (i.e., 50 years) and can be calculated thus:

$$WSE,\ \% = \frac{\sum_t^T Y_t}{\sum_t^T D_t} \times 100 = \left(1 - \frac{\sum_t^T M_t}{\sum_t^T D_t}\right) \times 100$$

where M_t is the volume of mains top-up (m^3), Y_t is the rainwater yield from the storage tank (m^3/day), and D_t is the water demand during time step t (m^3/day). If the WSE value is 100% (M = 0%), only rainwater from the storage is used. However, if it is 0% (M = 100%), only the mains water is used. WSE was used as an indicator to determine the optimum tank size of the given conditions in this study.

2.5. Cost analysis

Rainwater tank sizing can be addressed using financial scenarios. Life cycle costing (LCC) is an economic analysis technique for the evaluation of the financial feasibility of a system over its life span (Farreny et al., 2011a; Nnaji and Aigbavboa, 2020). LCC is defined as the sum of the capital and the total operational expenses over the lifetime of the project (CAPEX and OPEX). CAPEX includes the investment and installation costs, including storage tank, filter, pump, a data logging unit, delivery and labour while OPEX includes the operation costs (i.e., water and energy costs), routine and infrequent maintenance and

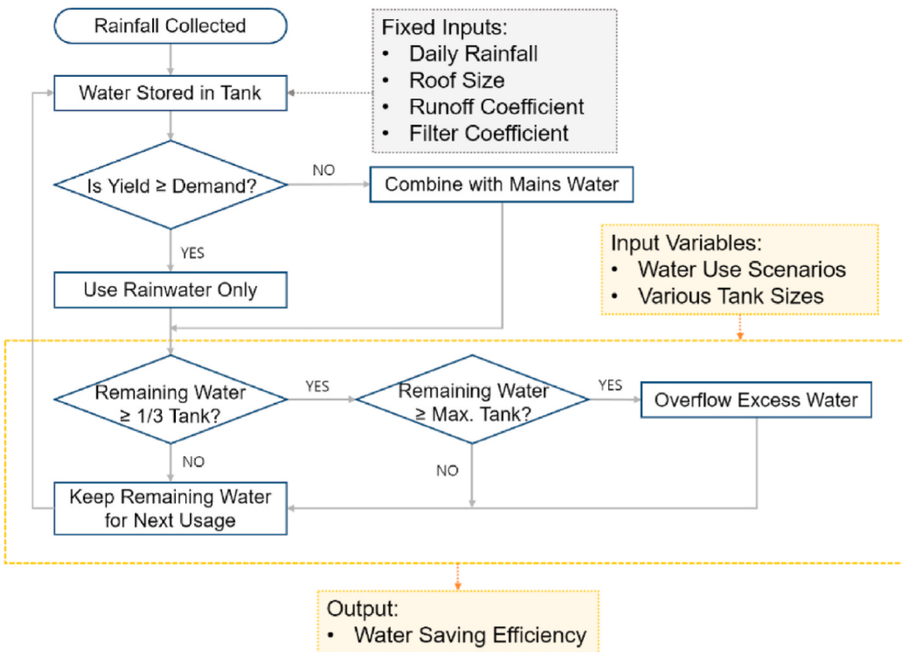

Fig. 3. The flow chart created to visualise a spreadsheet-based daily water balance model developed in this study based on the system's inputs and outputs (i.e. supply and demand streams).

replacement costs. It has to be acknowledged that the specific system components and associated costs for this study were adopted from both RainCycle tool, which focuses on UK use (Roebuck and Ashley, 2007) and previous studies (Roebuck et al., 2011; Słyś and Stec, 2020; Wang and Zimmerman, 2015).

The net present value (NPV), standardised to British Pound Sterling (GBP, £), was calculated by the sum of present values (PV) of the cost over the project life-time (Christian Amos et al., 2016; Umapathi et al., 2019). PV is a well-known and accepted financial term for calculating the present-day of an amount of money that is received at a future date (Linares et al., 2016). The annualised OPEX cost was then determined using capital amortisation (Christian Amos et al., 2016; Kim et al., 2017). The final unit water cost per m^3 of rainwater and mains water is the sum of capital cost and annualised expenditure cost. Therefore, the optimal tank size was assumed to correspond to the maximum value of savings over the project time (£) and the minimum value of total water cost per cubic metre of water supplied (£/m^3). The prices of drinking water and sewage considered in this study were based on the non-household services with a fixed cost. Equations and input parameters used for economic calculations are presented in Table S3 and Table S4, respectively.

2.6. Sensitivity analysis

The main variables in determining financial performances of the RWH system are rainfall variations (i.e., dry, wet and normal), mains water tariffs (i.e., the predicted cost) and discount rates (Lani et al., 2018; Zhang et al., 2018). A sensitivity analysis was conducted to evaluate the effects of these factors on the economic feasibility of the RWH system in terms of unit water costs with variations of the storage sizes. The optimal storage capacity was determined based on the unit water cost being lower than the mains-only supply water for the same water demand scenarios.

Water and sewage tariffs were assumed to increase by 1.8% and 0.8% per year, respectively (Roebuck et al., 2011). Thus, the predicted water for the next 10 and 20 years would be 2.9 £/m^3 and 3.3 £/m^3, respectively. Based on this estimation, the water price ranged from 1 to 3 £/m^3. In addition, three different years were selected to represent dry, wet and normal years based on the SPI analysis results. According to the LCC approach, a discount rate of 5% was taken as the baseline (Table S4). Since specific guidance on the selection of appropriate discount rates for the adaptation of the RWH system was unavailable, three possibilities of 5%, 10%, and 15% used in previous studies were adopted for this study (Matos et al., 2015; Nnaji and Aigbavboa, 2020; Roebuck et al., 2011). In this regard, the PBP, which is the time required to recover the capital investment, was estimated by considering water tariffs (2 and 3 £/m^3) and discount rates (5%, 10% and 15%).

3. Results and discussion

3.1. Rainfall variations

Although the historical rainfall trend (Section 2.2) indicates that the driest and wettest years are 1973 and 2012 respectively, the PCI and SPI

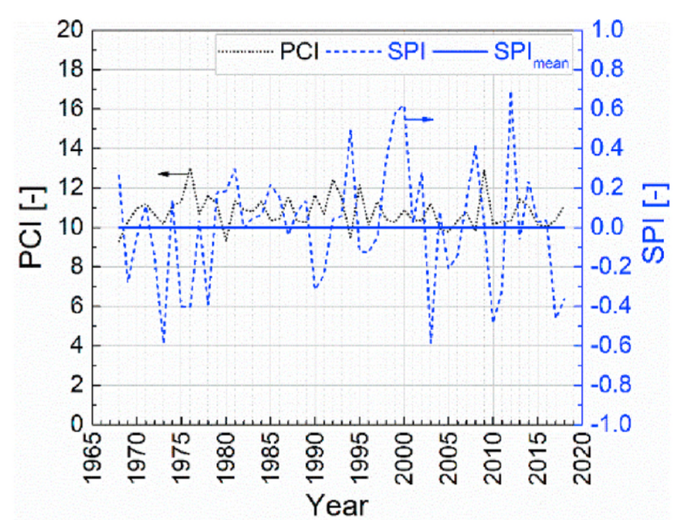

Fig. 4. Variations of the precipitation concentration index (PCI) and standard precipitation index (SPI) from 1968 to 2018.

values were further analysed to confirm the climatic regimes (dry, normal and wet years). Fig. 4 shows that the PCI values ranged from a minimum value of 9.3 to a maximum value of 13. Notably, the PCI value did not exceed 16 for Filton Airfield. This result indicates Filton Airfield's homogeneous rainfall distribution with moderate seasonality. Furthermore, as shown in Fig. 4, the SPI values remained between −0.6 and 0.7 (near normal and moderately wet), indicating that Filton Airfield tends to have maintained its moist conditions, which would be more beneficial for RWH even during the dry season. Throughout the historical period considered in this study, the highest and lowest SPI values were observed in 1973 and 2012 (−0.59 and 0.69, respectively). In addition, the SPI value for 1982 was −0.003, which is close to the average SPI value of 0. Therefore, 1973, 1982 and 2012 were selected for dry, normal and wet years, respectively. This study conducted the analysis of the economic impacts of rainfall patterns on the RWH system using the rainfall data of those years (Section 3.4). Overall, Filton Airfield has shown a moderate rainfall trend for the last 50 years, suggesting that the impacts of rainfall changes on the performance of the RWH system would be less significant than those of the water demand scenarios. This will be conducted as a separate study in the future using real rainfall data collected within Filton Airfield.

3.2. Effects of water demand scenarios on WSE

Fig. 5(a) illustrates the impacts of the toilet flushing scenarios (TF_{YA1}, TF_{YA2}, TF_{YA3}, TF_{YA4}) on the WSE of the RWH system with the storage capacity varying from 100 to 2000 m^3. For toilet flushing (TF_{YA1}, 22 m^3/day), when the storage capacity exceeded 800 m^3, the WSE of the RWH system remained constant, with a WSE of 98.3%. However, for a tank of between 400 and 800 m^3, the WSE of the system was between 21.8% and 42% for TF_{YA3} and TF_{YA4} (108–216 m^3/day). However, for TF_{YA2} (54 m^3/day), when the storage size exceeded 1800 m^3, the WSE of the RWH system was 79.8%. For irrigation, the use of rainwater for different irrigation areas was assumed: 50% and 100% for the Brabazon Park (BP, IR_{BP1} and IR_{BP2}) and the Filton Golf course (FG, IR_{FG1} and IR_{FG2}). For a tank size of less than 800 m^3, the WSE of the system was varied from 12.7% to 42% for $IR_{BP1,}$ showing the most sensitive to the storage capacity and followed by IR_{BP2}, IR_{FG1} and IR_{FG2}. However, when the storage size exceeded 800 m^3, the WSE of the RWH system remained constant between 7.2% and 14.1%, depending on the water demand (580–1159 m^3/day) for IR_{FG1} and IR_{FG2} as shown in Fig. 5 (b). Similarly, for IR_{BP1} and IR_{BP2} (151–302 m^3/day), the WSE of the RWH system for a tank 1000 m^3 was between 25.7 and 46.1%. However, when considering the tank's infinite capacity, the WSE was between 33.7% and 67.4%, depending on the water demand. Although a higher WSE was achievable from the system with a large storage tank, such a large capacity would increase the installation costs (Umapathi et al., 2019), hence 1000 m^3 for the maximum tank size which maximises the WSE of the system for this application. For the combined use of toilet flushing and the irrigation of BP, at a threshold value of 800 m^3, the WSE showed 24.1% and 25.6% for different ratios: 70:30 (242 m^3/day) and 50:50 (259 m^3/day), respectively, whereas, for the combined use of toilet flushing and the irrigation of the FG, the storage capacity exceeded 600 m^3, the WSE was varying between 11.8% and 14.7%, depending on the water demand (499–688 m^3/day). These results suggest that the WSE of the RWH system is highly influenced by the water demand scenarios. They further suggest that the threshold value ranged from 400 to 1000 m^3, depending on the water demand scenarios. As a result, a storage capacity of 400–1000 m^3 can be perceived as the optimal size for all scenarios considered in this study.

The results in Fig. 5 indicate that the WSE of the RWH system for this application can be enhanced by controlling the water demand scenarios, suggesting the importance of the water demand profile for the design and operational parameters of the RWH system. Larger rainwater storage volumes result in less overflow and more yield, hence a higher WSE of the RWH system. In contrast, smaller storage tanks limit the collection

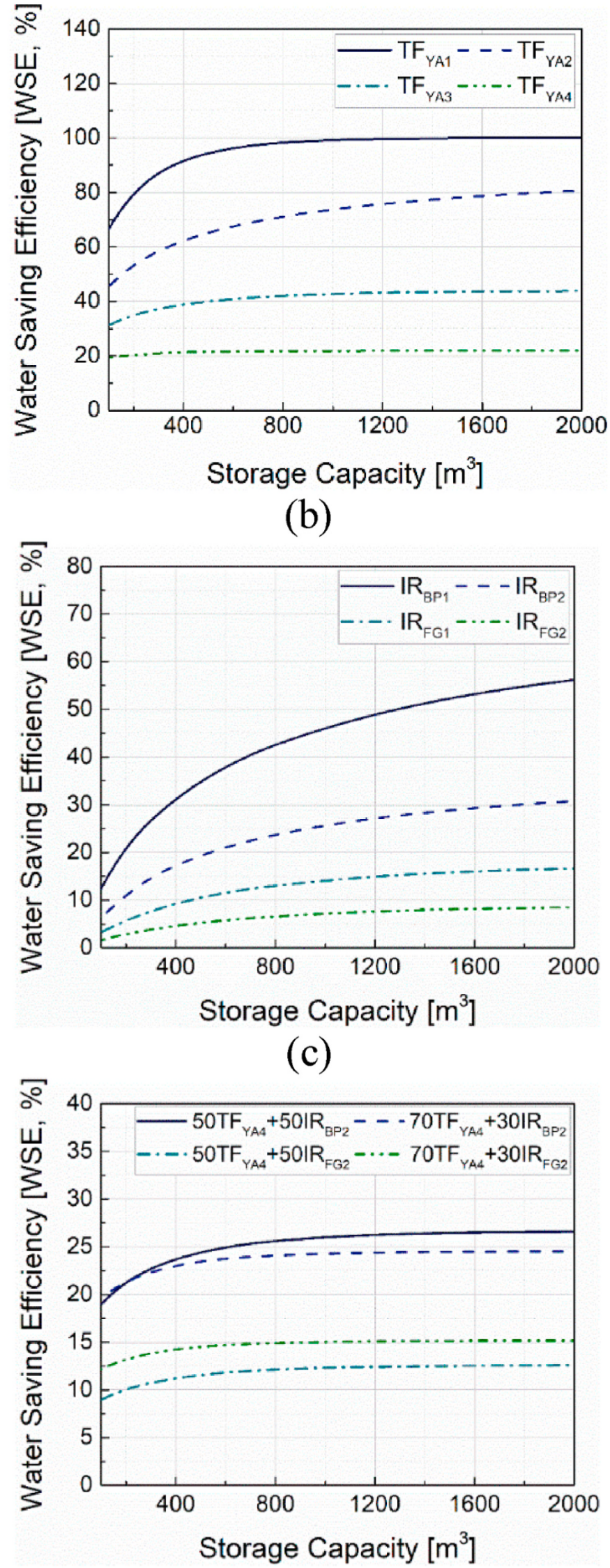

Fig. 5. Variations of water saving efficiency values as a function of storage capacity for single and combined use scenarios (a) YA toilet flushing with varying numbers of visitors (b) irrigation: BP and FG and (c) combined use: YA toilet flushing + Irrigation.

of rainwater, resulting in more overflow and less yield, hence a lower WSE of the RWH system. In this regard, the huge roof area of the arena requires a large storage tank, which could enhance the WSE of the RWH system and reduce the mains water consumption, albeit at higher capital and operational costs (Silva et al., 2015; Wang and Zimmerman, 2015). In this analysis, the WSE of the RWH system with different water demand scenarios was evaluated using the historical rainfall data. These results affirm the significance of the water use profiles in the performance of the RWH system. However, changes in future rainfall patterns due to climate change need to be considered in the design and optimization of the system, as the impacts of rainfall changes on the WSE of the RWH system are significant (Zhang et al., 2018).

3.3. Cost-effective storage sizing

To identify an optimal storage size of rainwater collected from the roof of the YA, the cost-effectiveness of the RWH system with different application scenarios was evaluated in terms of the cost savings of over 50 years and the unit water cost as a function of tank size variations (100–2000 m^3). Fig. 6 shows the cost savings, which include the difference between the total costs of the mains-only supply system and the RWH system for three different applications scenarios, toilet flushing (a), irrigation (b) and a combined use (c). Positive values of cost savings correspond to a range of storage sizes, which make the RWH system economically feasible for the given scenarios.

Fig. 6(a) shows the changes in the cost savings of toilet flushing with different numbers of visitors, as the storage capacity of the RWH system increases. The cost savings of TF_{YA1} and TF_{YA2} (21.6 and 54.0 m^3/day, respectively) remained negative values regardless of the tank sizes, indicating that the systems for these water demand scenarios are economically unfeasible. However, the systems can become economically viable if the water demand grows higher than 54.0 m^3/day. For example, the cost savings of TF_{YA3} and TF_{YA4} were shown to be positive values at a tank size between 100 and 600 m^3. However, when the tank size goes beyond 600 m^3 the result shows that the RWH systems for these applications are no longer economically beneficial mainly due to the increase of the tank size thus capital cost. This indicates that for toilet flushing in the YA, RWH systems with a tank size between 100 and 600 m^3 would be economically feasible. As shown in Fig. 6(b), when the collected rainwater was only used for irrigation applications (BP and FG), the cost savings of the RWH system were shown to be negative values for all tank sizes although its variation was more sensitive to the tank sizes, less than 800 m^3. For irrigation scenarios, this study assumed that that irrigation activities occurred between May and October (as mentioned in Section 2.3), discharging the excess runoff into a sewer drainage system. This practice increased the OPEX costs of the RWH systems, thus illustrating the negative values of cost savings regardless of the tank sizes.

Fig. 6(c) displays the combined use of the RWH systems with different application ratios of toilet flushing to irrigation (50 TF+50IR and 70 TF+30IR). The cost savings across all four scenarios give positive values at a tank size between 100 and 600 m^3, while the values turn negative at above 600 m^3. This indicates that combined regular and irregular water applications could make the system more cost-effective, thus suggesting an optimal storage capacity of between 100 and 600 m^3 for the RWH system at the YA.

Furthermore, Fig. 7 presents the unit rainwater costs for single and combined use scenarios ($TF_{YA3\&4}$, $50TF_{YA4} + 50IR_{BP2\&FG2}$, and $70TF_{YA4} + 30IR_{BP2\&FG2}$) with selected storage capacity variations from 100 to 1000 m^3, which are based on the results obtained from Fig. 6. The unit rainwater cost decreased gradually in tandem with an increase in the storage capacity, ranging from 100 to 200 m^3, depending on water demand scenarios. After that, the unit rainwater cost rapidly increased, exceeding that of the mains-only supply water cost. For example, at 700 m^3, the unit rainwater costs for across scenarios were between 0.42 and 0.45 £/m^3. From these results, it can be concluded that a storage

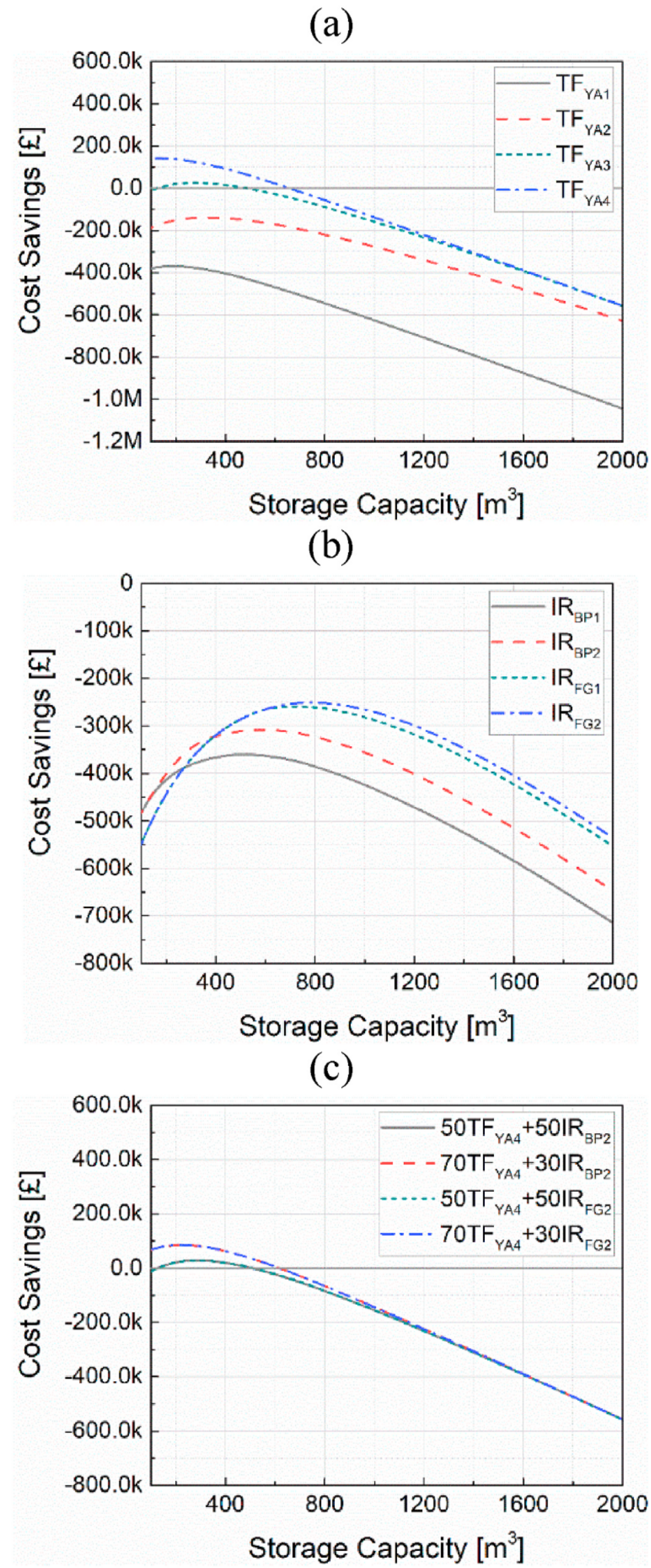

Fig. 6. Cost savings as a function of storage capacity ranging from 100 to 2000 m^3 (a) YA toilet flushing with different numbers of visitors, (b) irrigation of BP and FG and (c) combined use: YA toilet flushing + BP and FG.

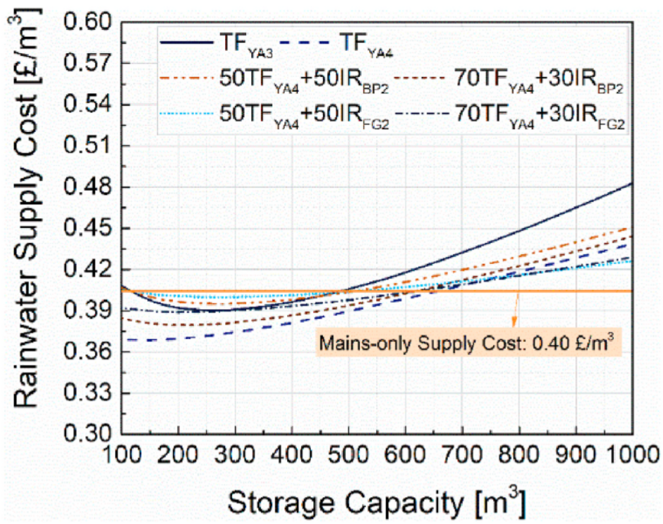

Fig. 7. Harvested rainwater cost and mains-only supply cost as a function of storage capacity ranging from 100 to 1000 m^3.

capacity of between 100 and 600 m^3 would be enough for the RWH system in the YA to maintain the unit rainwater cost range from 0.37 to 0.40 £/m^3, depending on the costs of water use scenarios, which are equal to or lower than the mains-only supply water cost (0.40 £/m^3).

The results of the economic analysis conducted in this study suggest that there is a correlation between the total cost of a RWH system and the level of water consumption. This means that the water demand pattern dominates the overall economic performance of the RWH system (Ghimire et al., 2017; Hajani and Rahman, 2014; Słyś and Stec, 2020; Ward, 2007). Considering hydraulic and economic performances, consequently, the use of the RWH system with a tank size between 400 and 600 m^3 for toilet flushing, coupled with the combination of toilet use and irrigation, can be the most favourable scenario under the conditions considered in this study.

3.4. Sensitivity analysis

Water prices, rainfall conditions, and discount rates are the three major factors contributing to the economic viability of RWH systems (Amos et al., 2018). A sensitive analysis was performed to assess those parameters and identify ways to further reduce the unit cost of rainwater of the RWH system compared to the unit cost of mains-only supply. Based on the results obtained from the previous section, a storage tank of 600 m^3, which could maximise the WSE and maintain the unit rainwater cost lower than the mains-only supply cost calculated using a 5% discount rate and 1.05 £/m^3 water price, and three water application scenarios were chosen: toilet flushing (TF_{YA4}) and combined use of toilet flushing and irrigation ($50TF_{YA4} + 50IR_{BP2}$ and $50TF_{YA4} + 50IR_{FG2}$).

Fig. 8(a) shows the sensitivity analysis of changes in water tariffs ranging from 1 to 3 £/m^3. As the water tariffs increased from 1 to 3 £/m^3, the mains-only supply costs increased accordingly. The baseline value in this figure represents the water tariff of 1.05 £/m^3 (Table S4). The unit rainwater cost across all scenarios increased in tandem with an increase in water tariffs. At lower water price (<1.05 £/m^3, baseline), the unit rainwater cost of all scenarios was slightly higher than the mains water cost, while, at higher water price (>1.05 £/m^3, baseline), the unit rainwater cost remained below (0.39–1.07 £/m^3) the mains water cost (0.40–1.16 £/m^3) under the given conditions. The results confirm that the economic performance of RWH systems is sensitive to variations of mains water prices (Lani et al., 2018).

Furthermore, Fig. 8(b) shows how the change in the climate conditions (dry, normal and wet) affected the unit rainwater cost of each scenario. The SPI of 0 represents the average rainfall condition. When

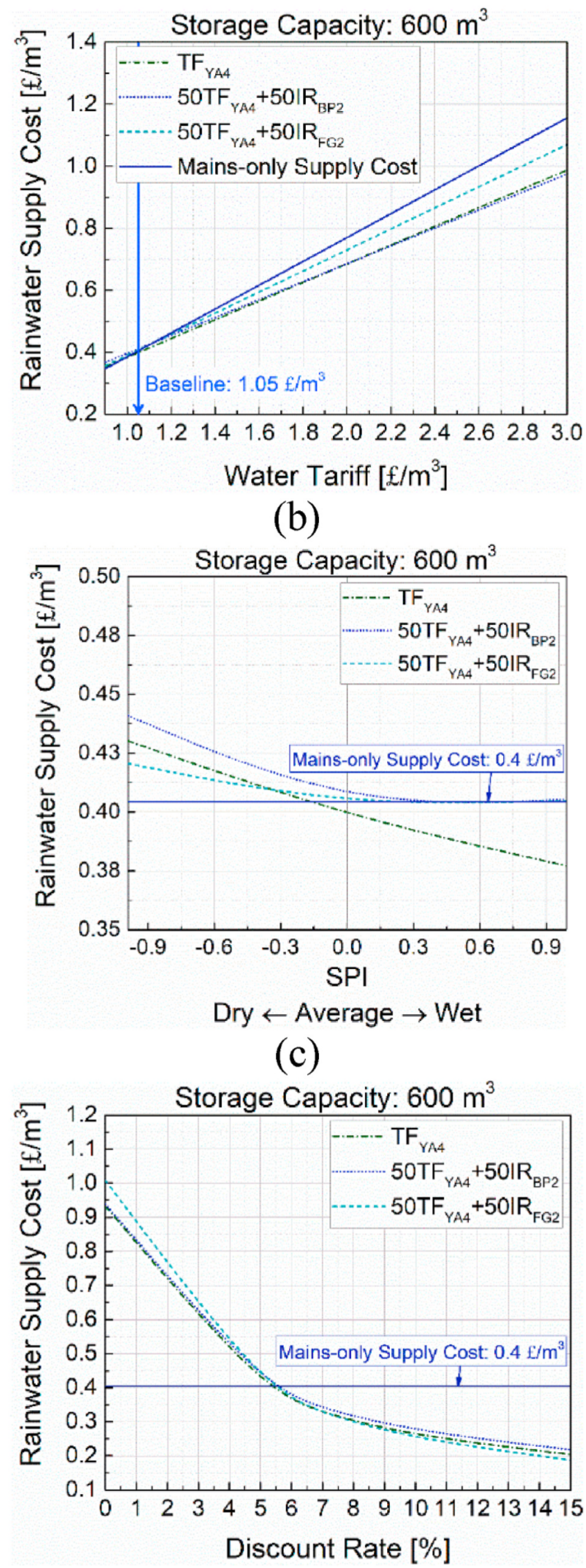

Fig. 8. Sensitivity analysis of the rainwater cost as a function of variations of (a) water tariff (1–3 £/m^3) (b) rainfall (SPI values refer to dry, normal and wet conditions) and (c) discount rate (0%–15%), considering three different application options: toilet flushing for 20,000 people and combined use of toilet flushing and irrigation.

the SPI values were below average (i.e. dry conditions), the mains-only water cost (0.40 £/m^3) was lower than the unit cost of rainwater ranging from 0.42 to 0.44 £/m^3, depending on the water use scenarios and the higher mains water requirements. In contrast, when the SPI values turned positive (i.e. wet conditions), the unit rainwater costs of all scenarios ranged between 0.38 and 0.40 £/m^3, depending on the water demand scenarios. During the wet years, the maximum achievable savings ranged between 3.7% and 12.3%, depending on the scenarios. Despite no significant reduction in the unit rainwater costs, the results indicate that the duration of the wet period could play a crucial role in enhancing the economic performance of RWH systems, as reported in previous research (Imteaz et al., 2017; Zhang et al., 2018).

The impacts of changes in the discount rates (0%–15%) on the unit water costs of RWH systems are shown in Fig. 8(c). The unit rainwater costs across all scenarios were higher than the unit cost of mains water (0.40 £/m^3) at the discount rate of below 5.5% which was lower than the mains water cost at the discount rate of above 5.5%. For toilet flushing, for example, the unit water cost was 0.94 £/m^3 at a 0% discount rate, while it was 0.21 £/m^3 at a 15% discount rate, which suggests a 77.3% reduction. This indicates that the economic results of the RWH systems were highly influenced by discount rates. Although no clear idea exists to determine the exact discount rates of specific applications, generally, social discount rates for institutions (e.g. water utilities and private companies, 10% and 15%, respectively) should be lower than the rates considered for individuals (e.g. homeowners, 5%) (Roebuck et al., 2011; Voinov and Farley, 2007). This sensitivity analysis illustrates the potential for making the RWH system of the YA cost-effective by considering the discount rates between 5.5% and 15%.

Table 2 presents the PBP of three selected scenarios considering two variables: the future water cost of 2 and 3 £/m^3 and the discount rates of 5%, 10% and 15%. Overall, no significant difference exists between water demand scenarios. For toilet flushing, when considering a future water price of 2 £/m^3, the PBP of the system is 19 and 35 years for 5% and 10% and above 50 years for 15%. However, when considering a future water price of 3 £/m^3, the PBP of the system is 10, 12 and 18 years for 5%, 10% and 15%, respectively. These results indicate that it is possible to achieve a shorter PBP at a lower discount rate. However, the water price increase could play a more significant role in the economic feasibility of the proposed RWH (Domènech and Saurí, 2011; Khastagir and Jayasuriya, 2011). The results suggest that the RWH system of the YA could be economically feasible in the light of a discount rate of lower than 10% and a water price of higher than 2 £/m^3. For the purpose of implementing RWH systems in a sustainable way, there would be an opportunity to negotiate a lower tariff for both drinking water and sewage as charges for commercial buildings are directly correlated to the amounts of the used water and the discharged sewage, the higher the water use or the sewage discharge the lower the charges. This can result in the further improvement of the economic feasibility of the RWH of the YA.

Table 2
Financial results of the RWH strategies for a 600 m^3 tank.

Scenario		TF_{YA4}	$50TF_{YA4}+50IR_{BP2}$	$50TF_{YA4}+50IR_{FG2}$
Water price = 2 £/m^3	PBP (years) at 5%	19	22	22
	PBP (years) at 10%	35	50	50
	PBP (years) at 15%	50	50	50
Water price = 3 £/m^3	PBP (years) at 5%	10	11	11
	PBP (years) at 10%	12	15	14
	PBP (years) at 15%	18	23	23

4. Implication

The implementation of RWH has two main benefits: first, it saves mains water, and second, it decreases the amount of rainwater runoff. Although the former benefit has been examined in previous studies, the latter has rarely been addressed because most of the studies have considered a combined sewage system. In other words, those studies did not consider the water disposal cost in the economic analysis since spillage from a rain tank is discharged to a combined sewer network, rendering the contribution of the water disposal cost to the total cost of the system insignificantly compared with other economic factors such as mains water price (Abas and Mahlia, 2019; Domènech and Saurí, 2011; Lade and Oloke, 2017; Nnaji and Aigbavboa, 2020). It is worth noting that in the Filton Airfield development, the mains water supply and the sewage network will be managed by two different water utilities: Bristol Water plc and Wessex Water Services Ltd, respectively (Table S4). In addition, as mentioned above, this study considered the water disposal cost, as it is a site-specific study, and all the assumptions were made in the light of Filton Airfield's development master plan. In the plan, this area is expected to have a separate sewage network system. Thus, this study considered the costs related to mains water supply and sewer discharge separately. The results of this analysis imply that the use of the RWH system allows reducing mains water consumption. However, if the harvested rainwater is not continuously utilised for non-potable end uses, the RWH system would become economically unfeasible. It is worth noting here that, although a detailed environmental impact analysis was not included within the current scope of the study, rainwater collection from large roof area could contribute to management of urban runoff volume and nonpoint source pollution, conservation of water resources and less drinking water consumption as reported in previous studies (Li et al., 2018; Pavolová et al., 2019; Wang and Zimmerman, 2015). It has been also reported that green rooftop RWH systems is highly beneficial to mitigate Urban Heat Island (UHI) and thus climate change (i.e. global warming potential) (An et al., 2015; Li et al., 2018). Likewise, if a rooftop garden is considered for the YA and other commercial buildings, it can be expected a similar cooling effect in the Filton area and thus climate change adaptation.

5. Conclusions

This study presented the results of a feasibility assessment of RWH from the rooftop of the YTL Arena near Filton Airfield (Bristol, UK) for non–potable purposes. Three water demand scenarios were considered: toilet flushing, irrigation and the combined use of toilet flushing and irrigation. The RWH systems of these applications were compared with the mains-only alternatives using hydraulic and economic indicators, thus determining the optimal rainwater storage size.

The results suggested that when the storage capacity was between 400 and 1000 m^3, the water saving efficiency of the system could be obtained between 7.2% and 98.3%, depending on the water demand considered in this study. The results of the economic analysis further confirmed that the economic performance of the RWH systems in terms of cost savings and unit water cost was significantly influenced by water demand scenarios. Cost savings values of the RWH system for irrigation use requiring significant water consumption compared to toilet flushing and combined use scenarios remained negative, regardless of the tank size, which was not cost-effective. However, when the RWH system was used for toilet flushing and combined toilet flushing and irrigation, positive cost savings were observed at the tank between 100 and 600 m^3, indicating that the tank size of the given applications should be smaller than 600 m^3. To maintain the unit rainwater cost lower than the mains-only supply cost (0.40 £/m^3), the results showed that the storage capacity of between 100 and 600 m^3 would be enough for the implementation of RWH at the YA (0.37–0.40 £/m^3). Consequently, considering the WSE and economic analysis results, the use of the RWH system with a tank between 400 and 600 m^3 for toilet flushing, coupled with the combination of toilet use and irrigation, can be the most favourable scenario under the conditions considered in this study.

At the fixed tank size of 600 m^3, the sensitivity analysis was conducted by considering three variables: water fees, rainfall changes and discount rates. The results indicated that the RWH system with a 600 m^3 tank is cost-effective when the discount rate reaches 10% or when the water price is higher than 2 £/m^3. Furthermore, the impacts of rainfall changes on the unit rainwater costs illustrated the importance of designing the water use scenarios of RWH systems, as unexpected rainfall changes are one of the main constraining factors affecting the performance of RWH systems. Moreover, a 5% discount rate and a water price of 3 £/m^3 yielded the shortest PBP for all water demand scenarios between 10 and 11 years.

It is important to note that more accurate results can be obtained if real rainfall data from Filton Airfield and future rainfall events become available on climate change. Thus, the conclusions drawn from this study will be compared with post-installation monitoring data on the actual performance of the RWH system within the YA in the near future, thus promoting the acceptance of RWH in urbanisation schemes as a sustainable management strategy. For practical purposes, the results provide wider support for other new towns and cities that are similar to Filton Airfield, to determine how mains water supply and downstream stormwater infrastructures benefit RWH systems in buildings. YA's experience with RWH systems in urban development would be of great interest to other new towns and cities.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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