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Improving the Multi-Objective Performance of Rainwater Harvesting Systems Using Real-Time Control Technology

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Abstract: Many studies have identified the potential of rainwater harvesting (RWH) systems to simultaneously augment potable water supply and reduce delivery of uncontrolled stormwater flows to downstream drainage networks. Potentially, such systems could also play a role in the controlled delivery of water to urban streams in ways which mimic baseflows. The performance of RWH systems to achieve these three objectives could be enhanced using Real-Time Control (RTC) technology to receive rainfall forecasts and initiate pre-storm release in real time, although few studies have explored such potential. We used continuous simulation to model the ability of a range of allotment-scale RWH systems to simultaneously deliver: (i) water supply; (ii) stormwater retention; and (iii) baseflow restoration. We compared the performance of RWH systems with RTC technology to conventional RWH systems and also systems designed with a passive baseflow release, rather than the active (RTC) configuration. We found that RWH systems employing RTC technology were generally superior in simultaneously achieving water supply, stormwater retention and baseflow restoration benefits compared with the other types of system tested. The active operation provided by RTC allows the system to perform optimally across a wider range of climatic conditions, but needs to be carefully designed. We conclude that the active release mechanism employing RTC technology exhibits great promise; its ability to provide centralised control and failure detection also opens the possibility of delivering a more reliable rainwater harvesting system, which can be readily adapted to varying climate over both the short and long term.

Keywords: rainwater harvesting system; real-time control; baseflow restoration; water supply; stormwater retention; continuous simulation

1. Introduction

Rapid urbanization since the mid-20th century has markedly increased the amount of impervious cover, resulting in gross changes to the natural water balance by decreasing infiltration and evapotranspiration [1–3]. Such changes greatly increase the volume and frequency of surface runoff and concurrently decrease groundwater recharge [1].

The increase in the volume and frequency of surface runoff from impervious surfaces greatly increases flooding risk, which has led to the construction of hydraulically efficient drainage infrastructure [4,5]. However, constructed drainage networks, which directly drain the impervious surfaces to receiving waters, while further limiting the natural infiltration process, are widely recognised as severely altering both low and high flow aspects of the stream flow regime [5,6], leading to urban stream degradation and biodiversity loss [7–13].

Stormwater control measures (SCMs) have been used for many years to manage urban runoff. Perhaps the earliest of these were simple on-stream retarding basins to reduce peak flows, but a wide range of SCMs has since been developed, targeting event runoff volume, low flow behaviour and runoff quality in addition to peak flows. Processes that modify flow magnitude include storage (ponds, wetlands), infiltration (swales, infiltration basins, and biofilters) and water extraction for reuse (parkland irrigation and rainwater tanks). The scale of SCMs ranges from individual allotments (site scale) to substantial urban areas with established watercourses (catchment scale).

This study explores the behaviour of site scale rainwater tank systems. The water yield of such systems for domestic supply has been extensively assessed [14–22], and their stormwater retention behaviour has also been investigated [23–29]. However, their potential to restore baseflows depleted by urbanization seems not to have been explored in detail.

The aim of simultaneously mitigating peak flows and restoring lost baseflows is a response to the "natural flow paradigm" proposed in 1997 by Poff et al. [14]. This paradigm suggests that aquatic ecosystems require a flow regime as close as possible to its natural level to remain in a healthy state. They propose aspects of the flow regime that should be considered, including the magnitude, frequency, timing, duration and flashiness. This paradigm implies that simply reducing peak flows from urban runoff through detention or retention systems will not be sufficient to protect or restore ecological function [11]. There is also a need to ensure that the magnitude, duration and timing of low flows are maintained close to their natural levels.

Rainwater Harvesting Systems (RWH) collecting roof runoff for household use are a traditional form of water supply in rural areas, and more recently are commonly applied to supplement urban water supply due to growing water demand in many urban environments [10,15–20]. They are also a type of stormwater control measure (SCM), designed to address flooding risk by capturing and storing stormwater runoff and supplying harvested rainwater to the household, essentially diverting rainwater from direct runoff to consumption [19,20]. Such RWH systems are typically designed to have an inflow pipe to collect runoff from connected impervious surfaces and an outflow pipe to draw harvested rainwater for household consumption. There is an overflow pipe located at the top of the system that allows uncontrolled overflow to leave the system during spillage [20,23].

The ability of conventional RWH systems to simultaneously provide the dual benefits of water supply augmentation and stormwater retention has been widely recognized and assessed through both modelling and empirical studies [24–28,30]. Increasingly, RWH systems are being designed with a focus on low-impact stormwater management.

Low-impact stormwater management not only requires the alleviation and mitigation of flooding, the same as conventional urban stormwater management, but also has the more-recently recognised aim of restoring the pre-development flow regime and urban water cycle [9–11]. Restoring pre-development flow regime at the catchment scale requires actions to be implemented mainly at the allotment scale, where the pre-development water fluxes (such as evapotranspiration and infiltration) have the greatest opportunity to be restored [31,32]. Moreover, delivery of natural flow regimes is not just about mitigating high flows; it is about restoring the whole perturbed flow regime to a more natural state, including restoration of lost baseflows. Releasing stormwater to the stream in a temporal pattern consistent with the pre-development state, which counteracts the loss of baseflows due to loss of infiltration under impervious surfaces, can help to achieve such restoration.

Therefore, the application of allotment-scale RWH systems has great potential to simultaneously reduce or eliminate excess runoff volume and provide water conservation benefits, while also mimicking natural baseflow regimes by means of carefully controlled discharge [10,33–35]. There are two innovative RWH systems that can deliver these multi-objectives: **the passive release system** and the **active release system**. Both can return some of the lost baseflow to streams, by providing a controlled slow-release either back to the landscape or directly to the stormwater system (and subsequently the receiving water).

The **passive release system** divides the RWH system into two segments, the stormwater detention volume and the retention storage volume, by adding a passive discharge orifice at an intermediate depth [36,37]. The retention storage volume is designed to supply the domestic consumption, and comprises the bottom portion of the storage, while the detention storage occupies the top portion of the system. Stormwater runoff held above the passive discharge orifice slowly drains out to contribute to in-stream baseflow [36–38].

In contrast to the passive release system, the **active release system** places an automated outlet at the bottom of the system which is operated by a novel approach—**Real-Time Control (RTC)**—which can control the RWH systems remotely via a wireless connection [37,39]. RTC technology can optimize RWH system performance, by the managed release of water from the system to reduce the volume of uncontrolled stormwater runoff, and/or to supply water for restoring baseflows in streams. This technology has been widely used in wastewater systems to monitor and control water quality [40,41] and address combined sewer overflow (CSO) and sanitary sewer overflow (SSO) issues [42,43]. However, the potential to incorporate RTC into RWH systems remains largely untested.

The active release system can utilize RTC technology to receive rainfall forecast data in real time and automatically trigger a pre-storm release through a customized valve according to the forecast precipitation and water level within the RWH system. Water in the system is only released if there is insufficient storage capacity to capture the forecast amount of precipitation. Consequently, this customization would preserve the water conservation function, and would significantly reduce or even eliminate the uncontrolled stormwater runoff that discharges into the storm drainage system creating a risk of flooding [38]. While the pre-storm release aims to reduce the risk of flooding, the baseflow release has the objective of restoring the infiltration lost at the source due to the impervious area at each allotment. It requires a constant and controlled release to satisfy the volume and frequency of instream baseflow. In doing so, these systems are likely much more effective than simple RWH systems in delivering a more natural flow regime.

While applied at the individual house scale, the real-time-controlled active release rainwater harvesting systems would likely be implemented by a water authority or private water company, who would install, operate and maintain the systems as part of their overall water service provision. Such technology could also be used to meet regulatory requirements for on-site detention (OSD). Such site-based OSD requirements are common in Australia [44] and many parts of the world (e.g., [45]). Combining this functionality with rainwater harvesting and restoration of stream flow regimes provides an attractive integrated water cycle solution.

A few places around the world, such as North Carolina, United States [38] and Seoul, South Korea [21], have deployed and monitored RWH systems operated by RTC technology to deliver and optimize the dual benefits of water conservation and stormwater retention. However, no studies to date have explored the potential to adapt such RTC systems to facilitate baseflow restoration. Such potential needs to be explored in the context of its associated impact on water supply and stormwater retention.

Here, we compared the modelled performance of RWH systems equipped with RTC technology versus both conventional systems and also systems designed to passively release water. System performance was characterized using metrics related to water supply, stormwater retention, and baseflow restoration.

Baseflow release provided by active and passive release systems is essentially a form of yield (use of water specifically to provide environmental flows) which is theoretically in conflict with the water supply objective. However, the specific impact of baseflow release on other objectives, along with the effect of RTC technology on system performance, remain unknown. Therefore, our paper addresses the following questions:

1. How does the addition of baseflow release affect the water supply and stormwater retention performance of RWH systems?

2. How does the addition of RTC operation affect the water supply and stormwater retention performance of RWH systems?
3. How do active and passive release systems compare in achieving multi-objectives?

Our work shows that RWH systems employed with RTC technology are generally superior in achieving the triple objectives compared with passive release systems, although the differences are relatively modest. Active release systems exhibit great promise in retaining stormwater runoff with only a small detriment to water supply, compared with conventional systems. Our work highlights the substantial potential of equipping RWH systems with RTC technology in a range of contexts.

2. Methods

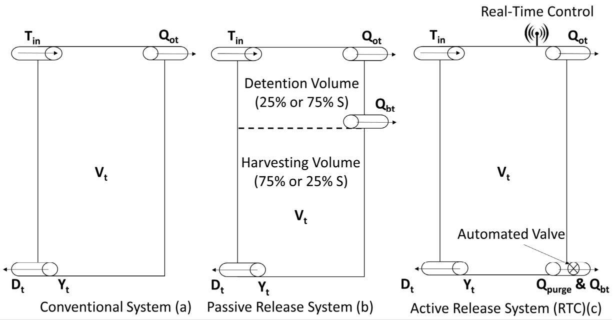
2.1. Study Area

To base this modelling study on reality, the study was founded on the Dobsons Creek catchment, a 4 km^2 catchment on the eastern fringe of the Melbourne metropolitan area, in Australia. The catchment is largely forested, with residential subdivision along the ridge line and downstream close to the gauging station. Average annual rainfall is 1090 mm, and the steam has persistent baseflow with only occasional cease-to-flow conditions. Sanitary sewers are separate from the stormwater system. Stormwater drains to local watercourses, which are significantly impacted by urbanization in the catchment. Rainwater tanks are common in the area, and are used to supplement, but not replace, the potable water supply, being primarily used for non-potable end-uses, such as irrigation, toilet flushing and hot water.

2.2. System Configurations

We constructed a model using the R software [46] to continuously simulate the behaviour of the three allotment-scale RWH systems: (1) conventional systems; (2) passive release systems; and (3) active release systems (RTC).

The **conventional system** (Figure 1a) is an allotment-scale RWH system collecting impervious runoff from roof areas and is connected to a range of household end-uses. It also has an (unregulated) overflow pipe at the top of the system which drains to the conventional drainage network.



Water Supply	√	√	√
Stormwater Retention	√	√	√
Baseflow Release		√	√
Pre-storm Release			√

Figure 1. Schematic representation and functions of the three types of RWH: (**a**) Conventional System; (**b**) Passive Release System; and (**c**) Active Release System using Real-Time Control. Tin is tank inflow (L/6 min), Q_{ot} is tank overflow (uncontrolled discharge) at timestep t (L/6 min), Y_t is rainwater yield at timestep t (L/6 min), V_t is volume in store (L) during time interval t, D_t is demand at timestep t (L/6 min), S is tank size (L), Q_{bt} is controlled baseflow discharge at timestep t (L/6 min) and Q_{purge} is controlled pre-storm release subject to rainfall forecast (L/6 min).

The **passive release system** (Figure 1b) is similar to the conventional one, but has an additional, elevated outlet—termed here "trickle-release". This outlet effectively divides the tank storage into a detention volume (the volume above the elevated trickle release) and a retention volume (that below the trickle release). Any water stored in the detention volume is slowly released to the receiving water (via the stormwater network) through a small orifice to mimic baseflow. We simulated passive release systems with detention volumes of 25% and 75%. The passive release systems with 25% detention volume favour the water supply performance of the RWH system, while the 75% detention volume favours increased stormwater retention and baseflow restoration performance. This allowed us to explore the impact of different system design on multi-objective performance.

The **active release system** (Figure 1c) is a conventional system equipped with RTC technology, which not only can contribute baseflow to the receiving stream via a controlled slow release, but also has the capability to receive rainfall forecasts in real time and provide a purge release from the system prior to the storm event. This provides additional storage for predicted stormwater runoff (to mitigate flooding). We term this controlled outlet the "pre-storm release". Thus, the pre-storm release volume is the predicted overflow volume which is determined by the difference between the available tank storage volume (freeboard) at the end of the previous day and predicted runoff volume. For example, if a 5000 L system is half full (2500 L) at the end of the previous day and predicted rainwater inflow is 3000 L, the volume of pre-storm release is 500 L (Detailed equations are provided in supplementary material S1).

This pre-storm release is delivered through a 10 mm automated valve, driven by gravity. The outflow rate q (m^3/s) was determined by the orifice equation (Equation (1)):

$$q = Cd\left(\frac{1}{4}\pi D^2\right)\sqrt{2gh} \tag{1}$$

where D is the equivalent orifice diameter (0.01 m), h is the head (m) acting over the centreline of the orifice at timestep t, Cd is the orifice discharge coefficient (Cd = 0.7 was adopted), and g is the acceleration due to gravity (9.81 m/s^2).

Similar to the approach in evaluating passive release systems, we simulated two configurations of this active release system using different logic control to favour either baseflow release or water supply: (i) water supply in any timestep occurs only once the baseflow has been delivered (**Baseflow-First Configuration**); and, in contrast, (ii) baseflow is only released after water supply is satisfied (**Supply-First Configuration**). In addition, we simulated the active release system (RTC) without any baseflow release, to compare it with the conventional system.

In all, we simulated six system configurations: (1) conventional system; (2) passive release system with 25% detention volume; (3) passive release system with 75% detention volume; (4) baseflow-first active release system (RTC); (5) supply-first active release system (RTC); and (6) active release system with no baseflow release.

2.3. Model Structure

The model was made up of three main modules, dealing with inflow, end-use demand and baseflow restoration (Figure 2). The model uses continuous simulation and calculates assessment metrics to allow the system configurations to be compared, and the impact of the various scenarios to be assessed.

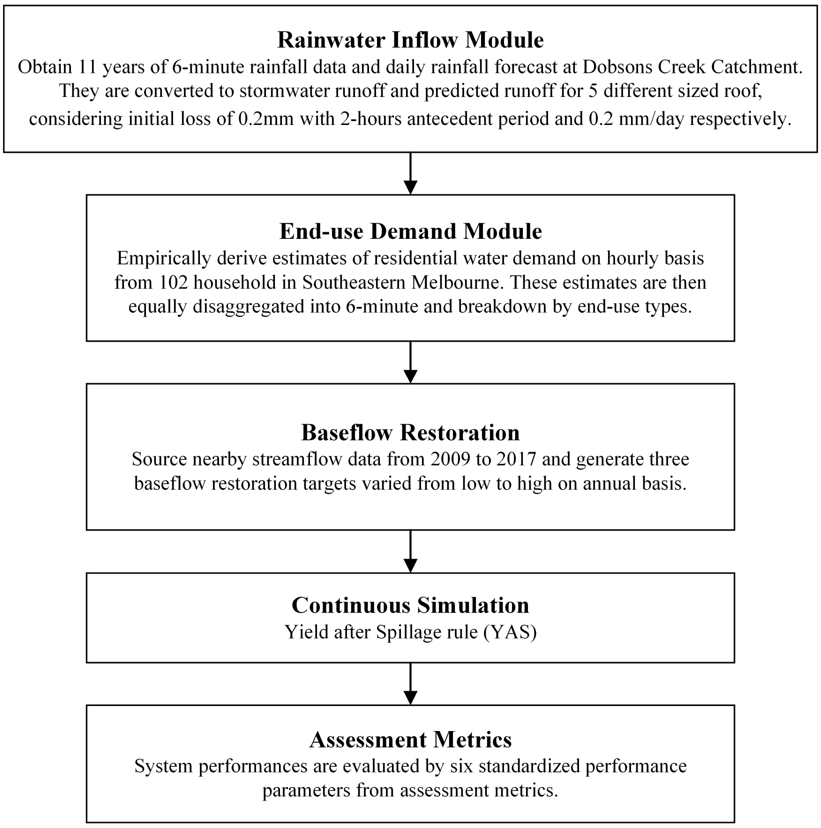


Figure 2. Modelling Flow Chart. All system simulations were run every 6-min.

2.3.1. Rainwater Inflow Module

To predict the inflows for the three types of RWH systems, we used 11 years of 6-min rainfall data recorded in the area of the Dobsons Creek Catchment. The period of record was 1 January 2005 to 31 December 2015.

Not all rainfall becomes runoff, with the first rain normally intercepted by "depression storages", resulting in a delay before runoff occurs. This is often referred to as the "initial loss". An initial loss model (i.e., 0.2 mm with 2-h antecedent period [47,48]) was used to convert rainfall data to stormwater runoff and therefore the volume of system inflow (Detailed equations are provided in supplementary material S1).

Moreover, as illustrated previously (Section 2.1), the active release system can initiate a pre-storm release according to predicted rainfall. The storm runoff volume was predicted using rainfall forecasts that had at least 70% probability of occurrence, considering the initial loss of 0.2 mm and resetting at every mid-night. We obtained 11 years of historical daily rainfall forecast data from the Bureau of Meteorology over the same period as the real rainfall data (1 January 2005 to 31 December 2015) at two nearby weather stations—Ferny Creek (−37.8748 Lat, 145.3496 Long) and Scoresby (−37.8710 Lat, 145.2561 Long) [49]. The rainfall forecast was predicted at midnight each day, indicating both rainfall depth and occurrence probability in the next 24 h.

2.3.2. End-Use Demand Module

Household end-use demands, including internal and external uses, were derived from real water consumption in residential houses, collected by the local water authority (South East Water). Their digital water meter records of total household consumption in hourly timesteps were obtained from 102 properties located in the southeastern region of the Melbourne metropolitan area for the period 1 December 2016 to 5 April 2017. The hourly water demand D_t (L/h) was determined by calculating the mean of supply in all monitored properties (Equation (2)):

$$D_t = \frac{\sum W_t}{n} \tag{2}$$

where W_t (L/h) is the water meter reading of each household at timestep t and n is the number of properties.

Each hourly demand calculated in Equation (2) was then equally disaggregated into 6-min timesteps and split into different end-use types based on the appliance usage data from the authority. This dataset indicated an average daily consumption of 427 L, with two peaks at 7:00 to 8:00 and 19:00 to 20:00. This pattern is consistent with previous studies [50].

The four demand scenarios described below are assembled from household water uses that may be suitable for rainwater tank supply after appropriate treatment [22,51], and exclude cooking, drinking, bath and shower use.

2.3.3. Baseflow Restoration

In modelling baseflow restoration performance, we used streamflow data from nearby Dobsons Creek as a "reference" waterway, allowing us to quantify the target baseflow rate. The Dobsons Creek catchment (4 km^2) is gauged by two flow monitoring gauges with flow recording available from 1 January 2009 to 26 April 2017. We adopted three individual flow percentiles (Q_x)—25th, 50th (also known as Median Flow) and 75th—to determine a range of flowrates that characterize variations in baseflow [29,52]. The pro-rata baseflow restoration target of each allotment was then determined using the three levels of baseflow rate weighted by the relative size of roof catchment to the overall catchment size (4 km^2).

In the *passive release system*, the baseflow trickle release rate is simply controlled by orifice diameter and head over the outlet (Equation (3)). We modelled the equivalent orifice diameter of the baseflow release outlet differently according to the baseflow target in each scenario, in order to better mimic the in-stream flow regime. We assumed that outflow is controlled by gravity and orifice diameter, and that the outflow rate matches the target baseflow rate when the detention volume is half full (half head of detention volume). Therefore, the appropriate orifice diameter D (m) was determined by the transformed orifice equation (Equation (3)):

$$\begin{aligned} h &= \frac{P \times \frac{1}{2} \times S}{A} \\ D &= \sqrt{\frac{4\ Qx}{Cd \times \pi \times \sqrt{2gh}}} \end{aligned} \tag{3}$$

where h is the head acting over the centreline of the orifice assuming water level of half detention volume (equivalent to the head of 1/8 or 3/8 tank height) (m), P is the proportion of detention volume (either 25% or 75%), S is tank size (m^3), A is tank area (m^2), Cd is the orifice discharge coefficient (0.7 was adopted), Q_x is the flow rate target in each scenario (m^3/s) and g is the acceleration due to gravity (9.81 m/s^2).

The modelled trickle-release rate in each timestep Q_b (L/6 min) was determined by the orifice equation (Equation (1)).

In the *active release system*, baseflow release can be delivered at the exact target baseflow rate, due to the ability to vary the valve aperture. It is noted that the actively controlled baseflow release was not initiated if overflow occurred. In addition, the pre-storm releases were not considered to contribute to the baseflow release, as their flow rates are generally much larger than target baseflow rate.

2.3.4. Continuous Simulation

The behaviours of the three systems were simulated at a 6-min timestep over the same period as the rainfall dataset (1 January 2005 to 31 December 2015). The Yield-After-Spillage (YAS) operating rule was employed to simulate system outflow and volume, which provides a more accurate estimate of yield (Equation (4)), given that the potential spillage flow rate is greater than the demand flow rate in a given timestep [53–55]:

$$\begin{aligned} Q_{ot} &= \max\begin{cases} V_{t-1} + T_{in} - S \\ 0 \end{cases} \\ Y_t &= \min\begin{cases} D_t \\ V_{t-1} \end{cases} \\ V_t &= \min\begin{cases} V_{t-1} + T_{in} - Y_t \\ S - Y_t \end{cases} \end{aligned} \tag{4}$$

where V_t and V_{t-1} are the volume in store (L) at timestep t (current) and $t - 1$ (previous), Y_t is the rainwater yield at the current timestep (L/timestep), Q_{ot} is tank overflow at timestep t (L/timestep), S is tank size (L), D_t is rainwater demand at timestep t (L/timestep), and T_{in} is the tank inflow (L/timestep).

Table 1 summarizes the assumptions of continuous simulation.

Table 1. Table of model assumptions.

Category	**Assumptions**
Baseflow	Each baseflow target remains constant during simulation period (no seasonal variation).
System	1. The initial system volume was fixed at zero 2. Yield always occurred after overflow (YAS rule)
End-Use	1. Each allotment was assumed to be occupied by 2.67 persons 2. Allotment size does not influence water demand. 3. All the end-use types are drawn at each time-step.

2.4. Model Scenarios

We identified a range of typical rainwater harvesting system scenarios, to assess the influence of given design and operating factors on system performance (Table 2). Five selected roof sizes represented roof catchment areas covering a range from low to high density allotments. We then considered four different tank sizes, covering a realistic range. Each allotment was assumed to be occupied by 2.67 persons per household, the average residential occupancy in Melbourne [56,57]. The household end-uses modelled for each scenario were four fixed combinations of toilet flushing, dishwasher, outdoor usage, clothes washing and hot water. Three baseflow regimes were defined to be applied as a target for the baseflow release by the RWH systems, as described previously (Section 2.3.3).

Table 2. Simulation Scenarios. Where TF is toilet flushing, D is dishwasher, O is outdoor usage (e.g., garden irrigation), C is clothes washing, and H is hot water.

Variables	**Scenarios**
Roof Size (m^2)	50, 100, 150, 200, 250
Tank Size (kL)	2.5, 5, 10, 15
Household Demand	TF (12%, approximately 51 L/day), TF + D + O (32%, approximately 137 L/day), TF + D + O + C (49%, approximately 231 L/day), TF + D + O + C + H (85%, approximately 401 L/day)
Baseflow Target	75% (1.5×10^{-3} mm/6 min), 50% (9.1×10^{-4} mm/6 min), 25%(6.0×10^{-4} mm/6 min)

In all, 240 different scenarios were generated for configurations that simulated baseflow, and 80 different scenarios for those that did not.

2.5. Assessment Metrics

The performance of each RWH system was measured by assessment metrics (Table 3) which characterize water supply, stormwater retention and baseflow restoration. Each of the three objectives is evaluated by two parameters to quantify both volumetric (efficiency) and frequency characteristics. As the scale of system inflow and baseflow target is dependent on the roof size, the six assessment parameters are all expressed as a proportion of total volume or total timesteps to ensure the performance between different configurations in different scenarios is comparable.

The optimal baseflow release is to deliver a flow that closely matches the flow rate and temporal pattern of the baseflow target. Thus, we assumed that only a baseflow release less than twice the target would count for contributing to stream baseflow (Table 3). It is noted that baseflow performance was not calculated for the conventional system and active release system (no baseflow release), given that they have no baseflow release.

Table 3. Assessment metrics to characterize the system performance of triple objectives. Each of the triple objectives is evaluated by two parameters quantifying the amount and frequency, respectively.

Objectives	**Assessment Indicator**	
	Efficiency	**Frequency**
Water Supply	Water Supply Efficiency E_{ws}:	Water Supply Frequency F_{ws}:
	$E_{ws} = \frac{\sum Y_t}{\sum D_t} \times 100\%$	$N_t = \begin{cases} 1, Y_t \geq D_t \\ 0, \text{else} \end{cases}$ $F_{ws} = \frac{\sum N_t}{n}$
	Y_t is water supply yield at current timestep t (L/6 min), D_t is household demand at timestep t (L/6 min), N_t is counted if demand is satisfied in timestep t and n is the total number of timesteps.	
Baseflow Restoration	Baseflow Efficiency E_b:	Baseflow Frequency F_b:
	$E_{bt} = \begin{cases} \frac{Q_{bt}}{Q_{target}}, \frac{Q_{bt}}{Q_{target}} \leq 1 \\ 2 - \frac{Q_{bt}}{Q_{target}}, 1 < \frac{Q_{bt}}{Q_{target}} \leq 2 \\ 0, \text{Otherwise} \end{cases}$	$N_t = \begin{cases} 1, 2Q_{target} \geq Q_{bt} \geq Q_{target} \\ 0, \text{else} \end{cases}$
	$Eb = \sum Ebt/n$	$F_b = \frac{\sum N_t}{n}$
	Eb is the overall baseflow restoration efficiency, Ebt is the baseflow restoration efficiency at timestep t, n is the number of timesteps, Qbt (mm/timestep) is the amount of baseflow delivered by the system at timestep t, Q_{target} is the baseflow target at each timestep defined by Q_x (L/6 min), N_t is counted if baseflow target is satisfied at timestep t and n is the total number of timesteps.	
Stormwater Retention	Retention Efficiency E_R:	Overflow Frequency F_o:
	$E_R = \left[1 - \frac{\sum Q_{ot}}{\sum A \cdot R_t}\right]$	$N_t = \begin{cases} 1, Q_{ot} \geq 0 \\ 0, \text{else} \end{cases}$ $F_o = \frac{\sum N_t}{n}$
	Q_{ot} is tank overflow at timestep t (L/6 min), A is roof size (m^2), R_t is roof runoff at timestep t (mm/6 min), N_t is counted if overflow occurs at timestep t and n is the total number of timesteps.	

3. Results

Rainwater harvesting systems employed with RTC technology were generally superior to the passive configurations in achieving the triple objectives, although the differences were relatively modest (Figures 3–5). These active release systems also generally exhibited greater ability to retain stormwater runoff with little detriment to water supply compared with the conventional systems (Figures 3 and 4).

3.1. The Impact of Baseflow Release on Water Supply and Stormwater Retention

The comparison between conventional systems and passive release systems indicated similar performance in both the frequency and efficiency of water supply. However, the passive release system showed a better ability to reduce uncontrolled overflow volume and frequency, without substantial impact on water supply. Indeed, the conventional systems showed less than 1% advantage in mean water supply efficiency and frequency, while the passive release system showed approximately 10% and 0.5% better performance in mean retention efficiency and overflow frequency respectively (Figures 3 and 4).

The ability to enhance stormwater retention without any major impact on water supply was also evident in the comparison between the conventional and active release system (RTC) (Figures 3 and 4); indeed, the active release system showed approximately 23% and 1% better mean retention efficiency and overflow frequency respectively with only about 2% less water supply efficiency and frequency, compared to the conventional system. For example, a 200 m^2 roof draining to 5 kL tank with all end uses connected has an annual yield of 125.7 kL and annual overflow of 79.8 kL (Table 4). The same scenario operated by RTC (Baseflow-First) has less annual yield of 120.8 kL, but reduced annual overflow to 46.8 kL, while the passive release system with 75% detention volume has an annual yield of 123.7 kL and annual overflow of 73.4 kL (Table 4). As a result, with appropriate operating rules, the additional baseflow release does not greatly affect system performance in terms of water supply, but delivers much greater stormwater retention due to better utilization of system storage.

Table 4. Numeric example of system performance in different configurations. The scenario of this simulation is a 200 m^2 roof draining to 5 KL tank with all end uses connected. The baseflow release target set for the active release system is Q_{25} (6.0×10^{-4} mm/6 min). All simulation results are listed in supplementary material S2.

Configurations	Yield (kL/Year)	Overflow (kL/Year)	Baseflow Release (kL/Year)	Pre-Storm Release (kL/Year)
Conventional System	125.7	79.8	N/A	N/A
Passive Release System (25%)	125.2	76.3	3.8	N/A
Passive Release System (75%)	123.7	73.4	8.2	N/A
Active Release System (no baseflow)	124.6	49.6	N/A	31.6
Active Release System (baseflow-first)	120.8	46.8	9.5	28.3
Active Release System (supply-first)	121	46.8	9.4	28.3

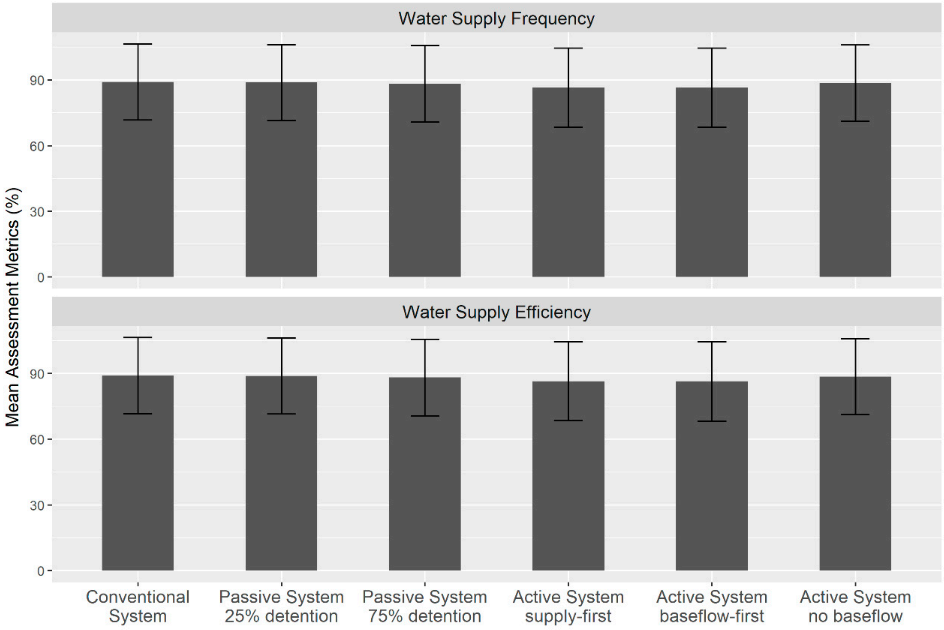


Figure 3. Mean value (bar) and associated standard deviation (error bar) for water supply efficiency and frequency in the six system configurations. Water supply efficiency and frequency are expressed as percentages.

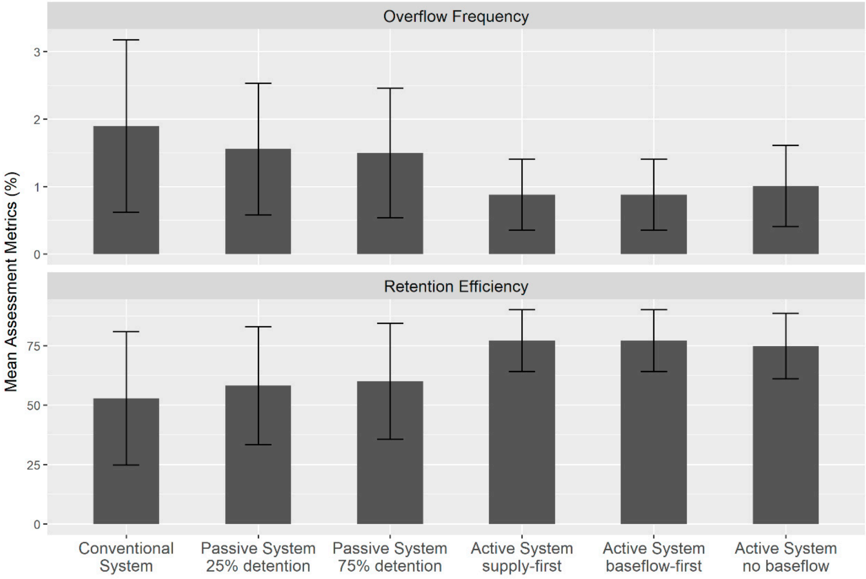


Figure 4. Mean value (bar) and associated standard deviation (error bar) for overflow frequency and retention efficiency in the six system configurations. Overflow frequency and retention efficiency are expressed as percentages.

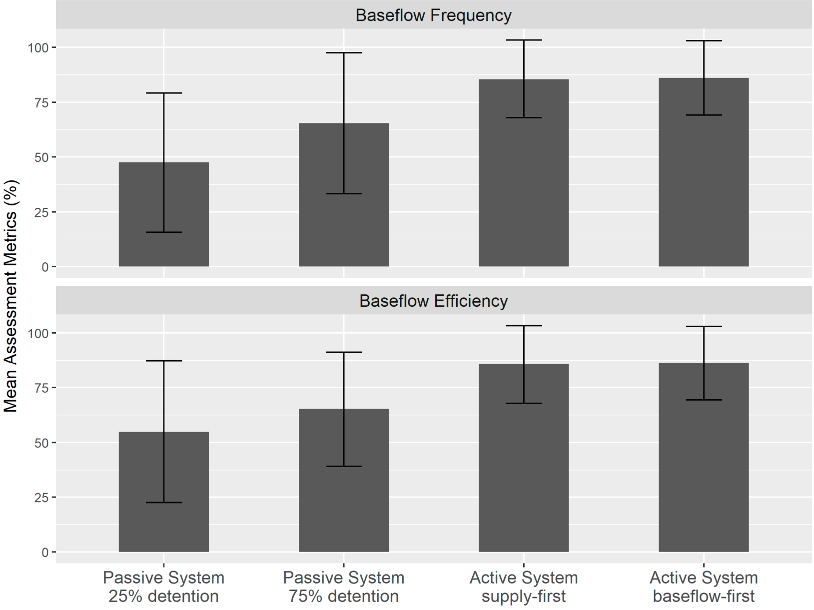


Figure 5. Mean value (bar) and associated standard deviation (error bar) for baseflow frequency and efficiency in the four system configurations that consider baseflow. Baseflow frequency and efficiency are expressed as percentages.

3.2. The Impact of RTC on Water Supply and Stormwater Retention

By employing RTC, stormwater retention volume and frequency reduction were improved dramatically among all modelled RWH system configurations (Figure 4), while water supply performance remained almost unchanged (Figure 3). The ability of active release systems to improve stormwater retention compared with conventional systems with little detriment to water supply has been previously discussed (Section 3.1). This can be further illustrated by comparing active release systems with passive release systems. The mean retention efficiencies of active release systems were approximately 16% higher than those of passive release systems. Accordingly, active release system overflows occurred about 0.7% less frequently than passive release system overflows (Figure 4). However, passive release systems only showed about 2% better performance than active release systems for mean water supply efficiency and frequency (Figure 3). For instance, a 200 m^2 roof draining to 5 kL active release system (no baseflow release function) with all end uses connection has an annual yield 124.6 kL and annual overflow of 49.6 kL. Therefore, the addition of RTC can substantially improve retention performance of RWH systems with little detriment to water supply.

3.3. Comparison of Active and Passive Release System in Achieving Multi-Objectives

Compared with the passive release systems, the active release systems showed distinct advantages in reducing overflow frequency and increasing stormwater retention, while only slightly decreasing water supply performance (Figures 3 and 4). The active release with supply-first configuration and the passive release with 25% detention volume both prioritise water supply over baseflow restoration, while in contrast, the active release system with baseflow-first logic and the passive release system with 75% detention volume prioritise baseflow restoration over water supply. We found that the active release system generally performed better in delivering sustainable baseflow to the receiving water, as it provided access to a greater proportion of the tank volume (Figure 5). The active release system with supply-first configuration delivered 30.7% and 38.1% higher baseflow efficiency and frequency than did the passive release system with 25% detention volume. Similarly, the active release system with baseflow-first configuration performed better than the passive release system with 75% detention volume, although the improvement in this case was smaller.

Although the advantage of the active release system is relatively modest in some circumstances, the overall performance of the passive release system is critically dependant on the diameter of the baseflow release orifice. To explore this effect, we investigated system performance sensitivity of active release systems and passive release systems to different baseflow release sizes. The variation in the passive release system's performance was generally larger than that of the active release system, especially in terms of baseflow restoration, while the variation in water supply performance between different baseflow target values remained moderately constant (Figure 6)

Therefore, the active release system can perform better in baseflow restoration and stormwater retention with less adverse impact on water supply. It is also able to deliver a more stable performance across the three objectives over the range of baseflow release targets.

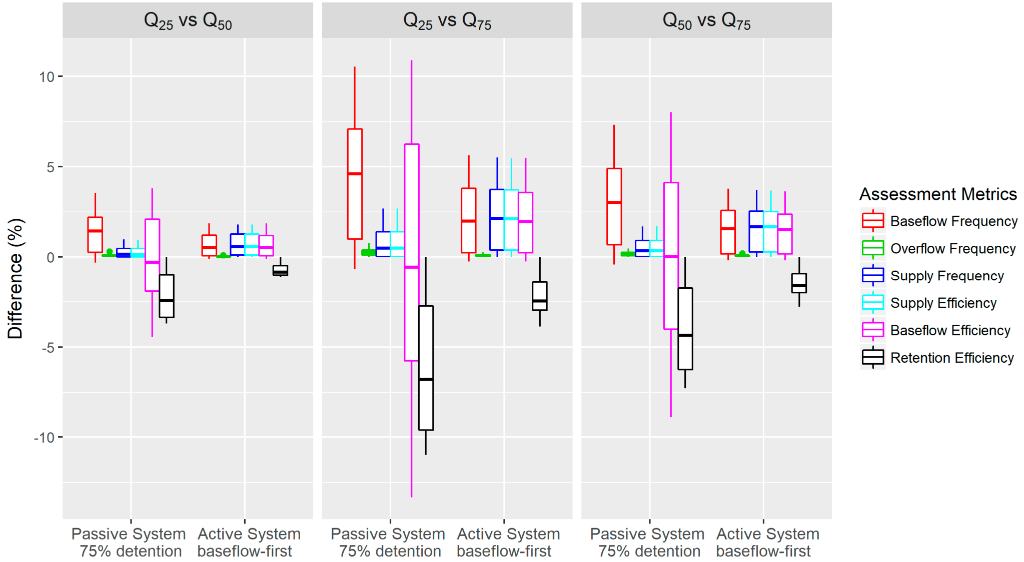


Figure 6. Distribution of difference in performance between baseflow targets among all possible scenarios in Passive Release System (75% Detention Volume) and Baseflow-First Active Release System (RTC-B) respectively.

3.4. Diameter of Trickle Outlet

We simulated and recorded the equivalent orifice diameter of the trickle outlet in two passive release system configurations, according to the baseflow target in each scenario. The passive release systems with 75% detention volume were predicted to have an equivalent orifice size from 0.17 to 0.95 mm, while the equivalent orifice size for 25% detention volume passive release system varied from 0.22 to 1.25 mm (Figure 7). We note that in practice such a small diameter would not be used, and other forms of restriction would be necessary to achieve the low flow rate required. For example, a pressure-independent dripper could be used to achieve the required flow rate.

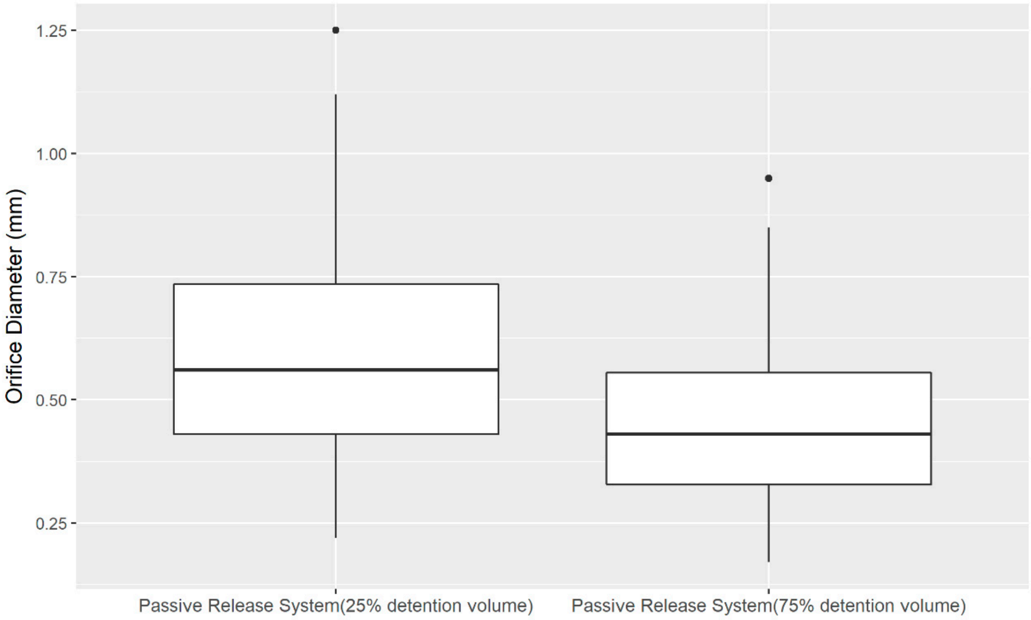


Figure 7. The theoretical prediction of equivalent orifice size for passive release system with 25% and 75% detention volume respectively.

4. Discussion

4.1. Impact of Baseflow Release

In theory, water released from RWH systems to augment stream baseflow conflicts with water yield for domestic use. Thus, conventional systems theoretically perform better on water supply than both active release and passive release systems. However, our results indicate that configuring rainwater harvesting systems for both passive and active baseflow release does not greatly impact water supply performance, which is consistent with another study [56]. Such a finding is linked to the fact that the volume of baseflow release is small relative to demand for water supply. Moreover, for most of the system configurations tested here, total system inflows were much higher than baseflow release and water supply demand. For example, a 250 m^2 roof had an average daily inflow of 705 L with the baseflow target varying from 36 L/day (Q_{25}) to 92 L/day (Q_{75}) and supply demand varying from 51 L/day to 401 L/day. Consequently, a big RWH system (such as a 15 kL system) is able to satisfy both the demand for water supply and baseflow release most of the time, due to its large storage. Overall, the results suggest that configuring RWH systems to release baseflow through either an active or passive mechanism is a win-win strategy which can provide alternative water supply, increase the system performance on stormwater retention and provide environmental benefit for urban streams [24,27]. Achieving this multi-objective outcome represents an evolution in the approach to stormwater control measures, where their design targets multiple aspects of the flow regime, rather than focussing only on peak flow reduction [11]. Given the evidence presented by Poff and others [14] that ecosystem health depends on all aspects of the flow regime, this is an important step forward in the design and operation of stormwater control measures.

4.2. Impact of Real-Time Control Technology

Our results suggest that operating RWH systems using RTC technology could substantially improve the system performance in terms of stormwater retention. This is achieved by receiving rainfall forecasts in real time and releasing water from the system before the rainfall occurs (pre-storm release). Pre-storm release can give the system additional capacity to contain upcoming storm runoff and reduce the possibility of generating uncontrolled system overflow. However, the volume of pre-storm release is often overestimated as the rainfall depth of forecasts is generally greater than real rainfall. Thus, the active release systems on occasion discharged an unnecessarily large volume of water during the pre-storm release, somewhat diminishing performance for water supply. Utilization of more accurate and sub-daily rainfall forecast data is the key to reducing this "wastage" and thus further optimizing the system.

4.3. Active Release System versus Passive Release System

We found that active release systems could deliver higher baseflow volume and reliability metrics than passive release systems. The novel active control provided by RTC technology can adapt the baseflow release to more accurately match the target baseflow. However, the baseflow release rate from the passive release system is entirely subject to the system water level and cannot be controlled in real time. The closer match to target baseflow achieved by the active release systems provides a higher baseflow restoration benefit.

4.3.1. System Design

The overall performance of both active and passive release mechanisms of the RWH systems depends on system design. For passive release systems, the size of the baseflow release will be critical in determining overall system performance. Their overall performance shows more variation than active release systems over the range of baseflow release targets (Section 3.3). More importantly, as noted in Section 2.3.3, we modelled the diameter of the passive release trickle outlet according to the baseflow target using the transformed orifice equation. As all three baseflow targets were comparatively low, the theoretical equivalent orifice sizes were generally impractical (Section 3.4). In reality, the passive release system could adopt a minimum orifice size of around 5 mm, resulting in higher releases, particularly when the head in the tank is large (i.e., the system is full).

For the active release system, its performance in restoring baseflow and retaining storm runoff is also highly related to the orifice size. A larger orifice can deliver the pre-storm release faster, thus making the storage available for upcoming inflows. However, an important concern is that a faster release achieved by a larger orifice (e.g., 25 mm) is simply shifting the timing of system overflow. The high flow rate delivered might still result in stream degradation, such as erosion [58]. This might not be a concern in the case of combined sewer systems where the stormwater will not be discharged into stream directly. In addition, pre-storm release may still help to mitigate the impacts of runoff from remaining impervious areas during the storm event. More importantly, unlike the pre-designed trickle orifice in passive release systems, the outlet orifice size of active release systems can be varied in real time through valve opening-closing control. Thus, the novel active control can provide active release systems with the ability to customize the outflow rate according to system water level, and even to deliver the pre-storm release at a rate similar to baseflow. Therefore, active release systems need to be carefully designed to meet their specific objectives.

4.3.2. Cost

The cost of active release rainwater harvesting systems applied at residential household scales will likely be greater than that of passive release systems, given the requirement for the valve control and communication systems [38,59]. However, these multi-objective RWH systems employed with RTC technology can be incorporated into combined sewer systems and become a feasible supplement to the existing centralized system, with great potential to reduce or even eliminate combined sewer overflow (CSO) [21,38,60]. One empirical study demonstrated that, by deploying a real-time controlled RWH system, the downstream sewer system could cope with 50-year rainfall without upgrading the existing system designed for a 10-year event [21]. This ability to provide decentralized stormwater control can potentially decrease the need for stormwater infrastructure upgrades, offsetting the cost of the active release system.

With the rapid development of technology in recent times, the cost of RTC technology has been greatly reduced due to improved devices, methodologies and tools. The active release system can be considered as a relatively low cost option to minimise adverse impacts of urban runoff on the environment, while providing a private benefit to water consumers [61]. This combination of public and private benefits is essential to the uptake of such environmental technologies [62].

4.3.3. Management Implications

The centralised control and failure detection abilities of active release systems open up possibilities for delivering a more reliable system, which can be monitored remotely, allowing faults to be identified and fixed. Such a system could also be readily adapted to varying local conditions and climate over both the short and long term.

The simpler passive release system has comparatively low direct costs, but the passive mechanism is non-variable in practical terms [28,37], reducing its adaptability to varying climate. Its ongoing efficient operation and reliability also depend entirely on the diligence of the household in providing regular maintenance, given that no centralised control system is present.

For the active release system, the advanced active control can customize the system from a centralized location to satisfy various objectives according to requirements. For example, the Star City RWH system [21] used a type of active releasing system as a supplement to enhance stormwater retention capacity of the existing centralized system during long term climate change adaptation, while also achieving energy savings through potable water supply reduction.

Moreover, the water quality of first flush roof runoff can be of concern for domestic supply [63], but there is the potential to incorporate a treatment train including filtration, ozonation and UV treatment to treat the harvested rainwater to potable standard in real deployment [20]. Such technologies suitable for application at the individual allotment scale are already readily available.

4.4. Future Deployment

The deployment of RWH systems to retrofit stormwater control and pre-development flow regime restoration at catchment scales is likely to require a mix of three different configurations: conventional, passive and active release systems. There is potentially a threshold to dictate which configuration is more appropriate in a given scenario. The simple and inexpensive passive release and conventional systems may be more suitable for small systems, while the active release system is more cost-efficient in large applications due to its promising performance in delivering multiple objectives and the relatively smaller contribution of fixed costs associated with control and communication components [38].

In this study a single baseflow target was applied, but future applications could consider modification of the active release system to adjust baseflow release in real time based on streamflow gauging, using its superior advantage of supervisory control and data acquisition. Such an approach would help to not only intercept excessive storm runoff before it enters receiving waters, but also reduce any deficit and deliver baseflow that better mimics the desired flow regime. Again, this increasingly sophisticated (and therefore complex) approach will go further towards delivering a "natural flow regime", which is necessary for a health aquatic ecosystem to be maintained [14].

Further research is required to develop a comprehensive cost-benefit analysis, including energy consumption, direct cost of different configurations, and cost-saving on reduced requirements for stormwater and water supply infrastructure. A more reliable and accurate prediction of precipitation is also essential to further improve the performance of the active release system.

Another area of required future research is the question of optimal scale and arrangement of such systems. Application of RTC at the household scale could, for example, work in concert with similar large-scale systems applied at precinct or suburb scale. Such systems could provide larger scale flood-protection for an area, or provide centralized stormwater harvesting. Determining the optimal combination of scales, and developing technologies to allow systems to integrate optimally, is a logical next step.

5. Conclusions

In this study, we conducted continuous simulation to model the ability of three types of allotment-scale RWH systems, including conventional, passive release and active release system, to simultaneously deliver: (i) water supply; (ii) stormwater retention; and (iii) baseflow restoration.

Our conclusions include:

1. The additional baseflow release has little effect on system performance in terms of water yield, but generally delivers greater stormwater retention.
2. The addition of RTC can dramatically improve retention performance of a RWT with little detriment to household water supply.
3. The active release system (RTC) can generally perform better in baseflow restoration and stormwater retention, but with a little more adverse impact on water supply, compared to the passive system. It exhibits great promise in revolutionising rainwater harvesting systems to simultaneously deliver stormwater management, water conservation, and flow regime restoration benefit. Its ability to provide centralised control and failure detection also opens up the possibility of delivering a more stable and reliable system, which can be readily adapted to varying climate over both the short and long term.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/10/2/147/s1. Three supplementary materials are submitted alongside the manuscript: S1. Supplementary Equations, S2. Raw results of continuous simulation, S3. Continuous simulation codes.

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Author Contributions: All authors conceived and designed the experiments. Wei D. Xu, Tim D. Fletcher, Matthew J. Burns and Hugh P. Duncan performed the experiments and analysed the data. All authors contributed to write the paper.

Conflicts of Interest: Bergmann and Breman are employees of South East Water, a government-owned water corporation, who are exploring a range of water supply technologies, including RTC-based rainwater harvesting.

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