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Real-Time Control of Rainwater Harvesting Systems: The Benefits of Increasing Rainfall Forecast Window

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Key Points:

- Four contrasting Real-Time Control strategies were applied to simulated rainwater harvesting systems
- Long lead-time rainfall forecast (7-day) enhanced the ability to reduce flood risk and restore baseflow, with little impact on water supply efficiency
- Using long lead-time rainfall forecast has the potential to holistically restore natural flow regimes.

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Abstract

Use of Real-Time Control (RTC) technology in Rainwater Harvesting Systems (RWH) can improve performance across water supply, flood protection, and environmental flow provision. Such systems make the most of rainfall forecast information, to release water prior to storm events and thus minimise uncontrolled overflows. To date, most advanced applications have adopted 24-hr forecast information, leaving longer-term forecasts largely untested. In this study, we aimed to predict the performance of four different RTC strategies, based on different forecast lead-time and preferred objectives. RTC systems were predicted to yield comparatively slightly less harvested rainwater than conventional passive systems, but delivered superior performance in terms of flood mitigation and delivery of environmental water for streamflow restoration. More importantly, using a 7-day rainfall forecast was shown to enhance the ability of RTC in mitigating flood risks and delivering an outflow regime that is close to the natural (reference) streamflow. Such a finding suggests that RTC combined with 7-day forecast can enhance the functionality of rainwater harvesting systems to restore and even mimick the entire natural flow regimes in receiving streams. This also opens up a new opportunity for practitioners to implement smart technology in managing urban stormwater in a range of contexts and for a range of stream health objectives.

Plain Language Summary

‘Smart tanks’ based on Real-Time Control (RTC) is increasingly used in rainwater harvesting systems to address water shortages, urban flooding and streams depleted of flow. Smart tanks, controlled by RTC, can use a range of digital information (e.g. rainfall forecast) to make optimal decisions to release some tank water before heavy rain, to reduce flood risks, while still supply water to households. Globally, most uses of this technology use 1-day forecasts of rainfall. To understand the effect of longer prediction window, we compared four strategies using either 1-day or 7-day rainfall forecast and modelled their performance using specialized computer code. We found that smart tanks using 7-day rainfall forecasts are superior in reducing urban flood risks and restoring baseflows to streams. More importantly, they can release the tank water in a pattern that is similar to natural streamflow, thus helping to restore and sustain healthy waterway habitats. Our study is the first reported application of 7-day forecast information in smart control rainwater tanks. It opens up a new opportunity in managing urban water in a range of contexts and for a range of stream health objectives.

1. Introduction

Urbanisation poses a range of critical challenges in water management. Water scarcity results from population growth and dwindling freshwater resources (Vörösmarty et al., 2010). The growth of impervious cover creates gross changes to the natural water cycle through reductions in infiltration and evapotranspiration (Barron et al., 2013; Haase, 2009), resulting in excessive stormwater runoff and concurrently decreased groundwater recharge (Bultot et al., 1990). This increases flooding risks (Nirupama & Simonovic, 2006) and perturbs the natural flow regimes, increasing peak flows and reducing baseflow (Booth & Jackson, 1997; Burns et al., 2012b; Price, 2011). Accordingly, the conventional hydraulic efficient drainage network, which directly connects the impervious runoff to receiving water, increases the frequency, magnitude and volume of storm flow (Leopold, 1968) and reduces storm recession time (Burns et al., 2005). Such a change drives channel erosion (Hammer, 1972; Russell et al., 2020) and ecological degradation in urban streams and leads to a subsequent loss of ecosystem services (Bunn & Arthington, 2002; King et al., 2005; Walsh et al., 2012). Similarly, loss of baseflow, results in loss of dry weather wetted habitat, thus further reducing biodiversity (Poff et al., 1997).

Urban stormwater impacts can be mitigated using Stormwater Control Measures (SCMs) such as Rainwater Harvesting Systems (RWH). Such systems are conventionally designed to capture and store surface runoff from impervious cover (e.g. roofs) to provide a source of water (Gardner & Vieritz, 2010; Mikkelsen et al., 1999). Diversion of rainwater from direct runoff to end-use also helps to mitigate the excess runoff delivered to receiving waters (Fletcher et al., 2007), thus reducing the risks of flooding (Schubert et al., 2017). However, there is an increasing recognition of the importance of SCMs being able to not only reduce peak flows, but also to restore lost baseflows (Hamel et al., 2013; Price, 2011; Walsh et al., 2016). As an example, in Melbourne, Australia, a new stormwater regulation has been piloted, incorporating requirements to both reduce runoff volume and frequency, as well as to make contributions to baseflow (DELWP, 2019). Releasing some of the retained rainwater, through a passive orifice, in a temporal pattern close to the natural flow regimes can help to restore baseflow (Burns et al., 2012a). One limitation of such a system, however, is that they often lack the constant and high demand to create sufficient headroom for upcoming storm runoff (DeBusk et al., 2013; Jones & Hunt, 2010), thus leading to frequent uncontrolled system overflows.

Real-Time Control (RTC), so called “smart” technology, is increasingly applied in RWH systems to maximise simultaneous outcomes related to water supply, flooding, and baseflow provision (Roman et al., 2017; Xu et al., 2018). One major advantage of RTC compared to conventional (i.e. passive) systems is the ability to use the available information (e.g. environmental monitoring and weather forecast) and adapt the system operation in coherence with the real-time situation (Kerkez et al., 2016). RTC systems are generally equipped with an active outlet and designed to release water prior to the event (termed here as *pre-storm release*) to minimize the magnitude and frequency of uncontrolled overflow. The released volume is determined by comparison of rainfall forecast from the local meteorological authority with current available headroom. Both modelling and empirical studies have demonstrated the ability of RTC in enhancing the stormwater retention and peak flow reduction (Di Matteo et al., 2019; Gee & Hunt, 2016; Liang et al., 2019), with very little detriment to water supply (Xu et al., 2018). Recent application also includes a new possibility to restore the stream baseflow through a persistent low-rate discharge that emulates the natural flow regimes (Xu et al., 2018).

One important concern in relation to the *pre-storm release* is that without attention to the flow regime, it could simply mimic the ‘uncontrolled’ overflow, but shifted in time, thus leaving the flow regime highly disturbed, with geomorphic and ecological consequences for downstream receiving waters. This is because most such RTC applications for flood mitigation are managed at best using a 24-hr forecast, meaning that the release needs to be rapid in order to be completed before the predicted rainfall. Therefore, system outflow is likely to retain the magnitude and flashiness of peak flows which are a feature of impervious runoff, potentially a posing risk of erosion and degradation to downstream receiving waters. The main questions addressed in this article are related to the optimal use of available forecast with different lead-time and its impact for the overall performance of an RTC rainwater harvesting system.

Globally, Numeric Weather Prediction (NWP) can anticipate rainfall events more than 24-hours ahead of their arrival, with forecasts of up to 7-days readily available (Clark & Hay, 2004; Damrath et al., 2000; Davies et al., 2005). While the accuracy of forecast remains a fruitful area of research, such an advance drives new improvement in water industry, such as hydrological forecasting (Georgakakos & Hudlow, 1984; Rossa et al., 2011). Operation based on 7-day rainfall forecast has been used in agriculture (Cai et al., 2011; Wang & Cai, 2009) and water supply (Tsai et al., 2008; Westphal et al., 2003). In theory, this would also allow RTC systems to perform pre-storm release long before the actual event, at a lower rate that is much closer to the natural hydrology. However, the use of 7-day forecast and the associated effect on pre-storm release remain largely untested.

In this study, we aim to design a RTC strategy to operate RWH and assess its effects using different forecast lead-times. We have developed and modelled four RTC strategies with different preferences in terms of maximizing the benefits for water supply, flood protection or streamflow preservation. These strategies are also based on contrasted forecast lead-times and are compared to a conventional (without any passive release) system during a 5.5-year simulation period. In a more detailed analysis, the impact of different RTC strategies on system outflow regimes is characterized and compared to the natural streamflow.

We hypothesis that systems using longer lead-time forecasts could improve the ability of RTC in flood protection, with little detriment to the supply of end-use. Our results confirmed this hypothesis and found that, by using the 7-day forecast, the benefits of RTC are not limited in reducing the peak flow and enhancing the baseflow. Importantly, it can deliver an outflow regime that is close to the reference streamflow, revealing a promising potential of RTC to restore and even mimick the entire natural flow regime. Our work brings valuable insights on both the advantage and trade-off of this technology and different forecast information. It highlights the substantial opportunity in equipping rainwater harvesting systems with RTC for a wide range of simultaneous water supply, flood mitigation and streamflow restoration objectives.

2. Methodology

2.1 Proposed RTC Strategies

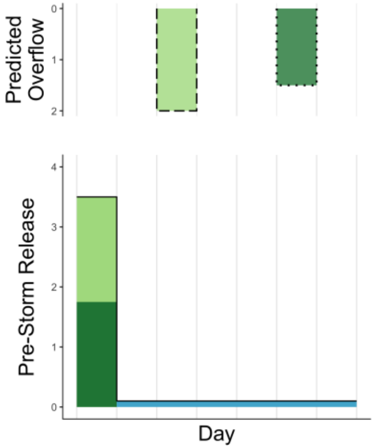
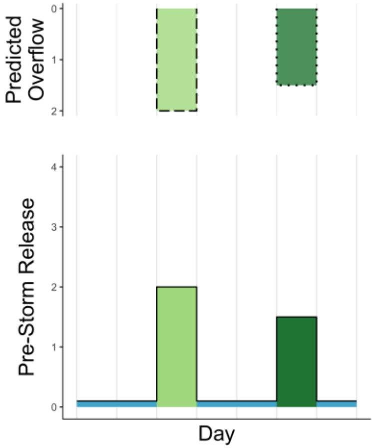
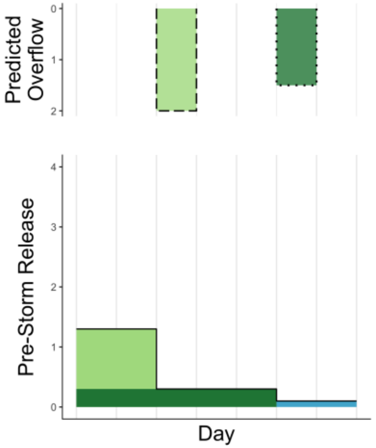
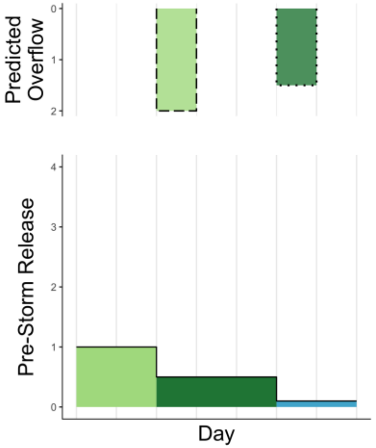
We developed four RTC strategies which utilised the rainfall forecast in different ways (Table 1). Strategy S1 (*Flood Protection*) is designed to minimise tank overflows through a 24-hr uniform release (termed here as ‘pre-storm release’) of any overflows that are forecast to occur within the next 7-days. Strategy S2 (*Supply Maximisation*) is similar to *S1*, but features a much shorter forecast lead-time (1-day) in order to increase the amount of tank water available for supply (i.e. the pre-storm release is not done until the day of predicted overflow, to reduce the probability of any discharges that turn out not to have been required to prevent overflows). In contrast, the pre-storm release in strategy S3 (*Longest Discharge*) and S4 (*Streamflow Preservation*) were designed to minimize the flashiness and magnitude of pre-storm release using the 7-day forecast to extend the discharge period, thus more closely reflecting natural streamflow. This is achieved by designing the release in *S3* with the longest possible discharge duration for each predicted overflow volume. In *S4*, the lowest possible discharge rate is used, to minimise changes to the flow regime.

Consider the following as an example. Assuming the demand patterns are the same for four RTC strategies (i.e. demand patterns are explained in section 2.4). If overflow was predicted on both day 3 and 6 over the next 7 days, *Flood Protection* would release all of the predicted overflow volume on day 1 to minimise the risk of overflow, while *Supply Maximisation* would release on the day(s) of predicted overflow (i.e. day 3 and 6). Under the *Longest Discharge* strategy, these overflows would be uniformly released over 2 and 5 days respectively to maximize the duration of pre-storm release associated to each event. Such a decision is then recalculated under the *Streamflow Preservation* strategy to minimize the peak release rate during the 7-day, while still preventing each predicted overflow (Table 1).

While the above all aim to reduce uncontrolled overflow, all RTC strategies were also designed to simultaneously restore some stream baseflow. This is achieved by a persistent (i.e. every time-step) controlled discharge (termed here as ‘baseflow release’) which attempts to counteract the lost baseflows common in urban streams (Price, 2011; Smakhtin, 2001). Such an operation is ceased when pre-storm release is required, or if the storage is empty (i.e. blue area in Example Table 1). The baseflow release target was determined by the median flow (i.e. daily Q50) from a reference natural stream (forested catchment); the median flow provides a reasonable estimate of a stream’s baseflow (Smakhtin et al., 1997).

Table 1

Four Proposed Real-Time Control Strategies.

Strategy	**Flood Protection (S1)**	**Supply Maximisation (S2)**	**Longest Discharge (S3)**	**Streamflow Preservation (S4)**
Principle	Prioritise minimising overflow risk over everything else	Prioritise water supply over all else, by preserving water in storage	Maximise discharge period to emulate natural flow behaviour	Minimise disturbances to the flow regime by minimising peaks
Lead-time (day)	7	1	7	7
Discharge volume	Sum of predicted overflows in next 7-day	Sum of predicted overflows in next 1-day	Predicted overflow on each day	(1) Sum of predicted overflows in next 7-day (2) Predicted overflow on each day
Discharge period	24-hr	24-hr	Until each predicted overflow *(may be multiple days)*	(1) Until last predicted overflow (2) OR each predicted overflow *(both may be multiple days)*
Rules	Discharge next 7-day predicted overflow volume in one day as soon as possible	Discharge predicted overflow volume on the day of prediction	(1) Discharge each predicted overflow uniformly during the period (2) Daily discharge is the sum of above	Optimize the individual discharge period of the *Longest Discharge* strategy to minimize the peak release rate.
Example				

2.2 Modelling Framework

A modelling framework, written using R (version 3.6.1), was developed to simulate the performance of the proposed RTC system under the four proposed strategies. This framework includes three different modules: prediction (M1), simulation (M2), and assessment metrics (M3) (Figure 1). The prediction module (M1) is run at a daily timestep (at 3pm), the simulation (M2) is run every 6 minutes and the assessment (M3) is the integration of all the 6-minutes step for the whole time series.

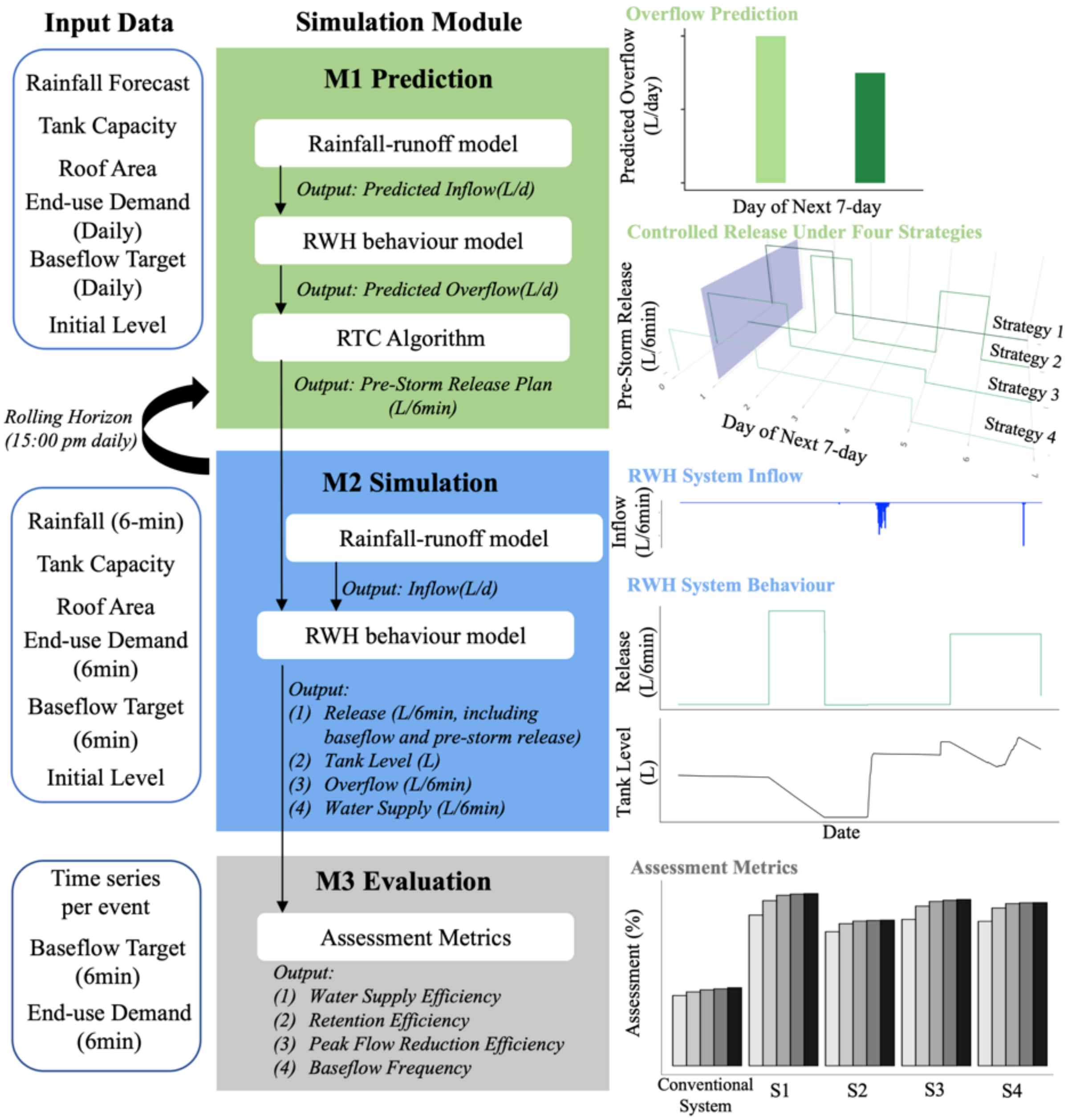


Figure 1. Conceptual representation of modelling framework to simulate and evaluate real-time controlled rainwater harvesting systems. Conventional system is simulated only by M2 and evaluated by M3.

2.2.1 M1 Prediction

The prediction module is the central component to decide control actions for different RTC strategies. It consists of three steps which are operated daily. Firstly, it predicts system inflow as a function of rainfall forecast data (Equation 1, Rainfall-runoff model):

$$Q_{in} = (R_t - R_{loss}) \times A \tag{1}$$

Where Q_{in} is the system inflow (L), R_t is the forecast rainfall depth (mm) at time t, R_{loss} is the initial loss (i.e. depression storage on the roof surface that delay the runoff) which is set as 0.2mm/day. A is the roof size which is selected as $150m^2$ to reflect a residential house.

Tank level is then sampled to predict future system overflow using Yield-After-Spillage rules which provides a more accurate estimation of yield (Fewkes & Butler, 2000; Jenkins et al., 1978) (Equations 2-5, Rainwater Harvesting Behaviour Model). Overflows in any systems are unregulated — i.e. they occurred whenever inflows exceeded system capacity. First flush was excluded in the tank behavioral model, given that the use, type and volumetric behaviour of filtration devices is highly variable.

$$Q_{ot} = \max \begin{cases} V_{t-1} + Q_{in} - S \\ 0 \end{cases} \tag{2}$$

$$Q_{bt} = \min \begin{cases} Q_{target} \\ V_{t-1} \end{cases} \tag{3}$$

$$Y_t = \min \begin{cases} D_t \\ V_{t-1} - Q_{bt} \end{cases} \tag{4}$$

$$V_t = \min \begin{cases} V_{t-1} + Q_{in} - Y_t - Q_{bt} \\ S - Y_t - Q_{bt} \end{cases} \tag{5}$$

Where V_t and V_{t-1} are the volume in store (L) at the end of time step t (current) and t-1 (previous) respectively, Y_t is the rainwater yield at t (L/timestep), Q_{bt} is the controlled release (i.e. baseflow release in prediction module) at t (L/timestep), Q_{ot} is tank overflow at t (L/timestep), S is tank size (L), D_t is rainwater demand at t (L/timestep), Q_{target} is the baseflow target at t (L/timestep), Q_{in} is the tank inflow (L/timestep)

Finally, four pre-storm release plans are developed based on strategies (previously explained in 2.1) and fed into the M2 simulation.

2.2.2 M2 Simulation

This module simulates the performance of the defined controls. The modelling process is similar to the prediction module in simulating system inflow and system behaviour. However, this module uses the actual observed rainfall, applying an initial loss of 0.2 mm (Laing et al., 1988), with an antecedent drying period of 2 hours (i.e. initial loss is only applied when there is a minimum of 2-hour dry period). As noted above, the tank behavioural model is run on a 6-min timestep, which is sufficient to capture system dynamics (Di Matteo et al., 2019; Mitchell et al., 2008).

The prediction (forecast) and simulation (observed) modules are run on a rolling horizon. The prediction module decides the controlled release for the next 7-day based on the rainfall forecast (i.e. 15:00 pm daily). However, only the control actions in the next 24-hour are implemented in the simulation modules. This is then renewed, on a daily basis, when forecast information is updated. Finally, the outputs from the simulation module are stored and evaluated by assessment metrics at the end of simulation period.

2.3 Assessment Metrics

Four metrics were selected to quantify the long-term performance on supply and flow regimes (Table 2). The baseflow frequency, retention and supply efficiency are based on total timesteps or volume, while the peak flow mitigation is evaluated in each event. An individual storm event was defined as having more than 0.2mm of rainfall and 1.2mm/hr rainfall intensity with an antecedent dry period of at least 2h, which is consistent with initial loss. The performance of different strategies is compared in the main text (see Section 3.1 and 3.2) by taking a mean of each assessment metric across five tank sizes, with detailed results presented in Figure 2. Finally, four of the largest events (i.e. max intensity (mm/hr) while duration is no less than 30min) were selected as examples to demonstrate peak flow mitigation.

The system outflow is also characterized using a flow duration curve. System outflow is defined as the sum of any uncontrolled overflow and any controlled release (i.e. pre-storm release and baseflow release). The outflow regime of four RTC strategies is then compared to conventional system (i.e. overflow) and the reference streamflow.

Table 2.

Assessment Metrics for Triple Objectives of Rainwater Harvesting

Assessment Metrics	Equation	Description
Water Supply Efficiency (%)	$Ews = \frac{\sum Y_t}{\sum D_t} \times 100\%$	Y_t is the rainwater yield on supply at time t (L/6 minutes), D_t is household demand at time t (L/6minutes)
Retention Efficiency (%)	$E_R = \left[1 - \frac{\sum Q_{ot}}{\sum A \times R_t}\right]$	Q_{ot} is overflow at time t (L/6minutes), A is roof size (i.e. 150 m^2), R_t is roof runoff at time t (mm/6minutes)
Peak Flow Mitigation (%)	$\rho = \frac{Q_{out,max_{convention\ system}} - Q_{out,max_{RTC\ system}}}{Q_{out,max_{convention\ system}}}$	Peak flow reduction efficiency of RTC strategies compared to the conventional system. Q_{out} refers to overflow in conventional system and sum of overflow and release in RTC systems
Baseflow Frequency (%)	$N_t = \begin{cases} 1, 2 * Q_{target} \geq Q_{bt} \geq Q_{target} \\ 0, else \end{cases}$ $F_b = \frac{\sum N_t}{n}$	N_t is count if baseflow target is satisfied at time t and n is the total number of timesteps.

2.4 Input data and Scenarios

Numeric Weather Prediction was obtained from the local meteorological authority (Bureau of Meteorology, 2020) to predict uncontrolled overflow, which is based on the Australian Community Climate Earth-System Simulator (ACCESS) (Bureau of Meteorology, 2010). In total, 66 months (i.e. 2014-03-01 – 2019-08-31) of 7-day lead precipitation forecast were extracted for Eastern Melbourne (i.e. Lat:-37.92, Long:145.32). We utilized mean daily predicted rainfall (in mm) which is updated daily at 15:00 pm and has a relative error of -9.5% compared to rainfall observation (i.e. forecast rainfall generally underestimates the actual rainfall).

Rainfall and streamflow observations were obtained at the same location during the same period, to compute system inflow (M2) and the baseflow release target (M1&M2) respectively. We extracted 550 rainfall events with an annual rainfall of 861 mm. Four baseflow targets were derived from median flow across the four seasons (to account for seasonal various), with mean of 0.26 mm/day.

We also simulated five scenarios to represent a range of household settings in terms of tank size and roof size. We considered a roof of 150 m^2, drained by five different sized storage tanks (2, 3.75, 7.5, 11.25, 15 kL), and are connected to a range of domestic water demands, including toilet flushing, dishwasher and cloth washing. The demand profile was adopted from Xu et al. (2018). It is consistent with a typical indoor diurnal pattern that has the peak consumption of 10.3 L/hr at 7pm and the lowest usage of 2.4 L/hr at 2am, with a total daily consumption of approximately 132 L/d.

3. Results

We predicted and compared system performance in terms of water supply, flood risk mitigation and baseflow restoration. Modelling of the RTC systems predicted them to yield comparatively less water supply than conventional (passive-release) systems, but to be much more effective in reducing flood risks and restoring baseflow. More importantly, using 7-day lead-time rainfall forecast, which offers longer prediction window, was shown to further enhance the ability of RTC in mitigating flood risks and delivering an outflow regime that is close to the reference streamflow.

3.1 Supply

According to the results of the simulation (Figure 2), RTC systems using a 1-day rainfall forecast could supply more water for end-use than those which utilise a 7-day prediction window. The Supply Maximisation strategy (S2) demonstrated an average of 7.7% higher supply efficiency compared to the Flood Protection strategy (S1), with an average (across all tank sizes) water supply volume of 234 kL (S1) and 255 kL (S2) over the 5.5 years, respectively. Comparatively smaller reductions in supply efficiency were predicted for the flow regime focused strategies — 3.2% for Longest discharge strategy (S3) and 2.6% for Streamflow preservation strategy (S4). Not surprisingly, a conventional system was predicted to yield most water, although differences between all the systems diminished with increasing tank capacity.

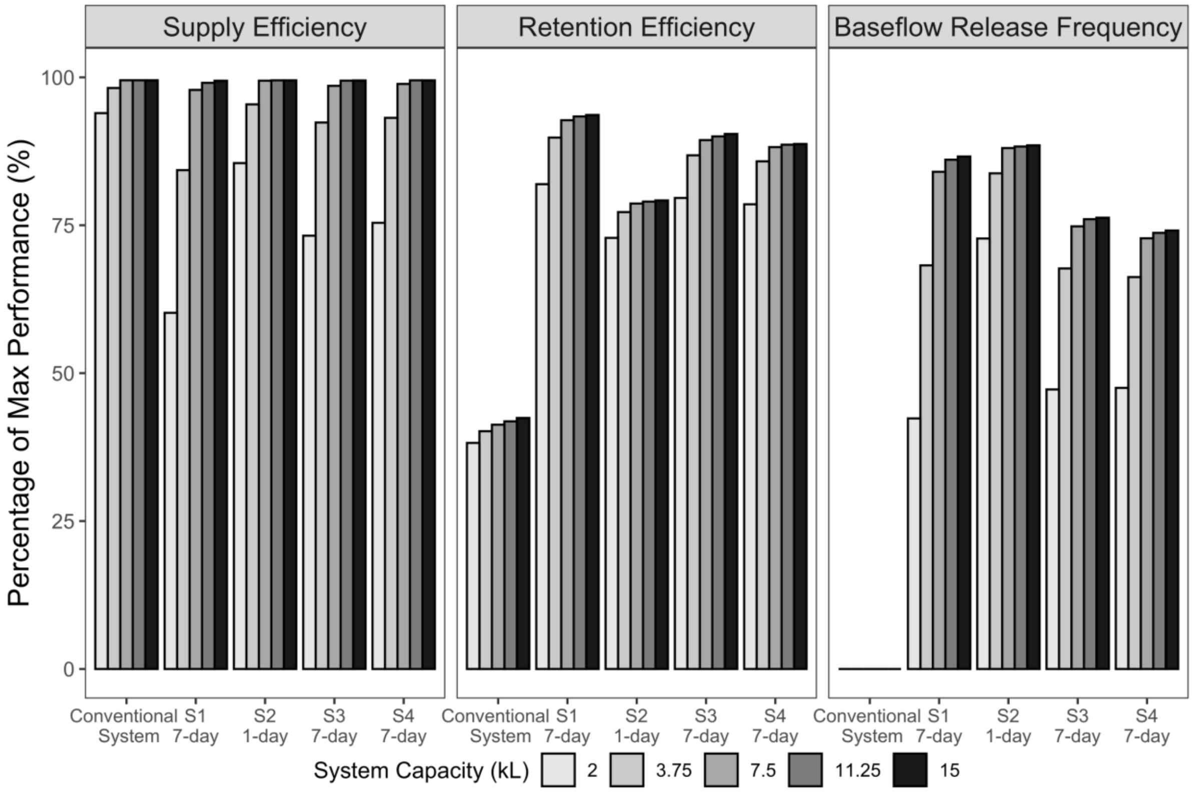


Figure 2. Performance evaluation of conventional system and four RTC systems with different system capacities. Three metrics are used from Table 2 to quantify the performance during the entire simulation period, which are supply efficiency, retention efficiency, and baseflow frequency. The strategies are *Flood protection* (S1), *Supply maximisation* (S2), *Longest discharge* (S3) and *Streamflow preservation* (S4).

3.2 Flow Regime

3.2.1 Flood risk mitigation

All RTC systems were predicted to reduce uncontrolled system overflows compared to the conventional system. The Supply Maximisation strategy, using 1-day forecast, nearly doubles the retention efficiency compared to conventional passive systems, with an increase ranging between 72% - 79% (Figure 2). Such an improvement is further elevated by use of the 7-day forecast information (i.e. Flood protection, Longest discharge and Streamflow preservation strategies), indicating an average further improvement of 10%, meaning an overflow reduction of 65.7 kL (i.e. out of 657.5 kL of the total inflow) during the 5.5 years simulation period. More importantly, the results show that increasing the lead-time from 1 day to 7 days providse a much better flood protection than simply increasing the tank capacity.

RTC using 7-day forecast was also predicted to mitigate flow peaks in both small and large rainfall events (Table 3). For small events (i.e. with rainfall magnitudes less than the design rainfall 5-yr, 1-hr storm), Supply maximisation strategy (S2) with capacity of 7.5 kL showed more than 30% reduction in peak flow compared to conventional systems. However, this benefit can be generally increased to 100% using 7-day rainfall forecast. For large rainfall events, while 1-day RTC has no difference to conventional system, RTC using 7-day forecast provides better performance in reducing the flow peaks, especially for events no more than 20-year ARI.

Table 3.

Peak Flow Mitigation of 7.5 kL Systems in Four Large Events.

Date	Depth (mm)	Max 30-min intensity (mm/hr)	Duration (hr)	ARI approx.[b]	Forecast error (%)[a]	Peak Reduction (%)			
						S1 (7-d)	S2 (1-d)	S3 (7-d)	S4 (7-d)
29th March 2016	65.09	96.4	2.3	>100	-73	33.8	0	0	0
27th January 2016	34.2	36.4	1.8	20	-49.3	100	0	100	99.8
21st March 2017	22.8	22.8	1	5	-42.4	100	30	100	95
25th January 2018	13.2	26.4	0.5	2	-59.7	100	54.2	100	100

Note: [a]ARI is approximated by the Intensity-Frequency-Duration design rainfalls from the local meteorological authorities (Bureau of Meteorology, 2016), using depth and duration in each event. [b]Forecast error is the mean relative error of daily rainfall observation and prediction, which is comparable with other study (Shrestha et al., 2013).

To illustrate (Figure 3), the Flood Protection strategy in a 7.5 kL system mitigated all uncontrolled overflow during the period of 23rd – 31st January 2016, achieving a 100% peak flow reduction in a 20 year, 2hr-storm on 27th January. Two overflow events were firstly predicted by 7-day rainfall forecast on 23rd Jan, which occurred on 27th and 28th January. Thus, the pre-storm release was performed in the next 24-hr accordingly at a steady rate of 40L/hr. As the system capacity was adequate to accommodate all predicted inflow, Flood Protection was then returned to routine baseflow release (i.e. 1 L/hr) on 24th and 25th January. However, this decision was reassessed when forecast information was updated at 15:00 pm 26th January due to five consecutive overflow predicted. Therefore, the pre-storm release overrode the baseflow release and discharged the storage at 210 L/hr until the tank was emptied, leading to 100% peak flow reduction during a 20 year, 2hr-storm. For the conventional system, the tank spilled most of the inflow through uncontrolled overflow (Figure 3).

Moreover, the peak flow in a long duration rainfall could also be reduced by discharging the storage during the event. Three subsequent events were predicted on 28th January in the next 7-day forecast period, with the largest rainfall happening in the next 24-hr. Thus, the Flood protection strategy determined a pre-storm release of 160 L/hr to avoid any overflow on the day, while simultaneously making room for future inflow on 29th and 30th January. This is performed during a 6-hr 1 in 1-year event (i.e. 28th January), achieving a peak flow reduction of 87% compared to conventional systems. Such a control was then decreased to 20 L/hr on 29th January due to an over-prediction in the previous forecast. Therefore, RTC using Flood protection strategy successfully mitigated all uncontrolled overflow during the 29th and 30th January event, achieving 98% and 100% peak reduction compared to conventional systems respectively.

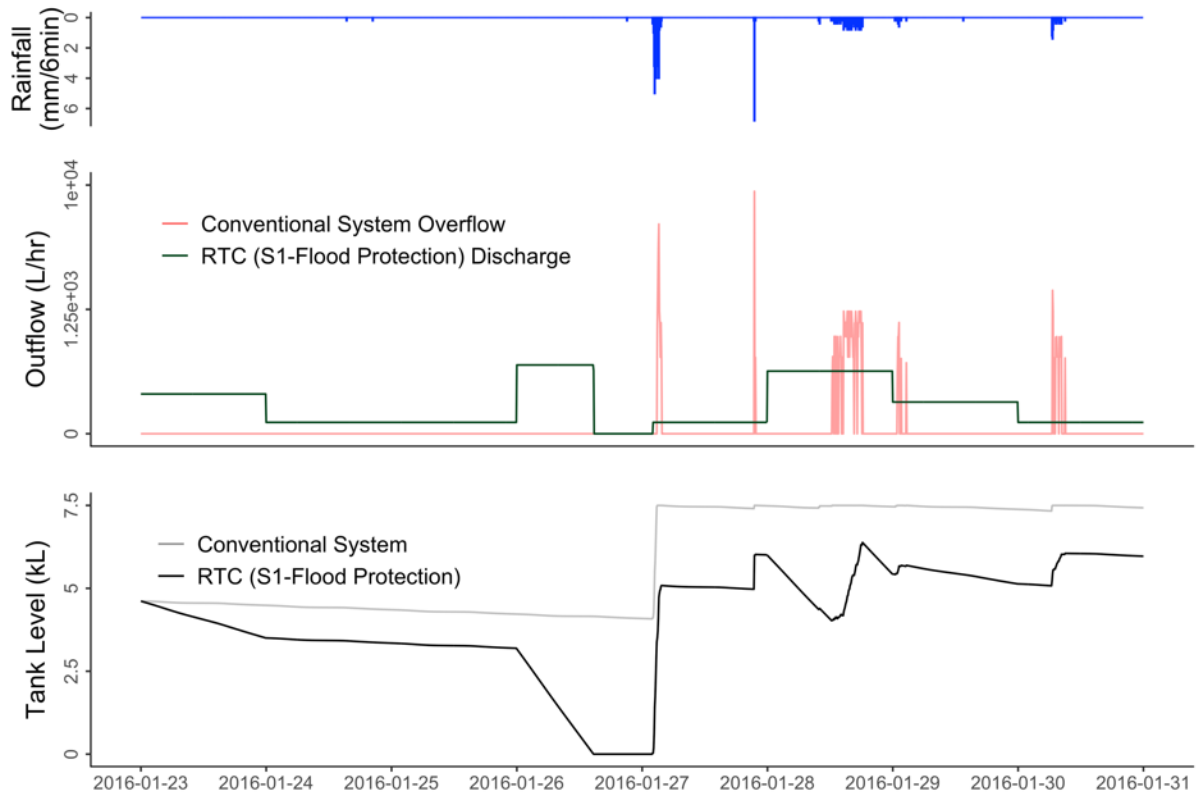


Figure 3. Illustration of a 7.5 kL system performance for the *Flood protection* strategy and conventional systems during 23rd – 31st Jan 2016, including hyetograph (top), outflow hydrograph (middle) and water level (bottom). The conventional systems performance was modelled separately using the same initial condition as the *Flood protection* strategy on 23rd Jan.

3.2.2 Baseflow Restoration

The 1-day forecast control was generally able to deliver more frequent baseflow release compared to strategies using 7-day information. The Supply maximisation strategy shows an average of 14.7% higher baseflow release frequency than system using 7-day forecast (Figure 2). Such an advantage is comparatively larger in small sized systems (e.g. 2 kL), diminishing in large systems, demonstrating a similar trend to the observations for water supply efficiency.

For systems using 7-day forecast, baseflow release frequency depended on system capacity. The Flood protection strategy was predicted to deliver more frequent baseflow release than the Longest discharge and the Streamflow protection strategies in large systems (i.e. capacity ≥ 7.5 kL), but was the opposite in small sized system. This demonstrates that discharging the pre-storm release early, which potentially lead to less water-in-storage available in the next 7-day, could affect the volume available for the baseflow release, especially in small systems.

3.2.3 Outflow Characterization

In addition to the baseflow release frequency, the outflows of all RTC systems were characterized by a flow duration curve, with a comparison to the reference streamflow (Figure 4). All RTC systems were predicted to successfully restore the low-flow aspects of the flow regimes (Figure 4C). They generally produce higher low flows across the different seasons (i.e. four stages), especially for Q75 – Q99 flows. In contrast, the stream gauge at the reference stream frequently experiences cease-to-flow conditions.

The RTC systems were also shown to reduce the magnitude and flashiness of high flows, especially for systems using 7-day forecast. RTC systems demonstrated lower high flows compared to conventional systems, especially for <Q1 flows (Figure 4B). System using 7-day information further lower the magnitude and rate of change compared to the Supply maximisation strategy, which are vital in restoring the natural flow regime (Poff et al., 1997). More importantly, in the 1-day forecast, the high flow regime of the Supply maximisation strategy almost duplicates the behaviour of the conventional system, while the 7-day forecast period allows the RTC systems to enhance mitigation of peak flows, thus reducing flooding risks. For system using 1-day forecast, despite the lower magnitude, it may overflow almost the same way as conventional systems during large events, which is consistent with the finding in peak reduction (Table 3).

Moreover, designing the pre-storm release to operate over a longer duration at a lower rate could better attenuate the flows, especially during Q5 - Q25 (Figure 4A). The outflow duration curve of Flood Protection and Supply Maximisation shows higher peak flow during Q0.5 - Q3, with a sudden 'drop-off' towards baseflow levels (Figure 4B). In contrast, the outflow regime of the Longest discharge and the Streamflow protection strategies generally produces more muted high flows, decreasing more gradually until the turning point occurred later at Q25. This gives a more constant overall flow regime. Most importantly, these designs more closely resemble the flow duration curve of the reference streamflow.

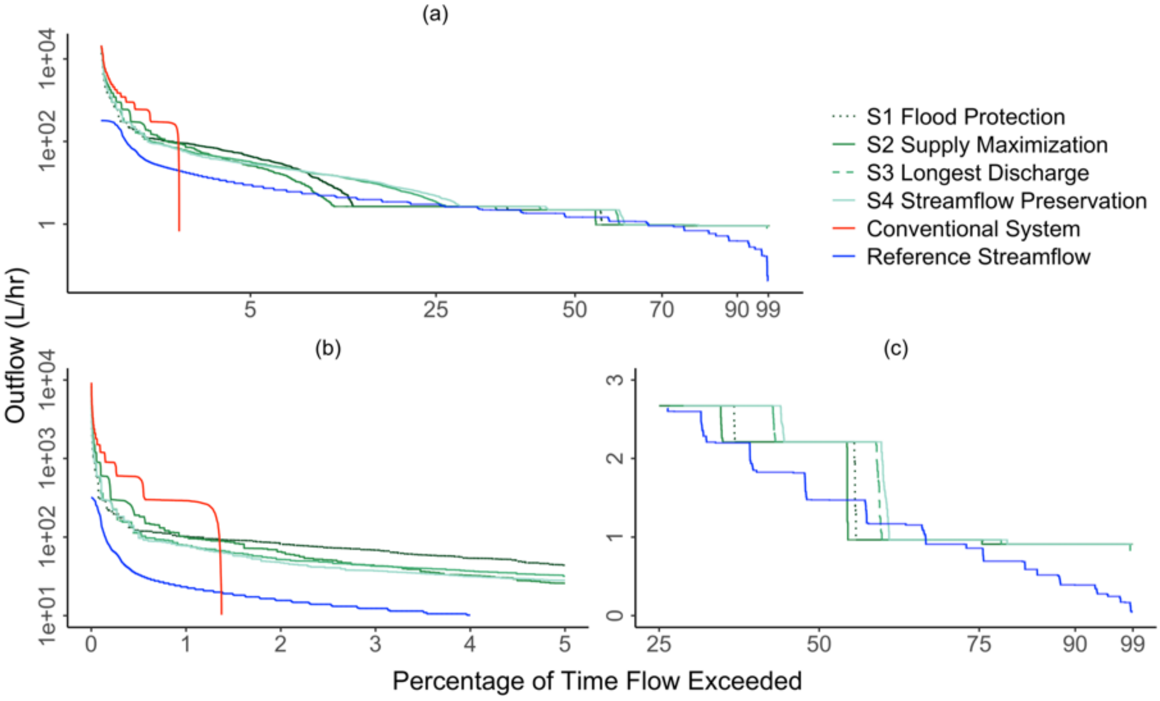


Figure 4. Outflow Duration Curve of a 7.5 kL system in conventional setting and four RTC strategies compared to the reference streamflow on a pro-rata base (i.e. considering catchment area of 150 m^2). System outflow is determined by the sum of overflow and release.

4. Discussion

4.1 The impact of forecast lead-time

Applying long lead-time forecast (e.g. 7-day) in RTC may result in small reductions in water supply, but dramatically enhances the performance in reducing flood risk. This is because a longer prediction window, which extends the ability to predict future overflow, results in higher tank volume dedicated to pre-storm release (Figure 5).

The impact of long lead-time forecast on water supply also leads to the same impact on baseflow release. The baseflow release operates a persistent discharge, which is equivalent to a low-but-steady 'demand' (albeit for the environment, rather than human water consumers) on water from the rainwater harvesting system. A previous study has shown that the level of baseflow release we simulated in this study has little detriment to water supply (Xu et al., 2018). Systems controlled with long lead-time forecast will release more water for flood mitigation, and thus hold less water to supply baseflow release, consistent with the effect observed for (human) water supply. The impact of the strategy on the storage available is confirmed when representing the storage duration curve for the four RTC strategies and the conventional tanks, for the 5.5-year simulation period (Figure 5).

As shown in Figure 2, the system capacity impacts the performance of the system. A RTC system using 1-day forecast may supply more end-use and baseflow release in small systems (where limitations on available water are amplified), but such a difference is diminished with increased tank capacity. However, while the difference in peak flow retention efficiency followed the same trend, systems using short forecast lead-time could not deliver the same level of service compared to those using longer lead-time (Figure 2), even in unusually large systems (e.g. 15 kL) (Figure 2). Such a finding highlights the importance of forecast information to the operation of RTC in mitigating flooding risks. Longer forecast period availability can be used to avoid the need for what would otherwise be larger storages to achieve the same level of flood mitigation performance. This can provide substantial benefits in highly dense urban environments, where flood protection is often prioritised (Nirupama & Simonovic, 2006), but where space for flood storage may be limited. In addition, the smaller performance increase in large sized systems (Figure 2) also implies a diminishing-marginal-returns relationship with system capacity when using different forecast information and strategies to achieve optimal outcome across the multiple objectives. Considering the capital and space-take involved in building large storage, there is likely a benefit of using RTC to avoid requiring large storages, although large storages may still be required where overall water supply security is important.

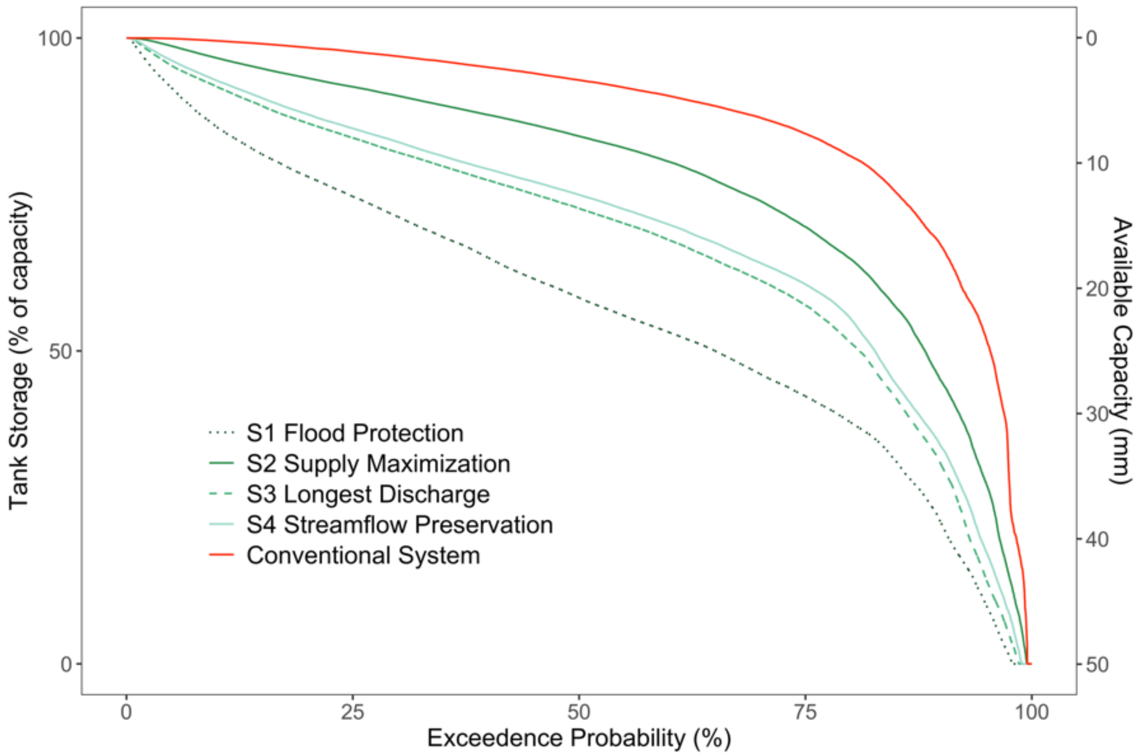


Figure 5. Tank storage duration curve of four RTC strategies compared with conventional systems. The available capacity (right Y axis expressed in mm of runoff from catchment) is the tank storage (kL) standardised linearly by roof size of 150 m^2, expressed in mm.

4.2 The impact of outflow control

Releasing the predicted overflow early over the forecast window can better reduce the flooding risks. Daily rainfall forecast generally does not provide the specific timing of the predicted storm events. This then makes the decision on the period of pre-storm release less certain, thus hindering the ability of RTC to create sufficient freeboard in time. Controlling the release early, such as occurs in S1 Flood Protection, can prepare empty space well before the actual storm events. But conversely, this leaves less water available for supply and baseflow release, albeit with benefits for retention performance of both the total runoff and flow peaks, which is vital for flood protection, especially in highly dense urban areas.

An RTC system without baseflow release is likely to achieve a similar level of flooding protection, through the pre-storm release. While increasing any type of consumption on tank water can help in making available headroom, thus enhancing the retention (flood mitigation) performance (DeBusk et al., 2013; Jones & Hunt, 2010), RTC can overcome a lack of demand, ensuring releases of the right quantity and timing to reduce the likelihood of overflows. Both the design of baseflow and pre-storm release are based on this rationale – to proactively create additional headroom when water supply is insufficient to provide it. In the system without baseflow release, the volume, which would otherwise have gone to supporting downstream baseflow, will instead to be assigned to pre-storm release. Thus, any change (i.e. reduction or even elimination) of baseflow release would not significantly modify the modelling results observed in this study.

By definition, the period over which pre-storm releases occur will affect the proportion of time that the target baseflow is being achieved. Operation of the RTC in such a way to quickly release the pre-storm release (primarily to minimise flood risk) will have the impact of minimising time when above-baseflow flow rates are delivered. However, releasing flow early also increases the chance that there will be inadequate water available to meet the baseflow ‘demand’, meaning that the pre-storm release operation’s effect on baseflow is a two-edged sword. Careful optimisation of these potentially conflicting objectives is necessary, to ensure that appropriate flow regimes and wetted habitats are available, particularly during dry periods (Leopold, 1968; Price, 2011).

However, reducing peak flow and maximising the period of base-flows may not necessarily achieve a full restoration of the flow regime. The ecological integrity of an aquatic ecosystem requires a flow regime as close as possible to its natural (pre-urbanisation) level (Poff et al., 1997). This includes, not only the magnitude and frequency of peak- and baseflow, but also the duration, timing and flashiness of flow events. Therefore, releasing the predicted overflow over a longer period at a lower rate, such as occurs in S3 Longest Discharge and S4 Streamflow Preservation (Figure 4), arguably better imitates the reference flow regime. Doing so also has the benefit of minimising the hydraulic disturbance and subsequent geomorphic degradation of the channels of receiving streams (Russell et al., 2020). In coupling with real-time flow monitoring (Kawanisi et al., 2018), RTC offers the potential to adapt the controlled release to real-time flow conditions, thus mimicking the natural streamflow, and delivering the flow regime determined appropriate for the ecological objectives of the receiving water.

A further consideration is the extent to which the pre-development or reference flow regime serves as a desirable ecological outcome. In this study, the reference stream showed significant periods of cease-to-flow conditions. In reality, many such natural streams will still experience flow during such periods, but it may be entirely hyporheic and not measured by standard flow gauges (Tonina, 2012). Regardless, there are broader ecological management questions about whether cease-to-flow conditions should be preserved (thus potentially contributing to regional biodiversity; (Poff et al., 2010)), or whether baseflow should be provided to increase local habitat and thus local biodiversity (Chiu et al., 2017). The RTC strategies we tested sought to maximise the period over which baseflow was sustained, but this could be easily adapted to mimic reference cease-to-flow conditions, if desired.

4.3 Forecast Error

The performance of RTC can be lost from forecast error. Precipitation forecast are subject to three types of error: localisation, timing and intensity of events (Habets et al., 2004). Location errors may lead to a prediction of rain that doesn’t occur in reality (thus leading to unnecessary release and reduction in water supply reliability) or vice versa (leading to uncontrolled overflows). Timing errors for system using short lead-time forecast may result in the pre-storm release being too late to reduce overflow, but this will have much lower impact for long forecast lead-time strategies, such as S1 Flood Protection. More importantly, error in rainfall intensity is the main source of forecast uncertainty, especially on the daily time scale (Shahrban et al., 2016). Over-prediction causes unnecessary release leading detriment to reductions in yield. In contrast, underpredicting rainfall events, which is common in our simulation (see details of forecast error in the supporting information), can lead to the underestimation of pre-storm release volume, and so may reduce flood mitigation performance, especially in large events (e.g. 29th December 2016 event in Table 3). RTC using long-lead time forecast can potentially minimise the effect of such errors, given that the longer prediction window, as demonstrated above, allows RTC to prepare empty space for future events earlier (e.g. S1 Flood Protection). Future work could investigate the benefits and costs of RTC systems that use rainfall forecasts with lower probability (e.g. 10% chance) to maximize the flood protection in large rainfall events. Another important future research area involves the exploration of how the RTC could adopt forecast with errors accounted for and thus minimize their impact on control outcomes.

It is of course likely that forecast accuracy will be improved in the future, thus informing a better control. Forecast accuracy can be improved by postprocessing the received Numeric Weather Prediction (NWP) (Shrestha et al., 2013), such as using Seasonality Coherent Calibration (Wang et al., 2019). Recent advances in downscaling NWP also offer RTC systems with finer spatial and temporal resolution ‘nowcast’ of upcoming storm events, such as Short Term Ensemble Prediction System (Bowler et al., 2006), which could better inform the pre-storm release in mitigating the flooding risks, especially in large events.

Our results showed that current forecast accuracy can affect the performance of RTC, but even so, the performance remains better than conventional systems. With growing advances in meteorology forecasting and better understanding on how to utilize the forecast information, the impact of forecast error on system performance could be minimized and even eliminated. Importantly, the impacts of forecast error on flood mitigation performance can be limited by use of long forecast lead-times, albeit with some cost in terms of water supply performance.

4.4 Implementation

Implementing RTC in rainwater harvesting systems is feasible. Such an application can be widely found in other urban water systems, such as water distribution networks (Leirens et al., 2010; Martínez et al., 2007) and combined sewers (Campisano et al., 2016; Mollerup et al., 2017). Current sensor technology enables the monitoring of present system states (e.g. pump flow, water level and valve status) and environmental condition (e.g. rainfall and streamflow) in real-time, which provides essential knowledge for RTC decision making (Schütze et al., 2004). Recent advances in low-cost sensors also provide an affordable and highly customized solution to tackle the technological and economical challenge during large scale implementation (Cherqui et al., 2019; Montserrat et al., 2013). The collected data and control decisions can be stored and transmitted through wireless communication and online platforms (Lefkowitz et al., 2016; Pellerin et al., 2016; Yang, 2006). Future broader adoption of RTC in stormwater management will, however, need to address the regulatory environment and governance. The operational jurisdiction and obscure ownership which characterise these systems, when applied at household scale, might slow down the development of the investment model for their ongoing effort for maintenance and deployment, which is likely to create inertia, impeding or delaying adoption (Brown & Farrelly, 2009; Brown, 2005).

4.5 Future Study

Future research is required to investigate the spatio-temporal behaviour of networks of RTC-based systems. This includes the hydraulic modelling of the propagation released tank water through a catchment and its associated impact to the downstream receiving water. Algorithms, such as flood routing, could be incorporated to further understand the benefits of RTC on flood mitigation and flow regime restoration. More stochastic simulation of end-use behaviour is also essential to reveal the yield performance of RTC, and the human-behaviour and other factors that may affect it. Temporal variation in demand (e.g. short duration use) can impact the simulation of rainwater harvesting systems (Campisano & Modica, 2016). However, in this study such variations are unlikely to modify the main conclusion, given the daily demand is small relative to the typical pre-storm release flows. Future consideration could also include various house configurations, such as different roof and tank sizes. All of these research questions will lead to a better overall understanding of the combined impacts of RTC systems.

Another very promising area of research is indeed the question of how multiple RTC systems can work collectively toward identified catchment-scale benefits. Application of RTC at different geographical locations could, for example, strategically adopt different release strategies to collectively meet the catchment-scale hydrological objective, both for the overall catchment and for various locations (sub-catchments) within the catchment. The investigation of such a distributed control strategy and assessment of its impact at catchment scales is a logical next step.

5. Conclusion

In this study, we aimed to design possible Real-Time Control (RTC) strategies to operate Rainwater Harvesting Systems and assess their effects using different forecast lead-times. We modelled four strategies with different preferences in maximizing the benefits for water supply, flood protection or streamflow preservation. These strategies are based on different forecast lead-times (i.e. 1-day and 7-day rainfall forecasts) and are compared to a conventional system during a 5.5-year simulation period. We concluded that RTC systems yield comparatively less water supply yield than conventional systems only in small systems, but had much greater performance in reducing flood risks and restoring baseflow, for all test strategies. More importantly, using 7-day lead-time rainfall forecast, which offers longer prediction window, enhances the ability of RTC in mitigating flood risks, releasing water over a longer period and at a lower rate, thus delivering an outflow regime that is close to the reference streamflow. Such a finding indicates the promising potential of RTC to holistically restore natural flow regimes. This work provides valuable insights on both the advantages and trade-off of RTC applied to rainwater harvesting, and highlights the benefits and costs of using long lead-time forecast in control strategies. There are substantial opportunities for future adoption of RTC Rainwater Harvesting System in a range of contexts to achieve “smart” management of urban stormwater.

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Figure 1.

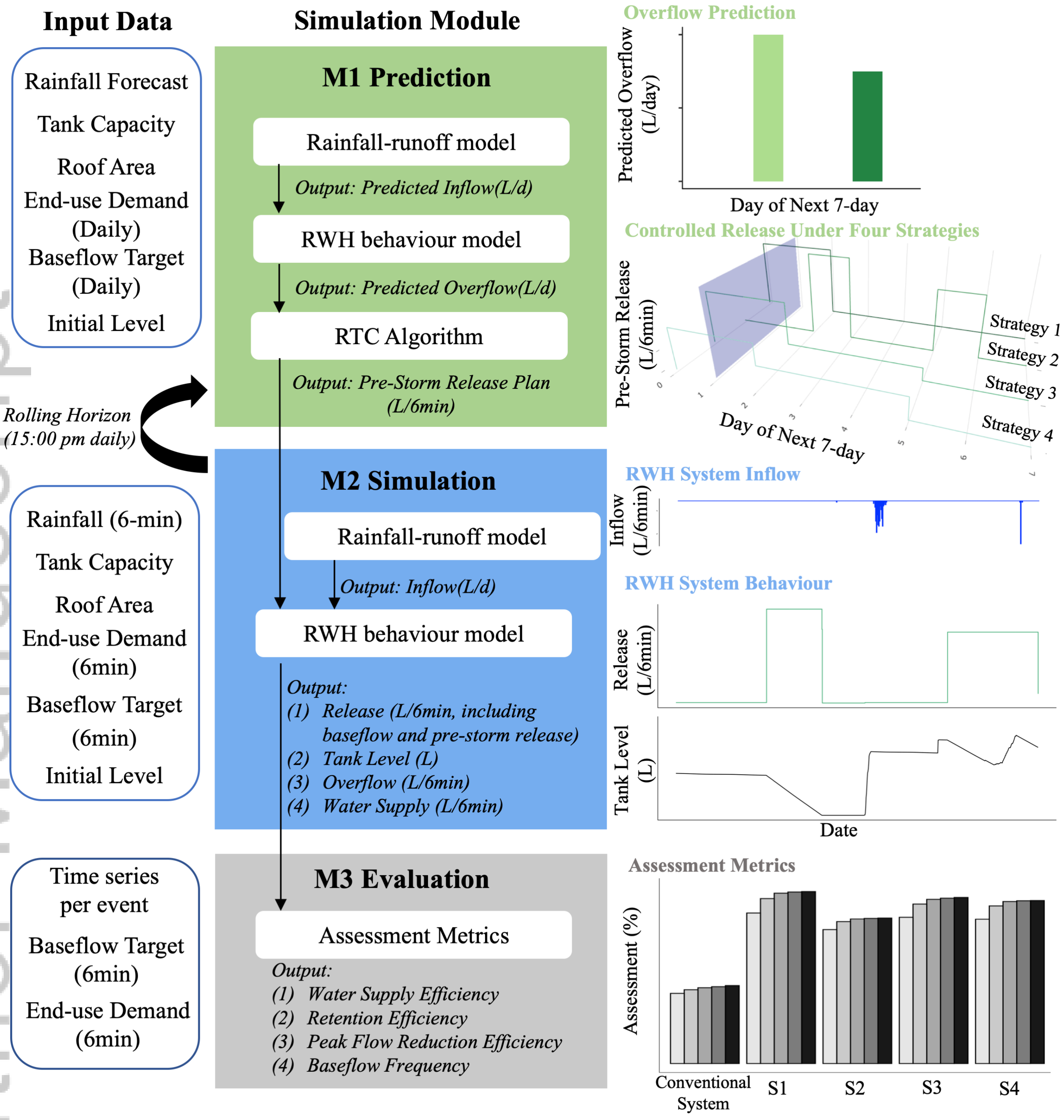

Input Data
Simulation Module
Rainfall Forecast
Tank Capacity
Roof Area
End-use Demand (Daily)
Baseflow Target (Daily)
Initial Level
M1 Prediction
Rainfall-runoff model
Output: Predicted Inflow(L/d)
RWH behaviour model
Output: Predicted Overflow(L/d)
RTC Algorithm
Output: Pre-Storm Release Plan (L/6min)
Rolling Horizon (15:00 pm daily)
Overflow Prediction
Predicted Overflow (L/day)
Day of Next 7-day
Controlled Release Under Four Strategies
Pre-Storm Release (L/6min)
0
1
2
3
4
5
6
7
Day of Next 7-day
Strategy 1
Strategy 2
Strategy 3
Strategy 4
Rainfall (6-min)
Tank Capacity
Roof Area
End-use Demand (6min)
Baseflow Target (6min)
Initial Level
M2 Simulation
Rainfall-runoff model
Output: Inflow(L/d)
RWH behaviour model
Output:
(1) Release (L/6min, including baseflow and pre-storm release)
(2) Tank Level (L)
(3) Overflow (L/6min)
(4) Water Supply (L/6min)
RWH System Inflow
Inflow (L/6min)
RWH System Behaviour
Release (L/6min)
Tank Level (L)
Date
Time series per event
Baseflow Target (6min)
End-use Demand (6min)
M3 Evaluation
Assessment Metrics
Output:
(1) Water Supply Efficiency
(2) Retention Efficiency
(3) Peak Flow Reduction Efficiency
(4) Baseflow Frequency
Assessment Metrics
Assessment (%)
Conventional System
S1
S2
S3
S4

Figure 2.

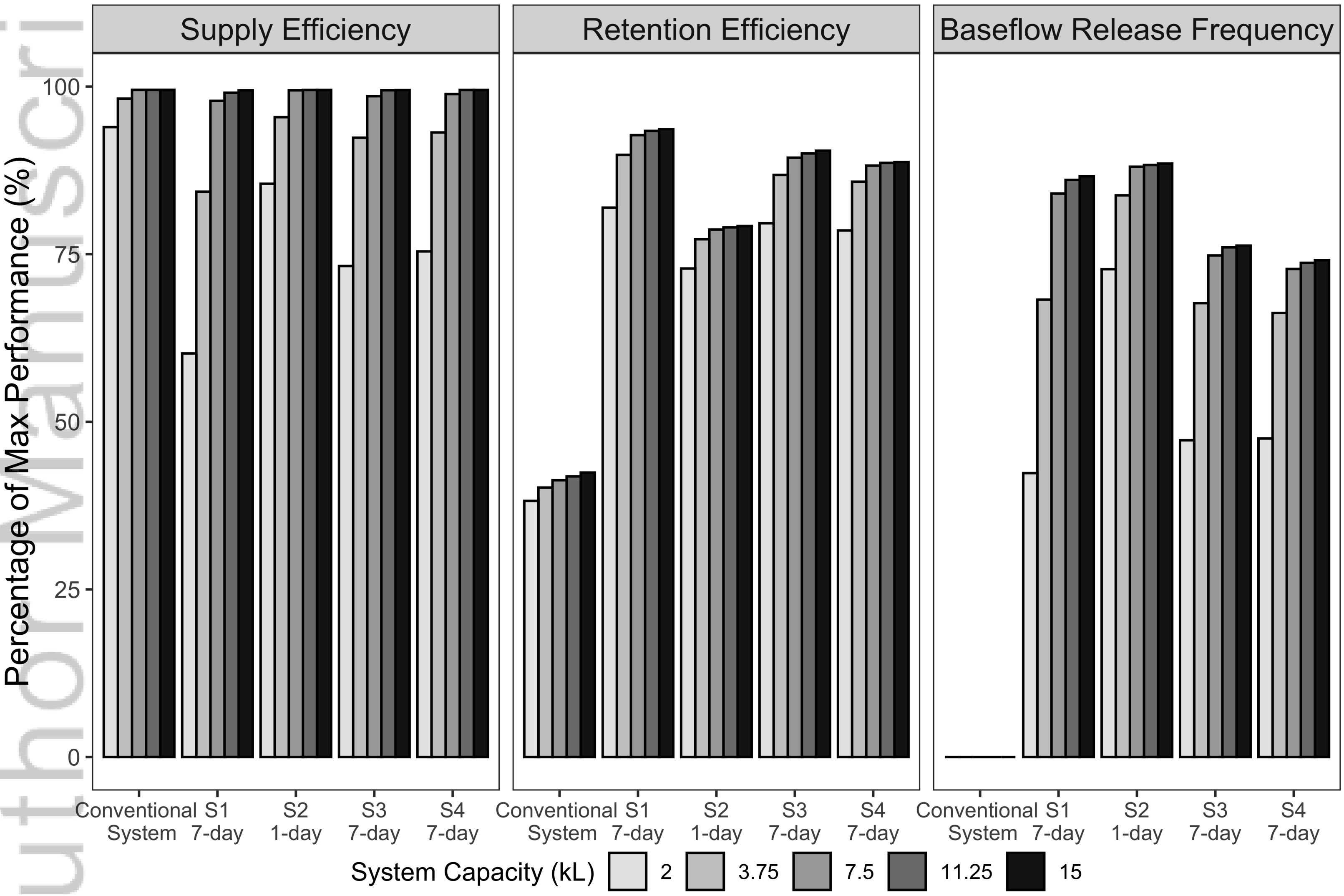

Supply Efficiency
Retention Efficiency
Baseflow Release Frequency
Percentage of Max Performance (%)
100
75
50
25
0
Conventional System
S1 7-day
S2 1-day
S3 7-day
S4 7-day
System Capacity (kL)
2
3.75
7.5
11.25
15

Figure 3.

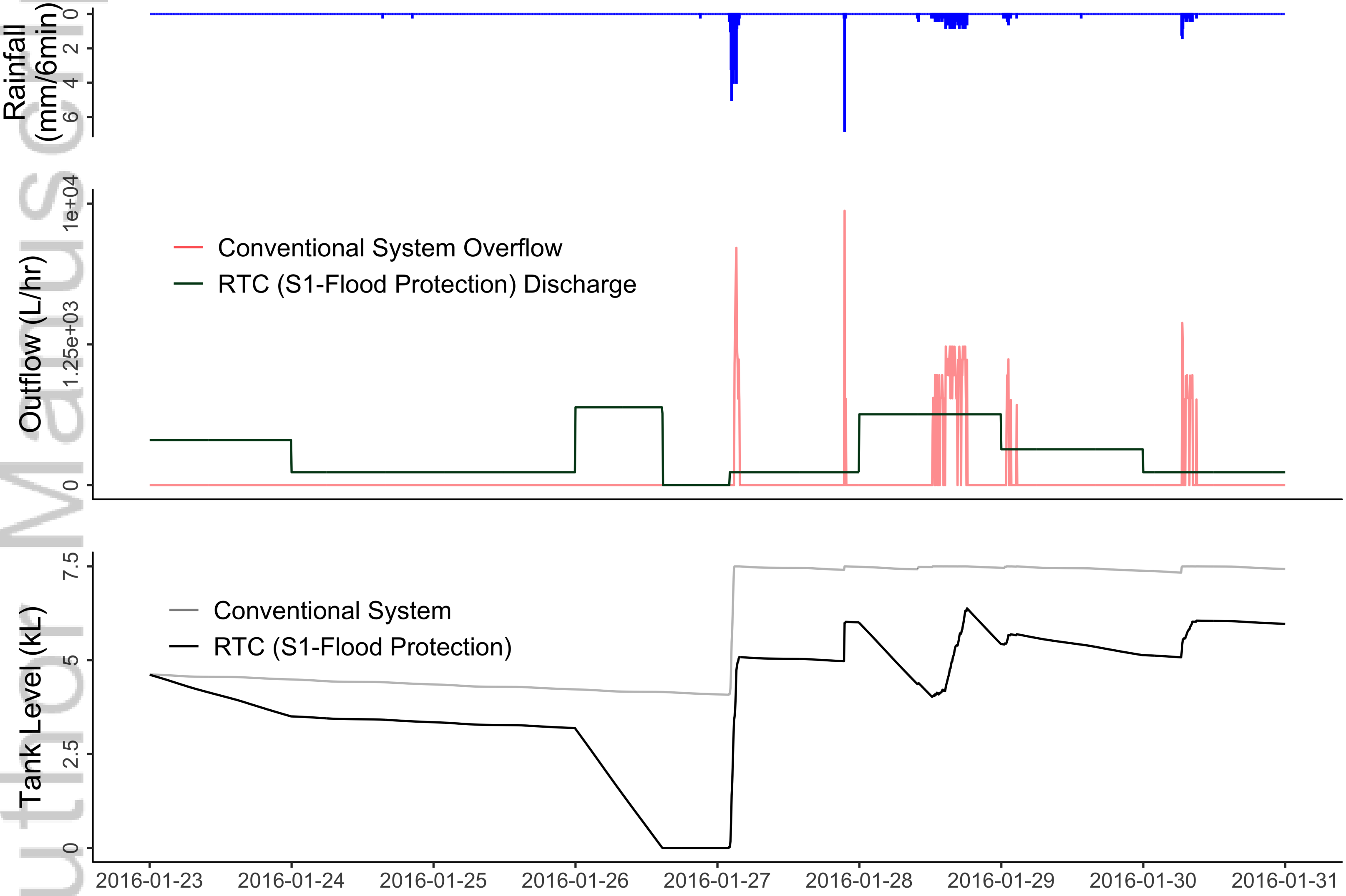

Rainfall (mm/6min)
0
2
4
6
Outflow (L/hr)
1e+04
1.25e+03
0
Conventional System Overflow
RTC (S1-Flood Protection) Discharge
Tank Level (kL)
7.5
5
2.5
0
Conventional System
RTC (S1-Flood Protection)
2016-01-23
2016-01-24
2016-01-25
2016-01-26
2016-01-27
2016-01-28
2016-01-29
2016-01-30
2016-01-31

Figure 4.

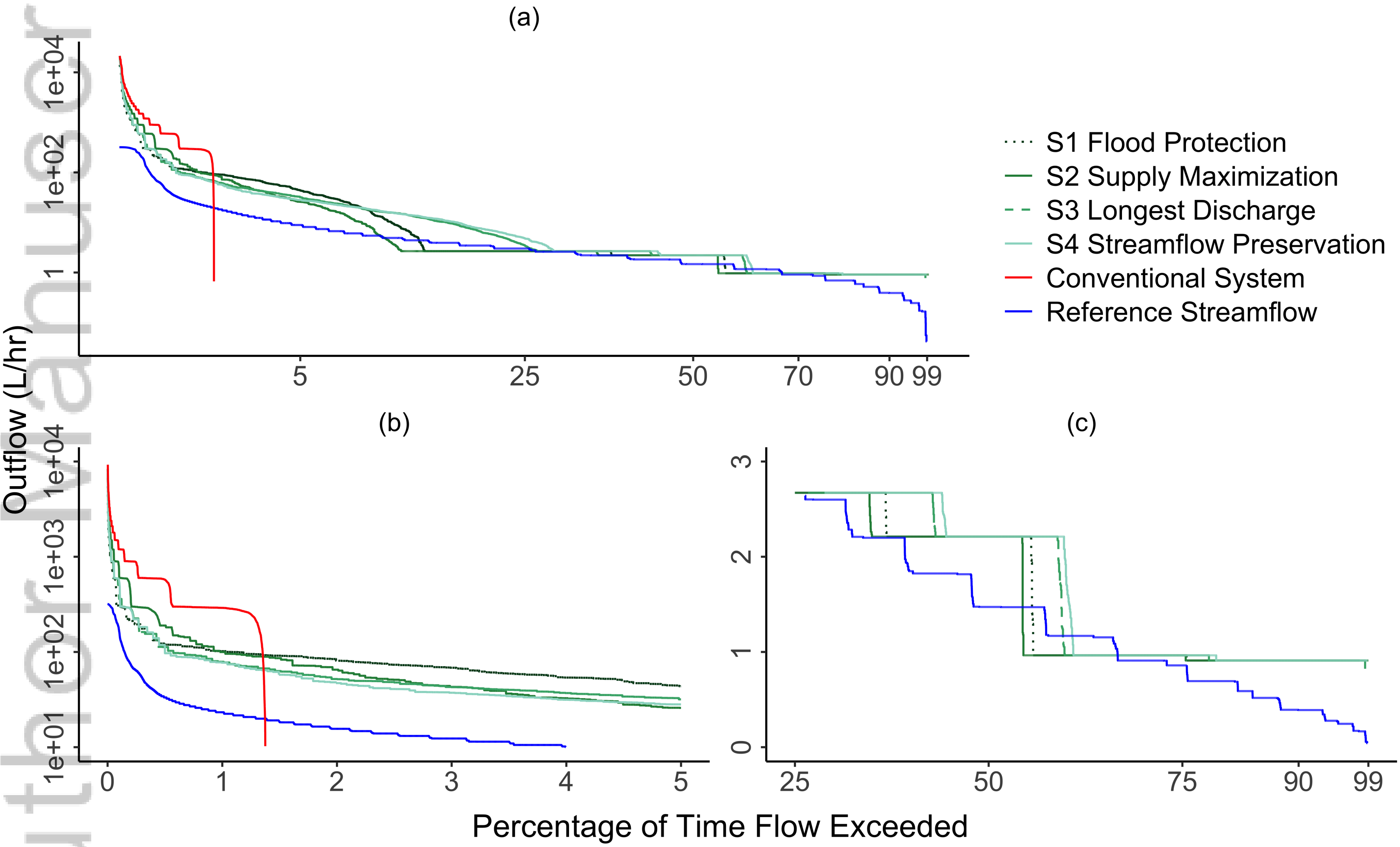
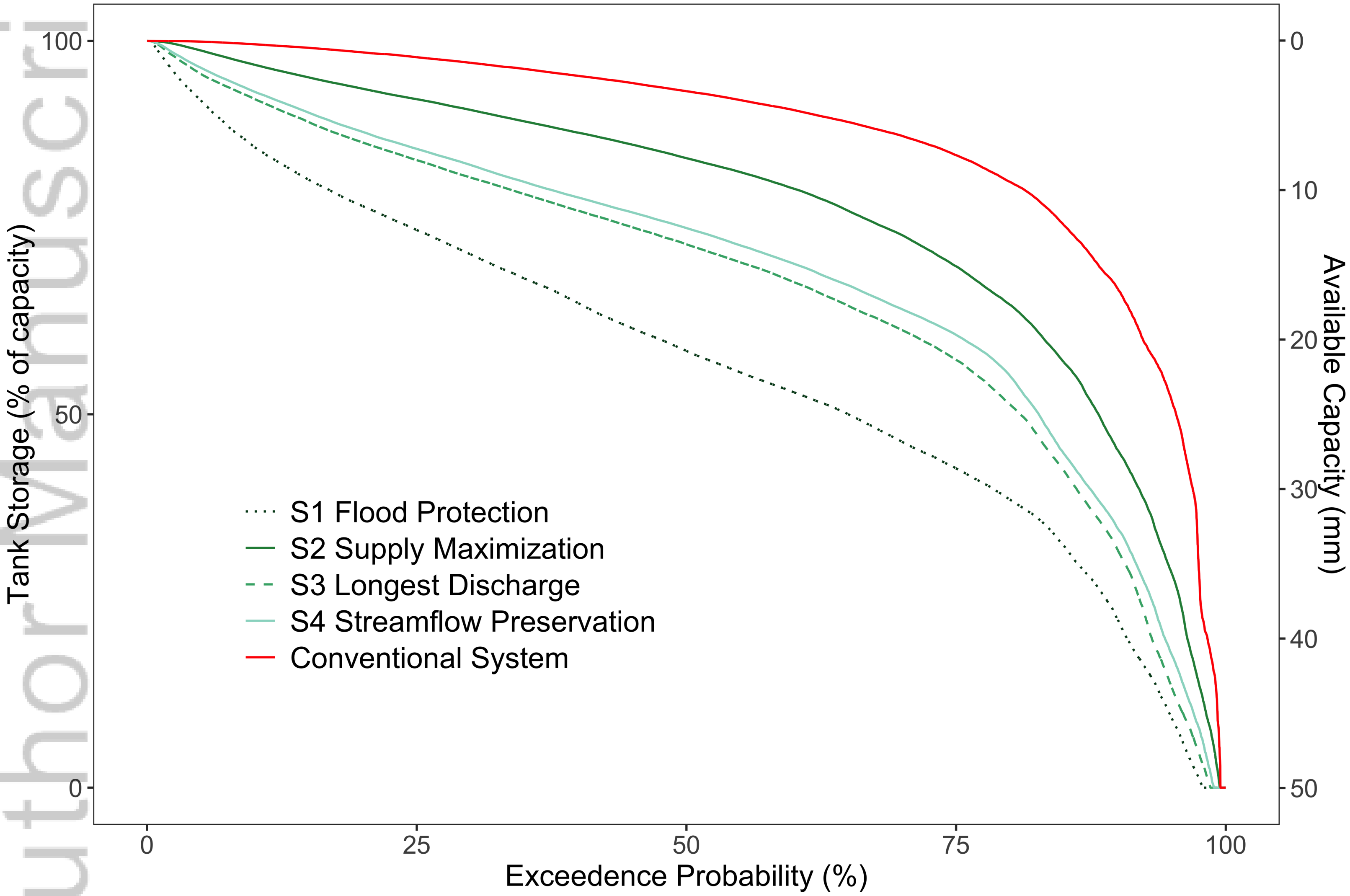

(a)
1e+04
1e+02
1
5
25
50
70
90 99
S1 Flood Protection
S2 Supply Maximization
S3 Longest Discharge
S4 Streamflow Preservation
Conventional System
Reference Streamflow
Outflow (L/hr)
(b)
1e+04
1e+03
1e+02
1e+01
0
1
2
3
4
5
(c)
3
2
1
0
25
50
75
90
99
Percentage of Time Flow Exceeded

Figure 5.



Tank Storage (% of capacity)
100
50
0
Available Capacity (mm)
0
10
20
30
40
50
Exceedence Probability (%)
0
25
50
75
100
S1 Flood Protection
S2 Supply Maximization
S3 Longest Discharge
S4 Streamflow Preservation
Conventional System