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

3
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10
11 **Key Points:**

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

18 **Abstract**

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

35 **Plain Language Summary**

36 ‘Smart tanks’ based on Real-Time Control (RTC) is increasingly used in rainwater harvesting
37 systems to address water shortages, urban flooding and streams depleted of flow. Smart
38 tanks, controlled by RTC, can use a range of digital information (e.g. rainfall forecast) to
39 make optimal decisions to release some tank water before heavy rain, to reduce flood risks,
40 while still supply water to households. Globally, most uses of this technology use 1-day
41 forecasts of rainfall. To understand the effect of longer prediction window, we compared four
42 strategies using either 1-day or 7-day rainfall forecast and modelled their performance using
43 specialized computer code. We found that smart tanks using 7-day rainfall forecasts are
44 superior in reducing urban flood risks and restoring baseflows to streams. More importantly,
45 they can release the tank water in a pattern that is similar to natural streamflow, thus helping
46 to restore and sustain healthy waterway habitats. Our study is the first reported application of
47 7-day forecast information in smart control rainwater tanks. It opens up a new opportunity in
48 managing urban water in a range of contexts and for a range of stream health objectives.

49 **1. Introduction**

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

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

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

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

107 Globally, Numeric Weather Prediction (NWP) can anticipate rainfall events more
108 than 24-hours ahead of their arrival, with forecasts of up to 7-days readily available (Clark &
109 Hay, 2004; Damrath et al., 2000; Davies et al., 2005). While the accuracy of forecast remains
110 a fruitful area of research, such an advance drives new improvement in water industry, such
111 as hydrological forecasting (Georgakakos & Hudlow, 1984; Rossa et al., 2011). Operation
112 based on 7-day rainfall forecast has been used in agriculture (Cai et al., 2011; Wang & Cai,
113 2009) and water supply (Tsai et al., 2008; Westphal et al., 2003). In theory, this would also

114 allow RTC systems to perform pre-storm release long before the actual event, at a lower rate
115 that is much closer to the natural hydrology. However, the use of 7-day forecast and the
116 associated effect on pre-storm release remain largely untested.

117 In this study, we aim to design a RTC strategy to operate RWH and assess its effects
118 using different forecast lead-times. We have developed and modelled four RTC strategies
119 with different preferences in terms of maximizing the benefits for water supply, flood
120 protection or streamflow preservation. These strategies are also based on contrasted forecast
121 lead-times and are compared to a conventional (without any passive release) system during a
122 5.5-year simulation period. In a more detailed analysis, the impact of different RTC strategies
123 on system outflow regimes is characterized and compared to the natural streamflow.

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

134 2. Methodology

135 2.1 Proposed RTC Strategies

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

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

158 While the above all aim to reduce uncontrolled overflow, all RTC strategies were also
159 designed to simultaneously restore some stream baseflow. This is achieved by a persistent

160 (i.e. every time-step) controlled discharge (termed here as ‘baseflow release’) which attempts
161 to counteract the lost baseflows common in urban streams (Price, 2011; Smakhtin, 2001).
162 Such an operation is ceased when pre-storm release is required, or if the storage is empty (i.e.
163 blue area in Example Table 1). The baseflow release target was determined by the median
164 flow (i.e. daily Q50) from a reference natural stream (forested catchment); the median flow
165 provides a reasonable estimate of a stream’s baseflow (Smakhtin et al., 1997).

Table 1
Four Proposed Real-Time Control Strategies.

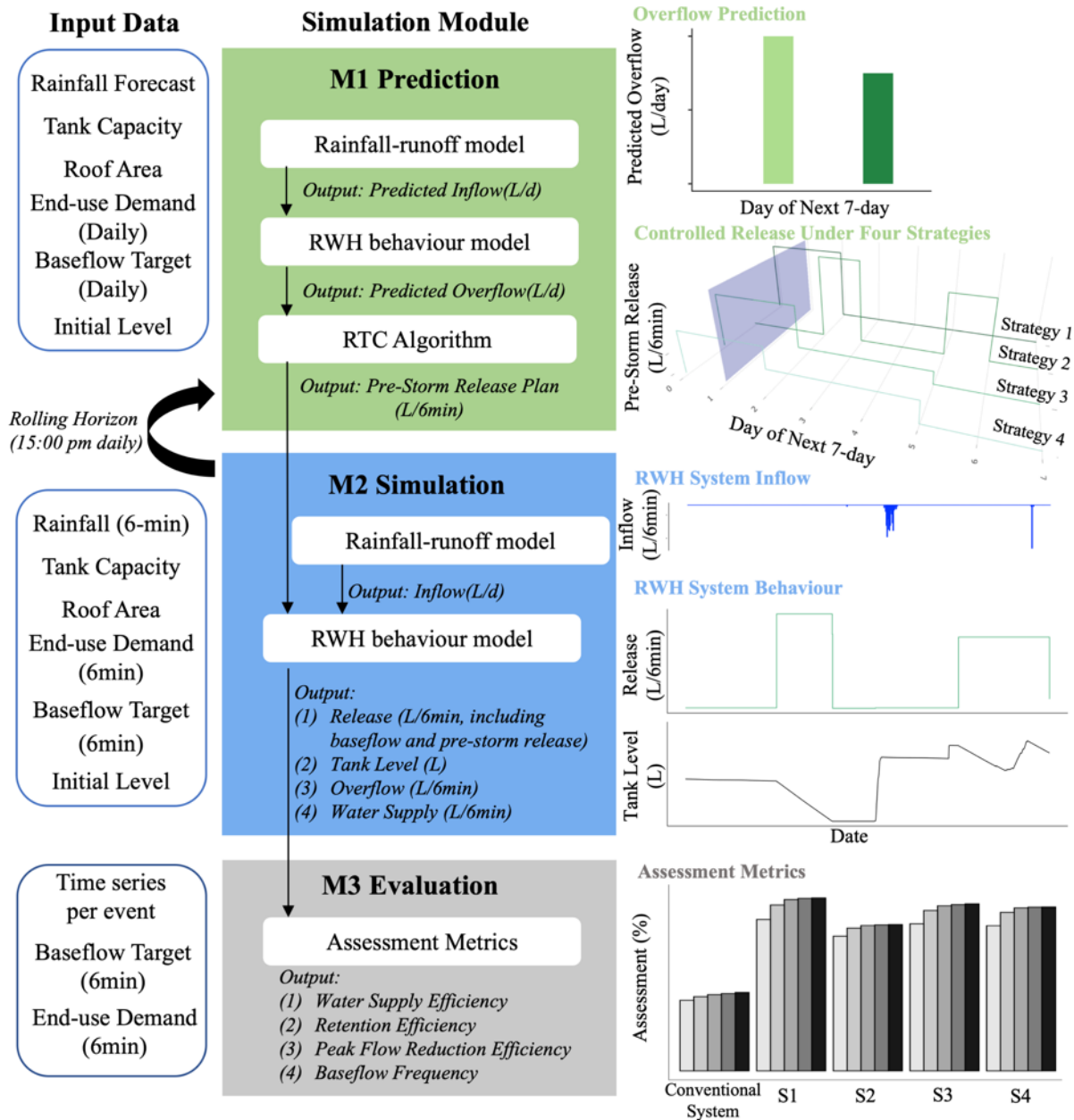
Strategy	Flood Protection (S1)	Supply Maximisation (S2)	Longest Discharge (S3)	Streamflow Preservation (S4)
Principle	Prioritise minimising overflow risk over everything else	Prioritise water supply over all else, by preserving water in storage	Maximise discharge period to emulate natural flow behaviour	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 (<i>may be multiple days</i>)	(1) Until last predicted overflow (2) OR each predicted overflow (<i>both may be multiple days</i>)
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 <i>Longest Discharge</i> strategy to minimize the peak release rate.
Example				

168

2.2 Modelling Framework

169

170 A modelling framework, written using R (version 3.6.1), was developed to simulate
 171 the performance of the proposed RTC system under the four proposed strategies. This
 172 framework includes three different modules: prediction (M1), simulation (M2), and
 173 assessment metrics (M3) (Figure 1). The prediction module (M1) is run at a daily timestep (at
 174 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.



175

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

178 2.2.1 M1 Prediction

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

$$182 \quad Q_{in} = (R_t - R_{loss}) \times A \quad (1)$$

183 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.
184 depression storage on the roof surface that delay the runoff) which is set as 0.2mm/day. A is the roof size which
185 is selected as 150m² to reflect a residential house.

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

$$192 \quad Q_{ot} = \max \left\{ \begin{array}{l} V_{t-1} + Q_{in} - S \\ 0 \end{array} \right. \quad (2)$$

$$193 \quad Q_{bt} = \min \left\{ \begin{array}{l} Q_{target} \\ V_{t-1} \end{array} \right. \quad (3)$$

$$194 \quad Y_t = \min \left\{ \begin{array}{l} D_t \\ V_{t-1} - Q_{bt} \end{array} \right. \quad (4)$$

$$195 \quad V_t = \min \left\{ \begin{array}{l} V_{t-1} + Q_{in} - Y_t - Q_{bt} \\ S - Y_t - Q_{bt} \end{array} \right. \quad (5)$$

196 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,
197 Y_t is the rainwater yield at t (L/timestep), Q_{bt} is the controlled release (i.e. baseflow release in prediction module)
198 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
199 (L/timestep), Q_{target} is the baseflow target at t (L/timestep), Q_{in} is the tank inflow (L/timestep)

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

202 2.2.2 M2 Simulation

203 This module simulates the performance of the defined controls. The modelling
204 process is similar to the prediction module in simulating system inflow and system
205 behaviour. However, this module uses the actual observed rainfall, applying an initial loss of
206 0.2 mm (Laing et al., 1988), with an antecedent drying period of 2 hours (i.e. initial loss is
207 only applied when there is a minimum of 2-hour dry period). As noted above, the tank
208 behavioural model is run on a 6-min timestep, which is sufficient to capture system dynamics
209 (Di Matteo et al., 2019; Mitchell et al., 2008).

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

216 2.3 Assessment Metrics

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

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

231 **Table 2.**
 232 *Assessment Metrics for Triple Objectives of Rainwater Harvesting*

Assessment Metrics	Equation	Description
Water Supply Efficiency (%)	$E_{WS} = \frac{\sum Y_t}{\sum D_t} \times 100\%$	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 (%)	$\rho = \frac{Q_{out,maxconvention\ system} - Q_{out,maxRTC\ system}}{Q_{out,maxconvention\ system}}$	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.

234 2.4 Input data and Scenarios

235 Numeric Weather Prediction was obtained from the local meteorological authority
236 (Bureau of Meteorology, 2020) to predict uncontrolled overflow, which is based on the
237 Australian Community Climate Earth-System Simulator (ACCESS) (Bureau of Meteorology,
238 2010). In total, 66 months (i.e. 2014-03-01 – 2019-08-31) of 7-day lead precipitation forecast
239 were extracted for Eastern Melbourne (i.e. Lat:-37.92, Long:145.32). We utilized mean daily
240 predicted rainfall (in mm) which is updated daily at 15:00 pm and has a relative error of -
241 9.5% compared to rainfall observation (i.e. forecast rainfall generally underestimates the
242 actual rainfall).

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

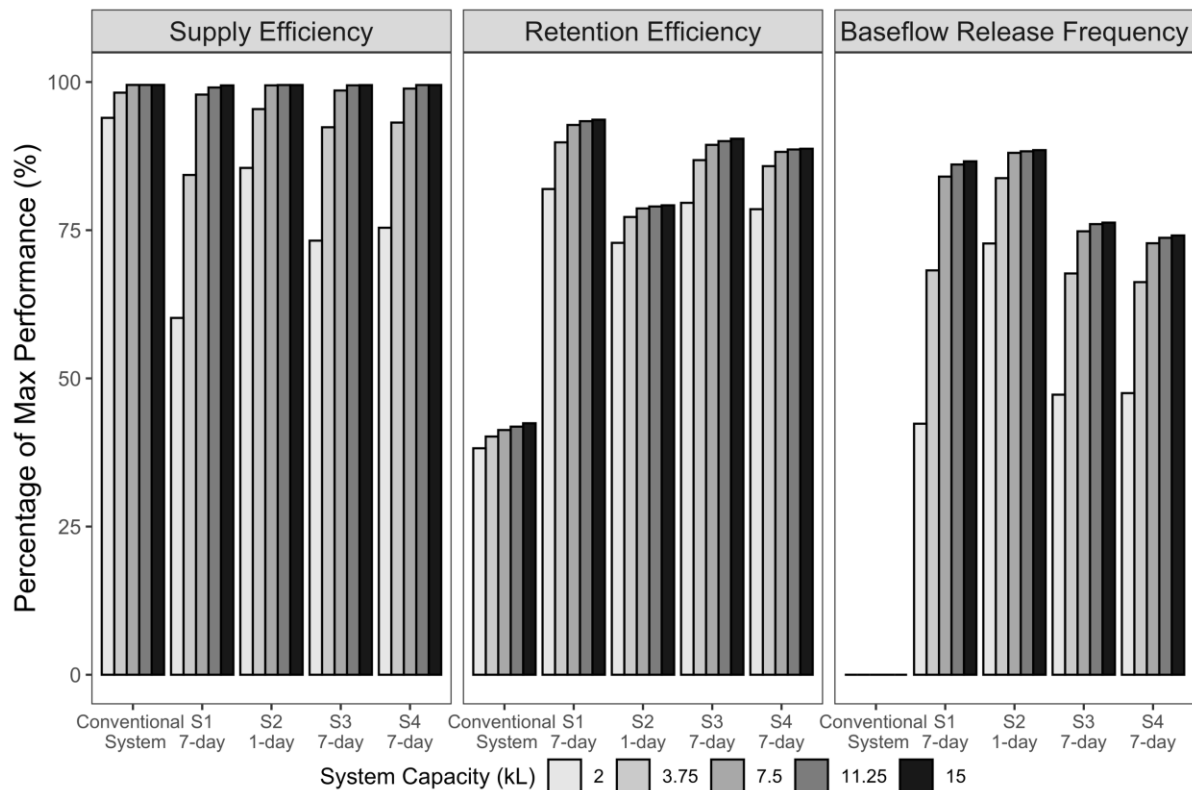
248 We also simulated five scenarios to represent a range of household settings in terms
249 of tank size and roof size. We considered a roof of 150 m², drained by five different sized
250 storage tanks (2, 3.75, 7.5, 11.25, 15 kL), and are connected to a range of domestic water
251 demands, including toilet flushing, dishwasher and cloth washing. The demand profile was
252 adopted from Xu et al. (2018). It is consistent with a typical indoor diurnal pattern that has
253 the peak consumption of 10.3 L/hr at 7pm and the lowest usage of 2.4 L/hr at 2am, with a
254 total daily consumption of approximately 132 L/d.

255 3. Results

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

263 3.1 Supply

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



274
 275 **Figure 2.** Performance evaluation of conventional system and four RTC systems with different system
 276 capacities. Three metrics are used from Table 2 to quantify the performance during the entire simulation period,
 277 which are supply efficiency, retention efficiency, and baseflow frequency. The strategies are *Flood protection*
 278 (S1), *Supply maximisation* (S2), *Longest discharge* (S3) and *Streamflow preservation* (S4).

279 **3.2 Flow Regime**

280 **3.2.1 Flood risk mitigation**

281 All RTC systems were predicted to reduce uncontrolled system overflows compared
 282 to the conventional system. The Supply Maximisation strategy, using 1-day forecast, nearly
 283 doubles the retention efficiency compared to conventional passive systems, with an increase
 284 ranging between 72% - 79% (Figure 2). Such an improvement is further elevated by use of
 285 the 7-day forecast information (i.e. Flood protection, Longest discharge and Streamflow
 286 preservation strategies), indicating an average further improvement of 10%, meaning an
 287 overflow reduction of 65.7 kL (i.e. out of 657.5 kL of the total inflow) during the 5.5 years
 288 simulation period. More importantly, the results show that increasing the lead-time from
 289 1 day to 7 days provide a much better flood protection than simply increasing the tank
 290 capacity.

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

299
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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)
29 th March 2016	65.09	96.4	2.3	>100	-73	33.8	0	0	0
27 th January 2016	34.2	36.4	1.8	20	-49.3	100	0	100	99.8
21 st March 2017	22.8	22.8	1	5	-42.4	100	30	100	95
25 th January 2018	13.2	26.4	0.5	2	-59.7	100	54.2	100	100

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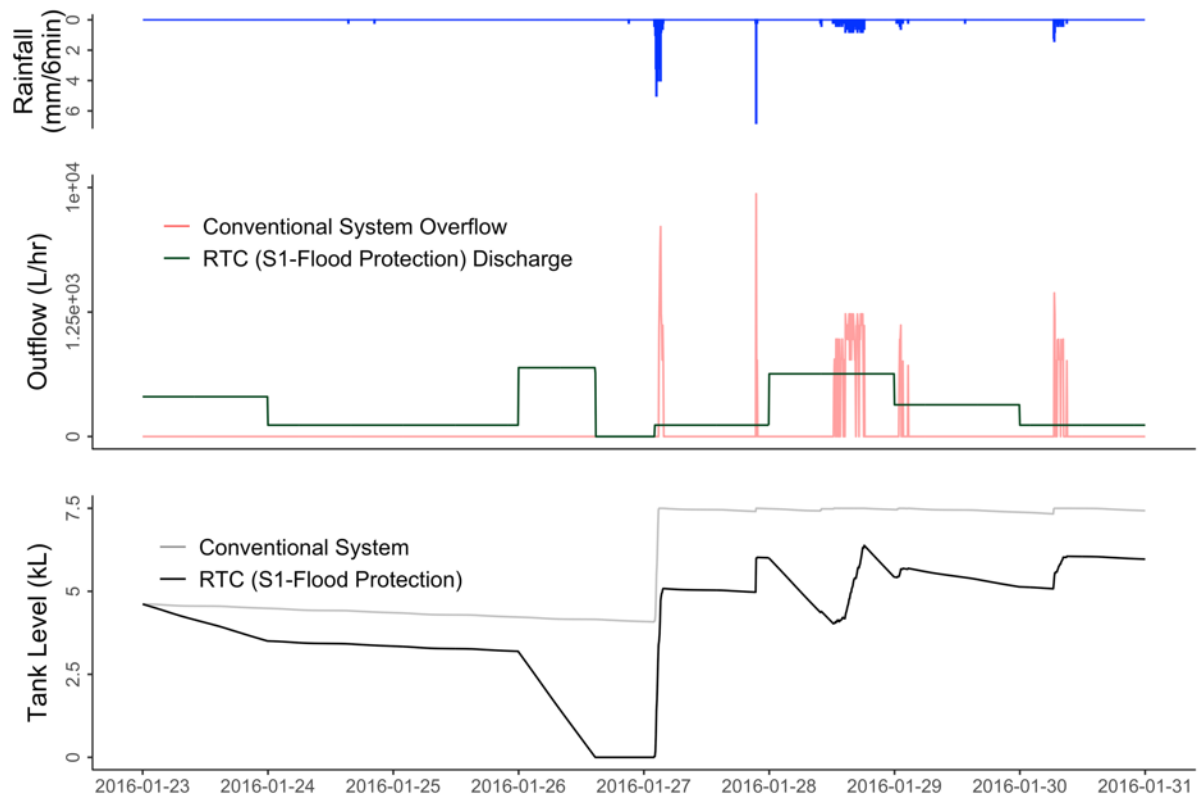
Note: ^aARI is approximated by the Intensity-Frequency-Duration design rainfalls from the local meteorological authorities (Bureau of Meteorology, 2016), using depth and duration in each event. ^bForecast error is the mean relative error of daily rainfall observation and prediction, which is comparable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

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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).

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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.



329
 330 **Figure 3.** Illustration of a 7.5 kL system performance for the *Flood protection* strategy and conventional
 331 systems during 23rd – 31st Jan 2016, including hyetograph (top), outflow hydrograph (middle) and water level
 332 (bottom). The conventional systems performance was modelled separately using the same initial condition as
 333 the *Flood protection* strategy on 23rd Jan.

334 **3.2.2 Baseflow Restoration**

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

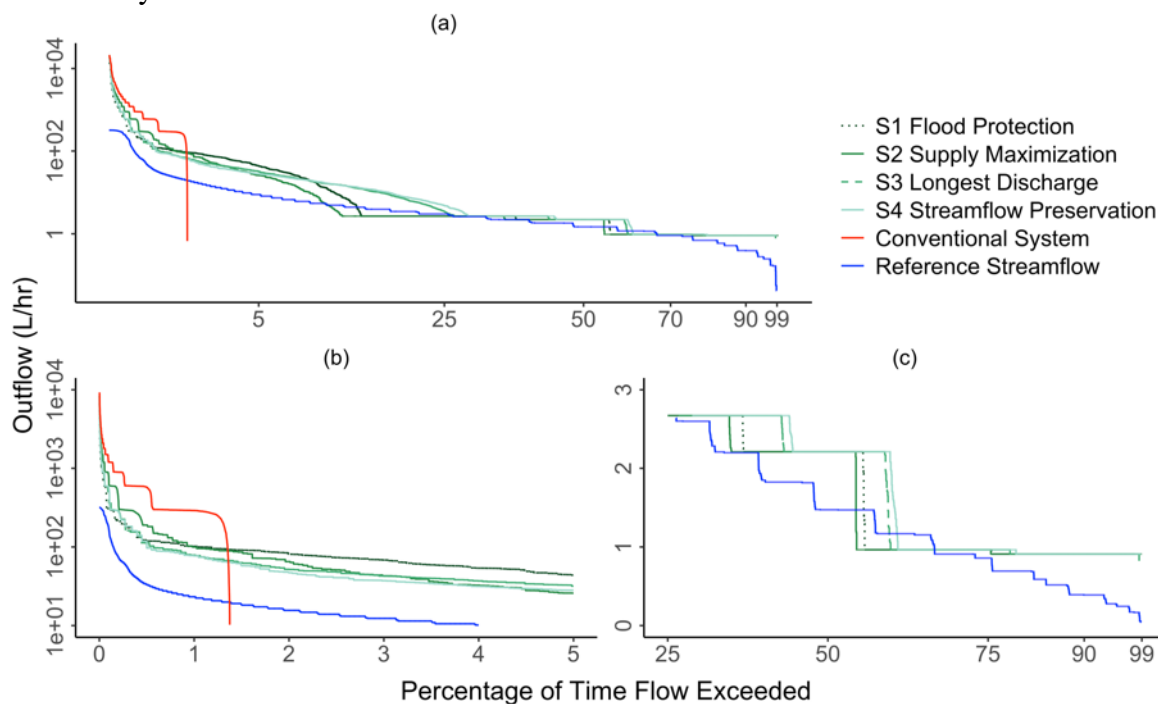
341 For systems using 7-day forecast, baseflow release frequency depended on system
 342 capacity. The Flood protection strategy was predicted to deliver more frequent baseflow
 343 release than the Longest discharge and the Streamflow protection strategies in large systems
 344 (i.e. capacity ≥ 7.5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

348 3.2.3 Outflow Characterization

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

355 The RTC systems were also shown to reduce the magnitude and flashiness of high
 356 flows, especially for systems using 7-day forecast. RTC systems demonstrated lower high
 357 flows compared to conventional systems, especially for <Q1 flows (Figure 4B). System using
 358 7-day information further lower the magnitude and rate of change compared to the Supply
 359 maximisation strategy, which are vital in restoring the natural flow regime (Poff et al., 1997).
 360 More importantly, in the 1-day forecast, the high flow regime of the Supply maximisation
 361 strategy almost duplicates the behaviour of the conventional system, while the 7-day forecast
 362 period allows the RTC systems to enhance mitigation of peak flows, thus reducing flooding
 363 risks. For system using 1-day forecast, despite the lower magnitude, it may overflow almost
 364 the same way as conventional systems during large events, which is consistent with the
 365 finding in peak reduction (Table 3).

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



374 **Figure 4.** Outflow Duration Curve of a 7.5 kL system in conventional setting and four RTC strategies compared
 375 to the reference streamflow on a pro-rata base (i.e. considering catchment area of 150 m²). System outflow is
 376 determined by the sum of overflow and release.
 377

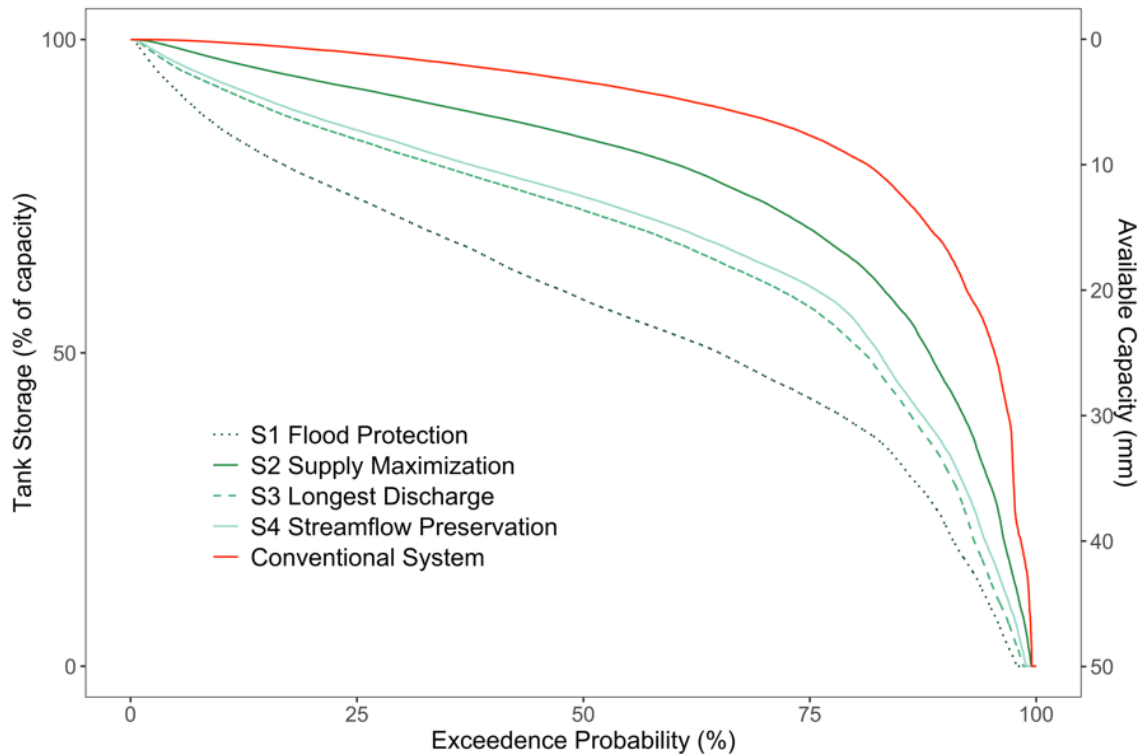
378 4. Discussion

379 4.1 The impact of forecast lead-time

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

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

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



412 **Figure 5.** Tank storage duration curve of four RTC strategies compared with conventional systems. The
 413 available capacity (right Y axis expressed in mm of runoff from catchment) is the tank storage (kL) standardised
 414 linearly by roof size of 150 m², expressed in mm.
 415

416 **4.2 The impact of outflow control**

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

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

436 By definition, the period over which pre-storm releases occur will affect the
 437 proportion of time that the target baseflow is being achieved. Operation of the RTC in such a
 438 way to quickly release the pre-storm release (primarily to minimise flood risk) will have the
 439 impact of minimising time when above-baseflow flow rates are delivered. However,
 440 releasing flow early also increases the chance that there will be inadequate water available to

441 meet the baseflow ‘demand’, meaning that the pre-storm release operation’s effect on
442 baseflow is a two-edged sword. Careful optimisation of these potentially conflicting
443 objectives is necessary, to ensure that appropriate flow regimes and wetted habitats are
444 available, particularly during dry periods (Leopold, 1968; Price, 2011).

445 However, reducing peak flow and maximising the period of base-flows may not
446 necessarily achieve a full restoration of the flow regime. The ecological integrity of an
447 aquatic ecosystem requires a flow regime as close as possible to its natural (pre-urbanisation)
448 level (Poff et al., 1997). This includes, not only the magnitude and frequency of peak- and
449 baseflow, but also the duration, timing and flashiness of flow events. Therefore, releasing the
450 predicted overflow over a longer period at a lower rate, such as occurs in S3 Longest
451 Discharge and S4 Streamflow Preservation (Figure 4), arguably better imitates the reference
452 flow regime. Doing so also has the benefit of minimising the hydraulic disturbance and
453 subsequent geomorphic degradation of the channels of receiving streams (Russell et al.,
454 2020). In coupling with real-time flow monitoring (Kawanisi et al., 2018), RTC offers the
455 potential to adapt the controlled release to real-time flow conditions, thus mimicking the
456 natural streamflow, and delivering the flow regime determined appropriate for the ecological
457 objectives of the receiving water.

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

469 4.3 Forecast Error

470 The performance of RTC can be lost from forecast error. Precipitation forecast are
471 subject to three types of error: localisation, timing and intensity of events (Habets et al.,
472 2004). Location errors may lead to a prediction of rain that doesn’t occur in reality (thus
473 leading to unnecessary release and reduction in water supply reliability) or vice versa
474 (leading to uncontrolled overflows). Timing errors for system using short lead-time forecast
475 may result in the pre-storm release being too late to reduce overflow, but this will have much
476 lower impact for long forecast lead-time strategies, such as S1 Flood Protection. More
477 importantly, error in rainfall intensity is the main source of forecast uncertainty, especially on
478 the daily time scale (Shahrban et al., 2016). Over-prediction causes unnecessary release
479 leading detriment to reductions in yield. In contrast, underpredicting rainfall events, which is
480 common in our simulation (see details of forecast error in the supporting information), can
481 lead to the underestimation of pre-storm release volume, and so may reduce flood mitigation
482 performance, especially in large events (e.g. 29th December 2016 event in Table 3). RTC
483 using long-lead time forecast can potentially minimise the effect of such errors, given that the
484 longer prediction window, as demonstrated above, allows RTC to prepare empty space for
485 future events earlier (e.g. S1 Flood Protection). Future work could investigate the benefits
486 and costs of RTC systems that use rainfall forecasts with lower probability (e.g. 10% chance)
487 to maximize the flood protection in large rainfall events. Another important future research

488 area involves the exploration of how the RTC could adopt forecast with errors accounted for
489 and thus minimize their impact on control outcomes.

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

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

504 4.4 Implementation

505 Implementing RTC in rainwater harvesting systems is feasible. Such an application
506 can be widely found in other urban water systems, such as water distribution networks
507 (Leirens et al., 2010; Martínez et al., 2007) and combined sewers (Campisano et al., 2016;
508 Mollerup et al., 2017). Current sensor technology enables the monitoring of present system
509 states (e.g. pump flow, water level and valve status) and environmental condition (e.g.
510 rainfall and streamflow) in real-time, which provides essential knowledge for RTC decision
511 making (Schütze et al., 2004). Recent advances in low-cost sensors also provide an
512 affordable and highly customized solution to tackle the technological and economical
513 challenge during large scale implementation (Cherqui et al., 2019; Montserrat et al., 2013).
514 The collected data and control decisions can be stored and transmitted through wireless
515 communication and online platforms (Lefkowitz et al., 2016; Pellerin et al., 2016; Yang,
516 2006). Future broader adoption of RTC in stormwater management will, however, need to
517 address the regulatory environment and governance. The operational jurisdiction and obscure
518 ownership which characterise these systems, when applied at household scale, might slow
519 down the development of the investment model for their ongoing effort for maintenance and
520 deployment, which is likely to create inertia, impeding or delaying adoption (Brown &
521 Farrelly, 2009; Brown, 2005).

522 4.5 Future Study

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

534 these research questions will lead to a better overall understanding of the combined impacts
535 of RTC systems.

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

543 **5. Conclusion**

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

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