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Research paper

Assessing the benefits of real-time control to enhance rainwater harvesting at a building in Cape Town, South Africa

Malesela Michael Mogano[1] and John Okedi[1]

[1]*Department of Civil Engineering, University of Cape Town, Private Bag X3, Rondebosch 7701, Cape Town, South Africa*

In the period 2015–2017, the City of Cape Town, South Africa, faced the possibility of taps running dry due to a prolonged drought. To mitigate the impacts of water scarcity, many households installed rainwater tanks to harvest water to use for non-potable purposes such as toilet flushing and washing. The installation of the rainwater tanks was mainly arbitrary, in response to perceived impact of water scarcity rather than a systematic needs assessment. This study was thus undertaken to determine the available opportunity to optimise the use of these rainwater tanks using real-time control (RTC) techniques. Many studies have demonstrated the potential of rainwater harvesting (RWH) systems to supplement potable water supply and minimize stormwater flows to downstream drainage networks. RTC technology can be used to enhance the performance of RWH systems in achieving these two objectives, by receiving a rainfall forecast and initiating pre-storm release in real time. In this study, RTC was applied on the RWH system at the New Engineering Building, University of Cape Town (UCT) to enhance water supply and increase rainwater retention period. The performance with RTC was compared with the conventional management of the RWH system. It was determined that RWH with RTC technology was generally superior in simultaneously achieving water supply and rainwater retention benefits compared to the conventional management approach. RTC provides an active operation which optimizes the performance of the system across varying conditions but requires an assiduous management process designed to meet set objectives. It was concluded that the active release mechanism employing RTC exhibited great potential; the system opens up the possibility of delivering a more robust and reliable system due to its ability to provide failure detection and centralised control. The system can readily be adapted to variation of local climatic conditions in the short and long term.

CORRESPONDENCE
John Okedi

EMAIL
john.okedi@uct.ac.za

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INTRODUCTION

In recent times, lack of appropriate management of stormwater flows has resulted in serious problems to society and the environment (Campisano et al., 2015). Due to urbanisation, natural vegetated areas are constantly being replaced by impervious surfaces, which results in increased runoff discharges and volumes during wet weather conditions (Marsalek, 2005). Increased runoff from impervious areas increases the risk of flooding and poses a threat to people and property.

Economic and social development depend on water, which is a vital element for humanity. Restrictions on water supply and water stress in many countries are a result of over-exploitation of water resources. Increasing the efficiency of water use reduces the demand for potable water, promotes sustainability and assures water quantity and quality for generations to come (EEA, 2009). Rainwater harvesting (RWH) systems aim to increase water use efficiency and reduce urban water consumption (EEA, 2012).

RWH is an ancient practice that is widely used across the world to handle water supply needs (Campisano et al., 2017). RWH systems have the potential of reducing potable water consumption. In Sweden, more than 60% of the main water supply could be saved when rainwater was collected for water closet (WC) flushing (Villarreal and Dixon, 2005). Various studies such as Chilton et al., (2000); and Muthukumaran et al., (2011) have shown that about 40% of potable water can be saved by implementing RWH. RWH systems are linked to three key research challenges, including, inter alia: lack of data on system operation; maintenance issues; and devoting research to the understanding of how best institutional and socio-political support can be targeted (Campisano et al., 2017).

Real-time control (RTC) can be defined as a flexible and cost-effective tool which can guide urban water managers to handle precipitation changes (Vezzaro and Grum, 2014). RTC can also be defined as a tool that integrates structural solutions, such as reducing the total investment that urban water utilities need to make to meet targets. Generally, RTC aims to effectively utilize available storage capacity and improve the management of RWH. Furthermore, RTC can benefit from future information input and models that provide results of the behaviour of a RWH system. Lastly, RTC considers the status of receiving water bodies and other variables such as energy consumption in the optimisation of a model.

Application of RTC techniques in RWH systems can enhance their performance in terms of both water supply and stormwater retention (Xu et al., 2020). RTC has a major advantage over conventional systems (CS) due to its ability to use available information such as weather forecasts and environmental monitoring (Kerkez et al., 2016). In addition, RTC systems usually utilize an active outlet and are mainly designed for pre-storm release to minimize uncontrolled overflows.

The released volume is computed by using local rainfall forecasts in comparison with current available headroom (Xu et al., 2020). There are studies that have shown the ability of RTC in enhancing stormwater retention and peak flow reduction (Di Matteo et al., 2019). Recent application of RTC includes a possibility of stream baseflow restoration through a persistent low-rate discharge that mimics the natural flow regimes (Xu et al., 2018). Pre-storm release without attention to flow regime could simply emulate the 'uncontrolled' overflow that can lead to a highly disturbed flow regime with ecological and geomorphic consequences for downstream receiving waters. Hence, RTC application for water supply and stormwater retention are best managed by using a 24-hr forecast, meaning that the release must take place rapidly for completion prior to the predicted rainfall (Xu et al., 2020).

Some studies have also shown that RTC combined with the 7-day forecast can enhance the functionality of RWH systems to restore and even mimic the entire natural flow regime in receiving streams (Xu et al., 2020). However, the practical use of the 7-day forecast and associated effect on pre-storm release requires further research.

In this study, the performance of RWH systems with RTC techniques was evaluated by model simulations using data based on rainfall forecasts in Cape Town. Rainfall forecasts can be used to initiate pre-storm release in real time to enhance the performance of RWH systems through RTC techniques. The study focused on linking rainfall forecast to RWH storage volume, prediction of inflow volume and the required storage, in order to minimize rainwater loss. In addition, the study explored model simulations such as the daily/monthly water balance method, the dry period demand method and dimensionless analysis.

Literature review

The preponderance of modelling and data coupled with rainwater harvesting is focused on developing countries, where basic human health is not a matter of economics but of water scarcity. There is a gap in the developing world that can be filled by rainwater harvesting to improve conditions of access to freshwater. Water scarcity may further increase with rising population and urbanisation associated with climate change. However, water scarcity can be overcome if rainfall is well harnessed. Various studies on rainwater harvesting optimisation have been identified in literature, including the following:

In Abeokuta, Nigeria, a study analysed and determined benefits of household rainwater harvesting using the daily water balance model (Imteaz et al., 2012). The model consisted of simple spreadsheet calculations of daily water balance, and variables such as rainfall, contributing roof area, water uses, storage volume, losses including leakage, spillage, and evaporation. Equations 1–5 describe the overall mathematical processes in the model (Imteaz et al., 2012):

$$S_t = V_t + S_{t-1} - D \tag{1}$$

$$S_t = 0, \text{ for } S_t < 0 \tag{2}$$

$$S_t = \mathrm{C}, \text{ for } S_t > C \tag{3}$$

where S_t is the cumulative water stored in the rainwater tank (L) after the end of the t^{th} day, V_t is the harvested rainwater (L) on the t^{th} day, S_{t-1} is the storage in the tank (L) at the beginning of t^{th} day, D is the daily rainwater demand (L), and C is the capacity of the rainwater tank (L)

Equation 4 is the town water use equation:

$$\mathrm{TW} = D - S_t, \text{ for } S_t < D \tag{4}$$

where TW is the town water use on the t^{th} day (L).

Equation 5 is the overflow equation:

$$\mathrm{OF} = S_t - C, \text{ for } S_t > C \tag{5}$$

where OF is the overflow on the t^{th} day (L).

Reliability is calculated with Eq. 6:

$$\mathrm{Re} = (N - U)/N \times 100 \tag{6}$$

where Re is the reliability of the tank to be able to supply intended demand (%), U is the number of days in a year the tank was unable to meet the demand, and N is the total number of days in a particular year.

The case study focused on the reliability of rainwater tanks for a typical dry year under varying tanks and different scenarios (low and high demand). Rainwater use for toilet flushing and for both toilet flushing and laundry was defined as low and high demand, respectively. The study showed that significant water savings can be achieved from rainwater harvesting even in the dry years. Hence, the findings revealed the importance of implementing rainwater harvesting as a water management strategy (Imteaz et al., 2012).

A study in Taiwan focused on the development of an easy-to-use methodology that could be combined with dimensionless analysis to design a domestic rainwater harvesting system (DRWHS) at a regional level. In the dimensionless analysis, various combinations of storage capacity, rainwater demand, rainfall, rainwater supply reliability and effective roof area were considered for the DRWHS. The development of the DRWHS can be defined as a production process needed to determine how inputs are integrated to construct a specific output, as shown in Eq. 7:

$$f(X, Z) = 0 \tag{7}$$

where X is total input vector and Z is the total output vector.

The rainwater supply performance of the DRWHS depends on various variables. In addition to the rainfall amount, effective roof area, water demand and storage capacity at the site are vital to evaluate the rainwater supply. The volumetric reliability and annual water demand can be used to compute the annual rainwater supply (Liaw and Chiang, 2014). Fewker et al., (2000) proposes two dimensionless ratios that consider several combinations of rainfall, effective roof area, water demand and storage capacity. The following illustrates two ratios defined as demand fraction (Eq. 8) and storage fraction (Eq. 9):

$$d = D_{\mathrm{awd}}/AR = \mathrm{D}_d/R \text{ (dimensionless)} \tag{8}$$

$$s = S/AR = \mathrm{S}_d/R \text{ (dimensionless)} \tag{9}$$

where d is the demand fraction; s is the storage fraction; A is the effective roof area in square meters; D_{awd} is the annual water demand in terms of volume (m^3); D_d is the annual water demand in terms of depth (m); R is the average annual rainfall (m); S is the storage capacity in terms of volume (m^3); and S_d is the storage capacity in terms of depth (m).

The DRWHS performance was related to the adopted dimensionless parameters using a regional regression analysis. The correlation between d and s can be shown as:

$$D_d/R = b'(S_d/R)^c \tag{10}$$

where b and c are regression coefficients that are adjusted based on simulation results. The correlation between these coefficients can be shown as $b' = b(AR)^{c-1}$.

A fixed daily water demand (q) can be shown as a function of the storage capacity, effective roof area and average annual rainfall as follows:

$$q = 0.0027\mathrm{b}'\mathrm{S}^c(\mathrm{AR})^{1-c} \tag{11}$$

Storage sizing for DRWHS design becomes difficult when detailed rainfall information is not available. Regional zoning was used to determine storage tank sizes in areas where rainfall data were unavailable. In addition, a regional scale analysis was used to design DRWHS storage tanks. Dimensionless graphs were developed in the study to design DRWHS at a regional level in northern Taiwan. Rainwater supply reliabilities of 50%, 70%, 80%, 90%, and 95% were obtained for each sub-region using dimensionless curves based on the two dimensionless parameters (storage and demand fraction). Furthermore, storage capacities obtained from dimensionless curves were compared with the adopted method in GBEM. The results revealed that the storage capacity obtained using the GBEM method was less than that obtained using dimensionless curves. The method adopted in the GBEM limits the storage capacity for a given effective roof area and lacks the concept of system reliability (Liaw and Chiang, 2014).

In another study in Greece, the dry period demand method and the daily water balance method were used to compute the optimal size of RWH systems. The two methods were used in 75 regions of Greece to meet in-house water demand of a household of 3 to 5 residents. A heuristic algorithm that was used to develop the daily water balance model allows excess water overflow and sets public water supply to zero. The simple method of maximum annual dry period was implemented to estimate the required rainwater harvesting tank size (Londra et al., 2015). The sizing of the rainwater harvesting tank was computed using the daily water balance model. The following water balance equation was used (Tsihrintzis and Baltas, 2013):

$$S_t = S_{t-1} + R_t - D_t,\ 0 \le S_{t-1} \le V_{\text{tank}} \tag{12}$$

where S_t is the stored volume at the end of the t^{th} day (m^3), S_{t-1} the stored volume at the beginning of the t^{th} day (m^3), R_t the harvested rainwater volume during the t^{th} day (m^3), D_t the daily water demand of the t^{th} day (m^3) and V_{tank} the capacity of rainwater tank (m^3).

The daily harvested rainwater volume (runoff), R_t (m^3), from a roof area is computed as:

$$R_t = C{\cdot}A{\cdot}P_{\text{eff,t}} \tag{13}$$

where C is the runoff coefficient, A is the rainfall collection area (m^2), and $P_{\text{eff,t}}$ is the daily effective rainfall depth at the end of the t^{th} day (m).

The daily rainwater demand, D_t, of a household is computed as:

$$D_t = N_{\text{cap}}{\cdot}q(p/100) \tag{14}$$

where N_{cap} is the number of residents (capita), q is the total daily water demand per capita, and p is the percentage of total water demand satisfied by harvested rainwater.

In the determination of minimum required rainwater collection area, the mean effective annual rainfall, P_{eff}, (m) based on the daily effective rainfall, can be computed as:

$$\overline{P_{\text{eff}}} = 365 \cdot \frac{\sum_{t=1}^{N} P_{\text{eff,t}}}{N} \tag{15}$$

where $P_{eff,t}$ is the daily effective rainfall depth at the end of the t^{th} day (m), and N is the number of data points of the record.

Accordingly, the mean annual harvested rainwater volume, $\overline{R}$(m^3), can be computed as:

$$\overline{R} = C \cdot A \cdot \overline{P_{\text{eff}}} \tag{16}$$

where C is the runoff coefficient, A is the rainfall collection area (m^2), and $\overline{P_{\text{eff}}}$ is the mean effective annual rainfall (m).

Conversely, using the daily water demand, the mean annual demand, $\overline{D}$ (m^3), can be computed as:

$$\overline{D} = 365 \cdot N_{cap} \cdot q \cdot \left(\tfrac{p}{100}\right) \tag{17}$$

where N_{cap} is the number of residents, q is the daily water use per capita (m^3), and p is the percentage of total water demand satisfied by harvested rainwater.

Assuming that the annual demand is equal to the mean annual harvested rainwater volume then the required rainwater collection, A_{min}, to satisfy the percentage p of the total water demand, is computed as (Tsihrintzis and Baltas, 2013):

$$\overline{R} = \overline{D} \xrightarrow{\text{Eq.(5) = Eq.(6)}} A_{\min} = 365 \cdot \frac{q}{C{\cdot}\overline{\text{Peff}}} \cdot \frac{p}{100} \cdot N_{cap} \tag{18}$$

where q is the daily water use per capita (m^3), N_{cap} is the number of residents, C is the runoff coefficient and $\overline{P_{\text{eff}}}$ is the mean effective annual rainfall (m).

Considering Eqs 17 to 19, the daily rainwater stored volume is computed as:

$$S_t = S_{t-1} + C \cdot P_{\text{eff,t}} - N_{\text{cap}} \cdot q \cdot \left(\tfrac{p}{100}\right) \tag{19}$$

where S_t is the stored volume at the end of the t^{th} day (m^3), S_{t-1} the stored volume at the beginning of the t^{th} day (m^3), C *is* the runoff coefficient, A is the rainfall collection area (m^2), $P_{\text{eff},t}$ is the daily effective rainfall depth at the end of the t^{th} day (m), N_{cap} is the number of residents, q is the daily water use per capita (m^3), and p is the percentage of total water demand satisfied by harvested rainwater.

The daily difference between runoff (inflow) and demand (outflow), ΔS_t (m^3), is computed using Eq. 20:

$$\Delta S_t = C \cdot A \cdot P_{\text{eff,t}} - N_{\text{cap}} \cdot q \cdot \left(\tfrac{p}{100}\right) \tag{20}$$

where C is the runoff coefficient, A is the rainfall collection area (m^2), $P_{\text{eff},t}$ is the daily effective rainfall depth at the end of the t^{th} day (m), N_{cap} is the number of residents, q is the daily water use per capita (m^3), and p is the percentage of total water demand satisfied by harvested rainwater.

The following heuristic algorithm can be used iteratively to compute the daily stored water in the tank. V_{tank} accounts for the capacity of the rainwater tank:

$$\begin{gathered}\text{if } S_{t-1} + \Delta S_t > V_{\text{tank}} \text{ then } V_{\text{tank}},\\ \text{if } S_{t-1} + \Delta S_t < 0 \text{ then } 0\\ \text{else } S_t = S_{\text{t,tank}} = S_{t-1} - \Delta S_t\end{gathered} \tag{21}$$

where S_t is the stored volume at the end of the t^{th} day (m^3), S_{t-1} the stored volume at the beginning of the t^{th} day (m^3), ΔS_t is the daily difference between runoff and demand (m^3) and $S_{\text{t,tank}}$ is the actual available stored water volume in the tank at the t^{th} day.

The following algorithm can compute the volume of water that overflows, O_t, from the tank when the tank is full:

$$\text{if } S_t \ge V_{\text{tank}} \text{ then } O_t = S_t - V_{\text{tank}} \text{ else } O_t = 0 \tag{22}$$

where S_t is the stored volume at the end of the t^{th} day (m^3), and V_{tank} is the capacity of the rainwater tank (m^3).

In the case when the demand, D_t, cannot be achieved using the stored water volume in the tank, $S_{\text{t,tank}}$, then the water delivered from public water supply, T_t, can satisfy the demand using the following algorithm:

$$\text{if } S_{\text{t,tank}} < D_t \text{ then } T_t = D_t - S_{\text{t,tank}} \text{ else } T_t \tag{23}$$

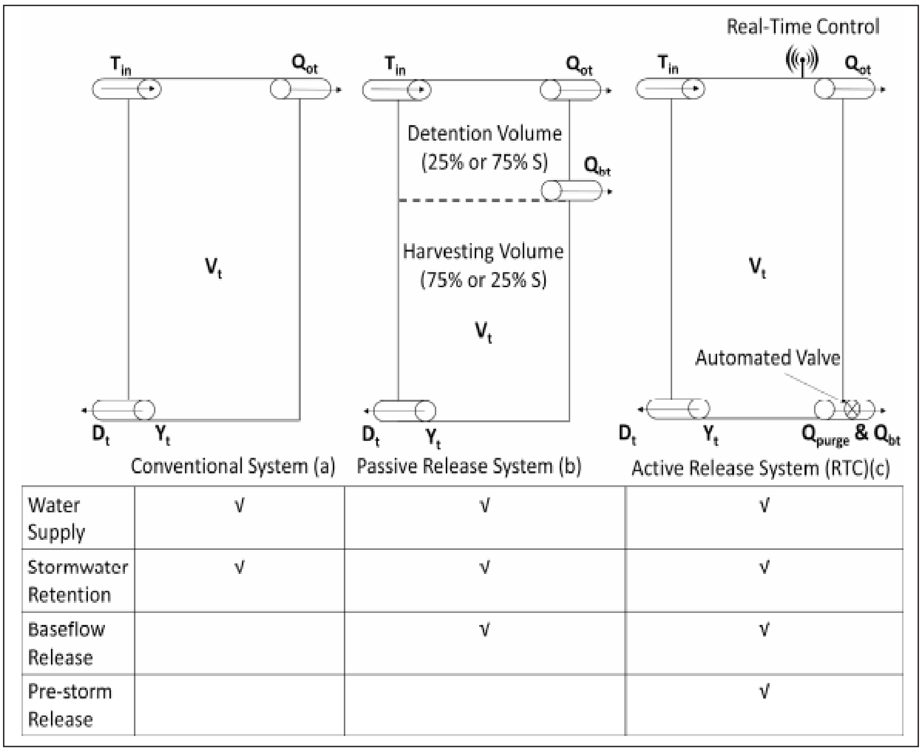
Daily rainfall record of at least 5 to 10 years for the area where the tank will be located must be available for the successful application of the procedure.

A study in Melbourne, Australia, applied RTC to optimise RWH (Xu et al., 2018). The study also presented two innovative RWH systems, i.e., passive and active release systems. The passive release system divided the RWH into two segments, namely, the retention storage volume and the stormwater detention via the addition of a passive discharge orifice at an intermediate depth. Water supply for domestic consumption was achieved via the retention storage volume, compromising the bottom portion of the storage, while the top portion of the system is occupied by the detention volume. The active release system (ARS) was operated by a novel approach – real-time control (RTC) – which uses a wireless connection to remotely control RWH systems. The performance of the RWH system was optimized by employing RTC technology via management of released water from the system to reduce the volume of uncontrolled stormwater runoff. Many wastewater systems use RTC technology to monitor and control water quality and address sanitary sewer overflow (SSO) and combined sewer overflow (CSO) issues. However, the possibility of employing RTC into RWH systems remains largely untested.

Rainfall forecast data in real time was received via the ARS which utilized RTC technology and automatically initiated a pre-storm release through a customized valve, in relation to the forecast precipitation and water level within the RWH system. The release of water in the system only occurred when there was insufficient storage capacity to capture the amount of forecast precipitation. Consequently, the water conservation function was preserved via this customization. In addition, pre-storm release was able to significantly reduce or even eliminate the uncontrolled stormwater runoff that discharges into the storm drainage system establishing a flood risk.

In Xu et al. (2018), the study focused on the comparison of the modelled performance of RWH systems employed with RTC technology to both conventional systems and passive release systems. Water supply, stormwater retention and baseflow restoration assessment metrics were used to characterize system performance. A model using the R software was constructed to simulate the behaviour of three allotment-scale RWH systems, viz., the conventional system, passive release system and active release system (RTC). The conventional system (Fig. 1a) is an allotment-scale RWH system that collects impervious runoff from roof areas and supplies a wide range of household end-uses. It has an overflow pipe at the top of the system which is unregulated and drains to the conventional drainage network. The passive release system (Fig. 1b) is identical to the conventional one but has an additional elevated outlet, i.e., 'trickle-release'. The tank storage is divided by this outlet into a retention volume (that below the trickle release) and detention volume (the volume above the elevated trickle release). The baseflow is mimicked using a small orifice by slowly releasing any water that is stored in the detention volume to the receiving water bodies (via the stormwater network). Passive release systems with detention volumes of 25% and 75% were simulated. The passive release systems with 25% and 75% detention volumes favour the water supply performance of the RWH system and increased stormwater retention and baseflow restoration performance, respectively. This provided opportunities to explore the impact of different system designs on multi-objective performance.

The active release system (Fig. 1c) is a combination of conventional system with RTC technology. It contributes baseflow to the receiving stream via controlled slow release, provides a purge release from the system prior to the storm event and can receive rainfall forecasts in real time. This mitigates flooding, as additional storage for predicted stormwater runoff is provided. The controlled outlet is termed 'pre-storm release'. The predicted overflow (pre-storm release) volume was computed as the difference between the predicted runoff volume and available tank storage volume at the end of the previous day.



	Conventional System (a)	Passive Release System (b)	Active Release System (RTC)(c)
Water Supply	√	√	√
Stormwater Retention	√	√	√
Baseflow Release		√	√
Pre-storm Release			√

Figure 1. Schematic representation of the three types of RWH systems (from Xu et al., 2018): (a) conventional system; (b) passive release system; and (c) active release system using real-time control. T_{in} is the tank inflow (L/6min), Q_{ot} is the tank overflow (uncontrolled discharge) at timestep t (L/6-min), Y_t is the rainwater yield at timestep t (L/6-min), V_t is the volume in store (L) during time interval t, D_t is demand at timestep t (L/6-min), S is the tank size (L), Q_{bt} is controlled baseflow discharge at timestep t (L/6-min) and Q_{purge} is the controlled pre-storm release subject to rainfall forecast (L/6-min) (Xu et al., 2018).

METHOD

Based on the extensive literature review, the most suitable model was selected to estimate benefits derived from application of RTC techniques in enhancing RWH using rainfall forecast at the New Engineering Building (NEB), University of Cape Town. The model used in this study was formed by the two main modules, i.e., rainwater inflow and end-use demand. The model was set to compute assessment metrics to allow system configurations to be compared using continuous simulation. The following steps were undertaken.

- **Rainwater inflow** – the main input data was daily rainfall forecasts obtained from Newlands station from the period 1 January 2017 to 31 September 2020 (Fig. 2). The rainfall forecasts were converted to predicted runoff volume from the NEB roof with initial loss of 0.2 mm, 2-h antecedent period and 0.2 mm/day.
- **End-use demand module** – the daily toilet flushing water demand at the NEB building was estimated as 1 333 L/day.
- **Continuous simulation** – was modelled using the yield after spillage rule (YAS) RTC algorithm.
- **Assessment metrics** – system performances were evaluated by four standardized performance parameters from assessment metrics.

The study focused on investigating the use of rainfall forecast to optimize storage volumes of RWH systems. The assessment of the prospects for RTC techniques on the NEB RWH system included modelling water balance to estimate the quantity of rainwater resource, identification of appropriate constraints and volumetric capacity, and the effectiveness of RTC to address the challenges of storage. In addition, issues such as appropriate demand to be supplied (potable or non-potable), costs (operation and maintenance), the extent of volumetric reliability, and benefits associated with RTC on RWH systems were assessed The modelling aimed at predicting inflow volume from forecasted rainfall and required storage to minimize overflow loss so that water can be used optimally for toilet flushing from the two 5kL rainwater harvesting tanks at the NEB.

A model was developed to continuously simulate and monitor the water level changes in the two RWH tanks. The assessment also included a comparison of the performance of CS and ARS using RTC. The CS (Fig. 3a) is an allotment-scale RWH system that collects impervious runoff from roof areas and is connected to the NEB end-use. It also has an overflow pipe at the top of the system which is unregulated and drains to the conventional drainage network.

The ARS in Fig. 3b is a combination of CS with RTC concepts. It provides a purge release from the system prior to the storm event and can receive rainfall forecasts in real time. This mitigates flooding as additional storage for predicted stormwater runoff is provided. The controlled outlet is termed ‘pre-storm release’. Hence, the predicted overflow (pre-storm release) volume is computed as the difference between the predicted runoff volume and available tank storage volume at the end of the previous day. For example, if the 5 kL system is half full (2.5 kL) at the end of the previous day and predicted rainfall inflow is 3 kL, the pre-storm release volume is 0.5 kL. This pre-storm release is discharged through a 10 mm automated valve, driven by gravity. The outflow rate q (m^3/s) was computed by the orifice equation:

$$q = C_d \left(\frac{\pi D^2}{4} \right) \sqrt{2gh} \tag{24}$$

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, C_d is the orifice discharge coefficient (C_d = 0.7 was adopted), and g is the acceleration due to gravity (9.81 m/s^2).

Rainfall data recorded from the period 1 January 2017 to 30 September 2020 were used to predict the inflows for the two types of RWH systems, i.e., conventional and RTC. The conversion of rainfall data to stormwater runoff (volume of system inflow) was estimated using initial loss model (i.e., 0.2 mm with 2-h antecedent period) as shown in Eq. 25.

$$T_{\mathrm{in}} = AR_t \tag{25}$$

where R_t is the roof runoff at timestep t in mm/day and A is the roof size (m^2)

A pre-storm release can be initiated using the ARS according to predicted rainfall. Rainfall forecasts that had at least 70% probability of occurrence were used to predict the storm runoff volume, considering an initial loss of 0.2 mm and resetting at every midnight. The rainfall forecast was predicted at midnight each day indicating both occurrence probability and rainfall depth in the next 24 h. The pre-storm release volume (Q_{purge}) is the predicted overflow volume (Q_{oTp}) which was determined by Eqs 26 and 27:

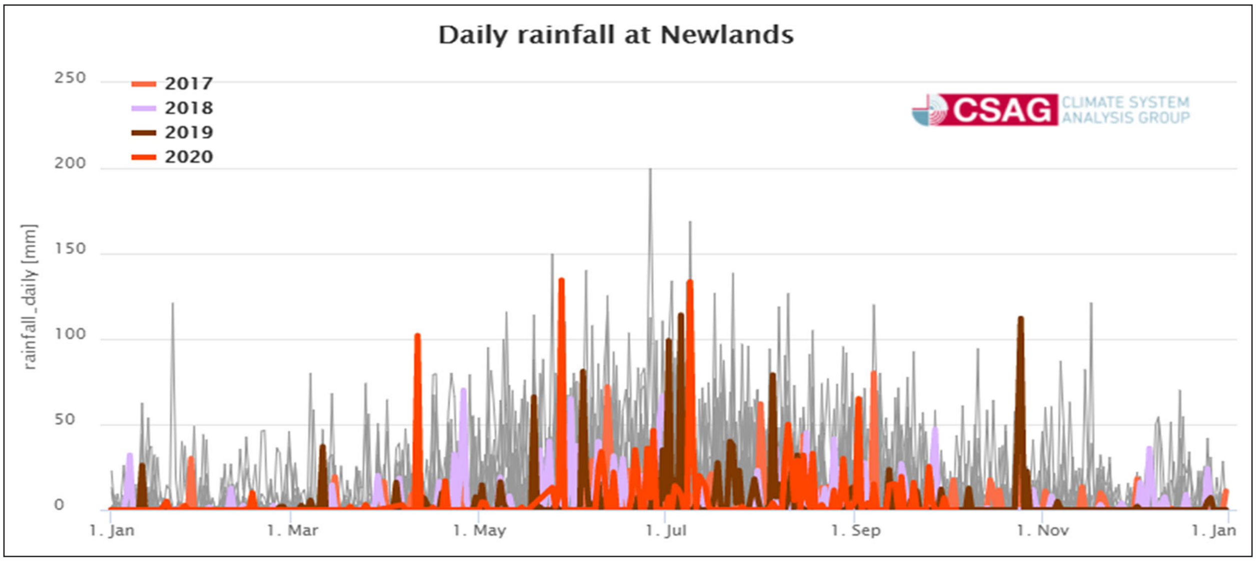
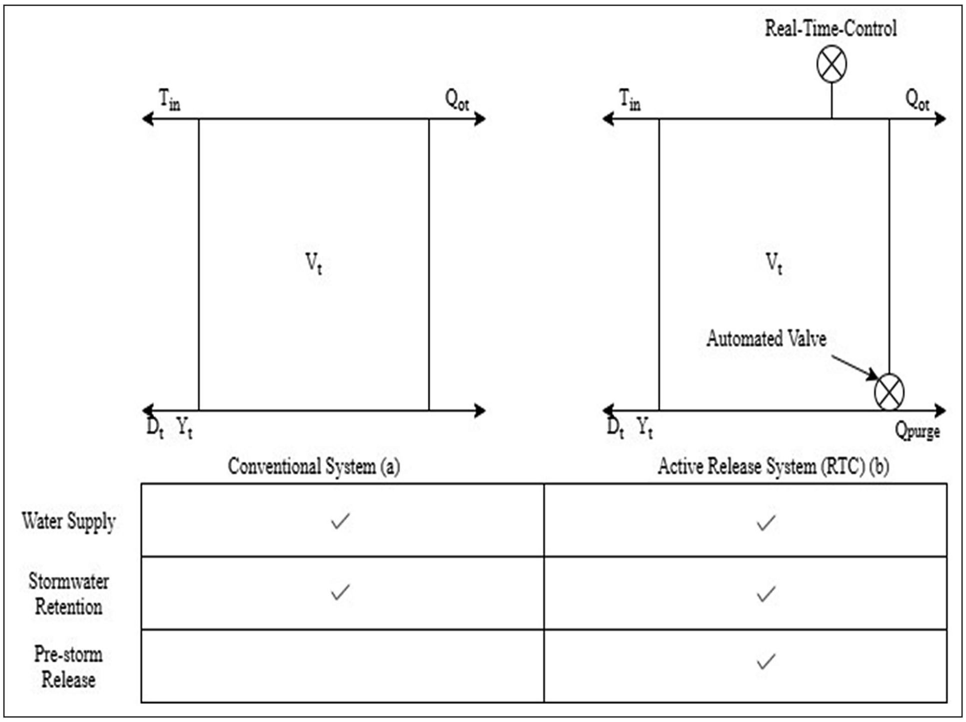


Figure 2. Forecast data (from CSAG, 2021)



	Conventional System (a)	Active Release System (RTC) (b)
Water Supply	✓	✓
Stormwater Retention	✓	✓
Pre-storm Release		✓

Figure 3. Schematic representation and functions of the two types of RWH systems: (a) conventional system (CS) and (b) active release system (ARS) using real-time control. T_{in} is the tank inflow (L), Q_{ot} is the tank overflow (uncontrolled discharge) at timestep t (L), Y_t is the rainwater yield at timestep t (L), V_t is the volume in store (L) during time interval t, D_t is demand at timestep t (L), S is the tank size (L) and Q_{purge} is the controlled pre-storm release subject to rainfall forecast (L).

$$T_{\text{inp}} = \begin{cases} A\left(R_{\text{Tp}} - D_{\text{il}}\right), R_{\text{prob}} \le 70\% \\ 0, R_{\text{prob}} < 70\% \end{cases} \tag{26}$$

$$Q_{\text{purge}} = Q_{\text{oTp}} = \begin{cases} \min\left(V_{t-1} + T_{\text{inp}} - S, V_{t-1}\right), V_{t-1} + T_{\text{inp}} > S \\ 0, \text{otherwise} \end{cases} \tag{27}$$

where R_{Tp} is the historical records of rainfall forecast on a daily basis (mm/day), R_{prob} is the probability of predicted precipitation, D_{il} is the Initial loss (0.2 mm/day), A is the roof size (m^2), V_{t-1} is the volume in store (L/day) at timestep (t–1)(previous), T_{inp} is the predicted system inflow in the next 24 h (L/day), Q_{purge} is the required volume of pre-storm release (L/day), Q_{oTp} is the predicted tank overflow (L/day), S is the tank size.

NEB end-use water demand was derived from real water consumption in the NEB building collected by the local water authority (City of Cape Town). The hourly water demand D_t (L/h) was determined by computing the mean of supply in the monitored NEB property:

$$D_t = \frac{\sum W_t}{n} \tag{28}$$

where W_t (L/h) is the water meter reading for the NEB at timestep t and n is the number of properties which is equal to one.

A daily timestep over the same period as the rainfall dataset (1 January 2017 to 30 September 2020) was used to simulate the behaviours of the two systems. The system outflow and volume were simulated using the yield-after-spillage (YAS) operating rule which provides a more accurate estimate of yield (Eqs 29, 30 and 31), given that the demand flow rate is less than the potential spillage flow in each timestep:

$$Q_{ot} = \max\begin{cases} V_{t-1} + T_{\text{in}} - S \\ 0 \end{cases} \tag{29}$$

$$Y_t = \min\begin{cases} D_t \\ V_{t-1} \end{cases} \tag{30}$$

$$V_t = \min\begin{cases} V_{t-1} + T_{in} - S \\ S - Y_t \end{cases} \tag{31}$$

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

In the model scenario, three assumptions were applied: i.e., the initial system volume was fixed at zero; yield always occurred after overflow (YAS rule); and the end-use was drawn at each time step. One rainwater harvesting system scenario was used to assess the influence of given operating and design factors on system performance. Roof catchment area was represented through the selection of one roof size. Only one tank size was considered and, lastly, the NEB end-uses modelled toilet flushing as the only end-use type. The physical parameters used included roof size – 350 m^2; tank size – 5 kL; NEB toilet flushing demand – 1 333 L/day.

The assessment metrics which characterize the two objectives, i.e., stormwater retention and water supply, measured the performance of each RWH system based on two assessment indicators shown in Table 1. The assessment indicators, i.e., efficiency and frequency, were used to quantify volumetric efficiency and frequency characteristics. The roof size controls the scale of the system inflow, and the assessment parameters are all expressed as a proportion of total volume for comparison of the performance of the two system configurations, i.e., conventional and RTC.

The objectives are evaluated by two parameters quantifying the amount and frequency. For water supply: Y_t is water supply yield at current timestep (L/day), D_t is the NEB demand at timestep t (L/day), N_t is counted if demand is satisfied in timestep t and n is the total number of timesteps. For stormwater retention: Q_{ot} is tank overflow at timestep t (L/day), A is roof size (m^2), R_t is roof runoff at timestep t (mm/day), N_t is counted if overflow occurs at timestep t and n is the total number of timesteps.

Table 1. Assessment metrics to characterize the system performance of two objectives

Objective	**Assessment indicator**	
	Efficiency	**Frequency**
Water supply	Water supply efficiency, E_{ws}: $E_{ws} = \frac{\sum Y_t}{\sum D_t} \times 100\%$	Water supply frequency, F_{ws}: $N_t = \begin{cases} 1, Y_t \geq D_t \\ 0, \text{else} \end{cases}$ $F_{ws} = \frac{\sum N_t}{n} \times 100\%$
Stormwater retention	Retention efficiency, E_R: $E_R = 1 - \frac{\sum Q_{ot}}{\sum A \cdot R_t}$	Overflow frequency F_o: $N_t = \begin{cases} 1, Q_{ot} \geq 0 \\ 0, \text{else} \end{cases}$ $F_o = \frac{\sum N_t}{n}$

RESULTS

The RWH system configuration was modelled with and without RTC in terms of stormwater retention and overflow frequency, while water supply remained unaltered. The ability to enhance stormwater retention with no detriment to water supply was evident in the comparison between ARS (with RTC) and CS (without RTC). The results of yield and overflow are shown in Fig. 4. A 7-day smoothed moving average was applied on the results to remove the noise and volatility due to the rapid changes caused by the small-sized RWH storage tanks. The smoothed values provide a clearer picture of the overall and long-term trends over a long period of time. Figure 5 shows monthly yields for both ARS and CS.

The study determined that for a 350 m^2 roof draining to two 5 kL tanks with only toilet flushing as the end-use connection, the average annual yield and overflow for ARS was 660 kL and 170 kL, respectively. The average annual yield and overflow for CS was 470 kL and 360 kL, respectively. Hence, the retention and pre-release performance of the RWH system significantly improved water supply and reduced overflow (loss of water resource). The performance results based on assessment metrics for both ARS and CS are shown in Figs 6 and 7. These results can be improved with increased RWH storage to about 30% of yield (Okedi, 2019). The 2 x 5 kL RWH storage was small compared to the 350 m^2 catchment, and this resulted in significant loss of water through overflow, even from the ARS (see Fig. 4).

In summary, the results show that the stormwater retention performance of RWH systems can be substantially improved by using RTC technology. This is accomplished by collecting rainfall forecasts in real time and discharging water from the system before the rainfall occurs (pre-storm release). Upcoming storm runoff can be contained using pre-storm release which gives the system additional capacity. In addition, the possibility of generating uncontrolled system overflow can also be reduced by pre-storm release. However, the rainfall depth of forecasts is generally higher than real-time which often produces an overestimated volume of pre-storm release. Thus, during pre-storm release, an unnecessarily large volume of water was discharged on occasion from the active release system. Hence, this has the possibility of diminishing performance for 'water supply'. This 'wastage' can be reduced through the utilization of more accurate and sub-daily rainfall forecast data which optimizes the system.

System design controls the overall performance of the active release mechanism of the RWH systems. Xu et al. (2018) showed that the performance of the ARS in retaining storm runoff is closely related to the storage size and outlet orifice size. The storage available for upcoming inflows can be achieved by a large orifice which can deliver the pre-storm release faster. The timing of the system overflow can simply shift when a large orifice is utilized (faster release). The valve opening-closing control would vary the outlet orifice size of the ARS in real time. Thus, the outflow rate of ARS can be customized according to system water level by the novel active control. Therefore, specific objectives of the ARS can be met by designing the system carefully.

Active release systems open possibilities for delivering a more reliable system due to their centralised control and failure detection abilities, which can be monitored remotely, allowing faults to be identified and fixed. In addition, such a system can adapt to variation of climate and local conditions over both the short and long term. Various objectives of the ARS can be satisfied according to requirements using an advanced active release that can customize the system from a centralised location. Moreover, the water quality for harvested rainwater can be of concern for potable water supply but there is the potential to integrate a treatment train including UV, filtration, ozonation, etc., to purify the first flush to potable standard in real deployment. These technologies would be suitable for application in buildings such as the NEB since they are readily available.

CONCLUSIONS AND RECOMMENDATIONS

In this study, a continuous simulation was conducted to model the performance of two types of RWH systems, i.e., conventional and active release systems, to simultaneously deliver: (i) water supply and (ii) extended stormwater retention. The study established that application of RTC techniques can improve the retention performance of a RWH system with limited impact to water supply. The ARS with RTC exhibited great potential in enhancing rainwater harvesting systems to simultaneously deliver stormwater management and water conservation. The system opens the possibility of delivering a more reliable and stable system due to its ability to provide failure detection and centralised control, which can be readily adapted to variation of climate and local conditions over both the short and long-term. The deployment of RWH systems to retrofit stormwater control is likely to require a combination of two different configurations: conventional and active release systems. This study has shown that the conventional system, which is simple and inexpensive, may be more suitable for small systems at household residences. But for large commercial buildings and other high-demand users, the ARS is more efficient, and shows a promising ability to deliver on multiple objectives.

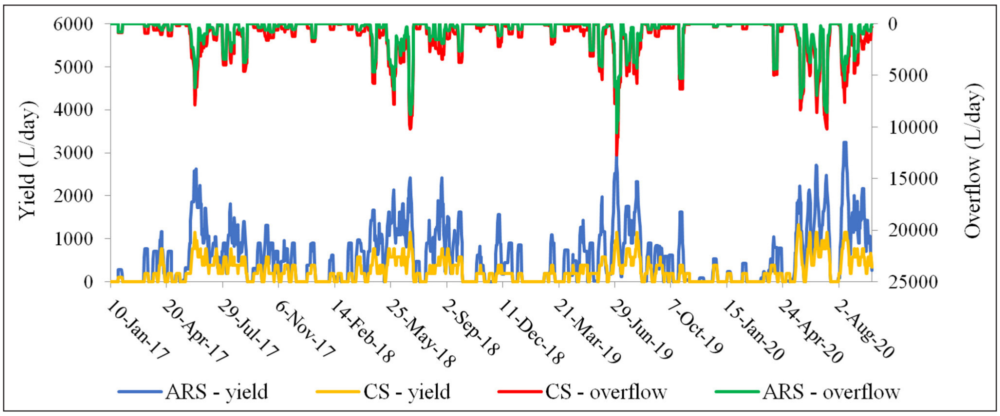


Figure 4. Smoothed moving average yield and overflow for active release system (ARS) with real-time control (RTC) and conventional system (CS)

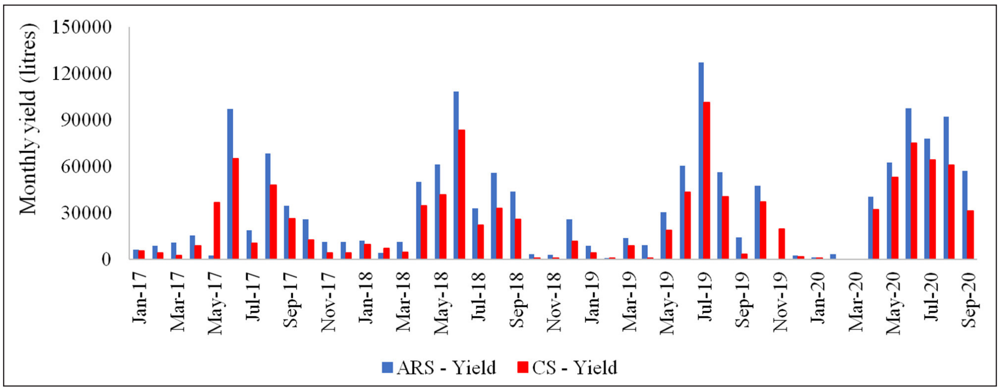


Figure 5. Total monthly yield: active release system (ARS) with real-time control (RTC) and conventional system (CS)

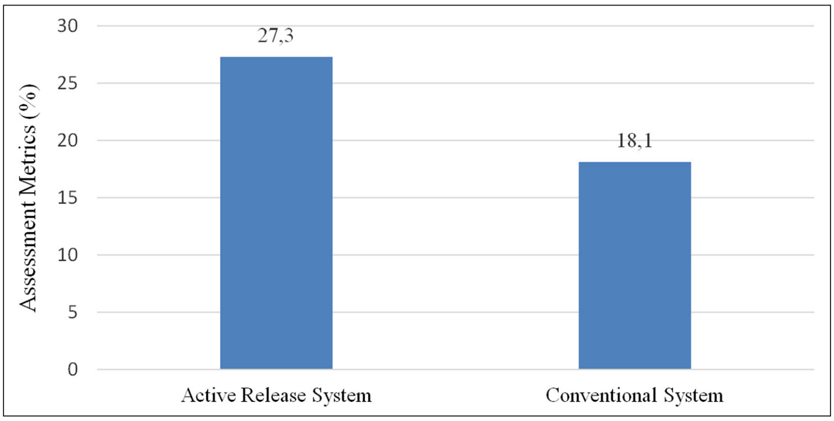


Figure 6. Water supply efficiency for the active release system (ARS) and conventional system (CS) configurations

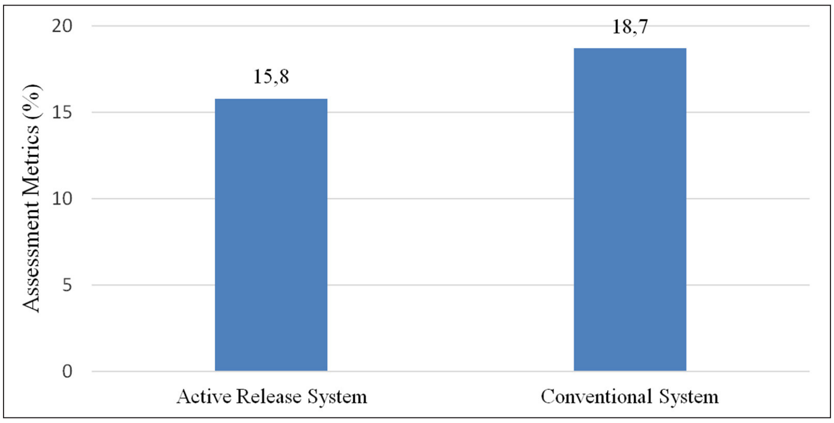


Figure 7. Overflow frequency for the active release system (ARS) and conventional system (CS) configurations

In other studies, such as Xu et al. (2020), it was also determined that the feasibility of implementing RTC in rainwater harvesting systems can be improved by using current sensor technology. This enables real-time monitoring of environmental conditions (e.g., rainfall and streamflow) and the present system (water level, pump flow and valve status) in real time (Schütze et al., 2004). For large-scale implementation, an affordable and highly customized solution to tackle economic and technological challenges can be attained using low-cost sensors, as indicated by recent advances (Montserrate et al., 2013). Platforms and wireless communication can be used to transmit and store collected data and control decisions (Yang, 2006). Future research is required to develop a comprehensive cost-benefit analysis, including cost-saving on reduced requirements, direct cost of different configurations, and energy consumption for water supply and stormwater infrastructure (Xu et al., 2018). Further improvement of the performance of the ARS using more reliable and accurate prediction of precipitation is also essential. As shown in Xu et al. (2018), this study confirmed that future work is required to maximize flood protection for large rainfall events by investigating the costs and benefits of RTC systems that use low-probability (e.g., 10% chance of) rainfall forecasts. Moreover, the exploration of how RTC techniques can minimize the impact of forecast errors would require investigating associated uncertainty in future studies. Further, optimal scale and suitable arrangement of such systems is an area that would be addressed by future research. The study also identified potential for active release systems to provide centralized stormwater harvesting and larger scale flood protection for an area. The development of technology to allow systems to integrate optimally, and determining the optimal combination of scales, is a logical next step.

AUTHOR CONTRIBUTIONS

Malesela Michael Mogano undertook the research including the literature review, selection of a suitable method, development of the assessment model, generation of the results, wrote the draft paper, and implemented the revisions from feedback/comments received from co-author.

John Okedi proposed the research topic, managed and supervised the study, assisted in the paper writing process, and formatted the paper for submission.

ORCID

John Okedi
https://orcid.org/0000-0001-7707-2721

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