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1 **Real-time controlled rainwater harvesting systems can improve the performance**
2 **of stormwater networks**

3
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17
18 **Keywords:**

19 Real-Time Control; Rainwater Harvesting Systems; Stormwater Control Measures; Flood
20 Mitigation; Source Control; Climate Change

21 Abstract

22 Real-Time Control (RTC) technology is increasingly applied in Rainwater Harvesting (RWH)
23 systems to optimise their performance related to water supply and flood mitigation. However,
24 most studies to date have focussed on testing the benefits at an individual site scale, leaving
25 the potential benefits for downstream stormwater networks largely untested. In this study, we
26 developed a methodology to predict how at-source RTC RWH systems influence the behaviour
27 of a stormwater network. Simulation was enabled by coupling the drainage model in SWMM
28 with an RTC RWH model coded using the R software. We modelled two different RTC
29 strategies across a range of system settings (e.g. storage size for RWH and proportion of storage
30 to which RTC is applied) under two different climate scenarios—current and future climates.
31 The simulations showed that RTC reduced flooding volume and peak flow of the stormwater
32 network, leading to a potential mitigation of urban flooding risks, while also providing a
33 decentralised supplementary water supply. Implementing RTC in more of RWH storages
34 yielded greater benefits than simply increasing storage capacity, in both current and future
35 climates. More importantly, the RTC systems are capable of more precisely managing the
36 resultant flow regime in reducing the erosion and restoring the pre-development conditions in
37 sensitive receiving waters. Our study suggests that RTC RWH storages distributed throughout
38 a catchment can substantially improve the performance of existing drainage systems,
39 potentially avoiding or deferring expensive network upgrades. Investments in real-time control
40 technology would appear to be more promising than investments in detention volume alone.

41 1. Introduction

42 Urbanisation creates critical challenges for water management. Water scarcity, caused
43 by population growth and dwindling freshwater resources, is still a major social and economic
44 challenge in many cities (Vörösmarty et al., 2010). Urban flooding risks are increased by the
45 excessive surface runoff and intensified peak flow, which result from increased impervious
46 areas in conventional stormwater drainage networks (Jongman et al., 2012; Nirupama &
47 Simonovic, 2006). These conventional stormwater networks, which aim to drain stormwater in
48 the quickest possible time through hydraulically-efficient infrastructure (e.g. pipes), also
49 connect impervious runoff directly to the receiving water, grossly altering natural flow regimes
50 through increased frequency and magnitude of stormwater flow (Bhaskar et al., 2016; Leopold,
51 1968), along with reduced recession times (Burns et al., 2005) and stream baseflow (Booth &
52 Jackson, 1997; Price, 2011). Such hydrological changes cause substantial channel erosion
53 (Hammer, 1972; Russell et al., 2020), habitat loss and ecological degradation in urban streams,
54 with subsequent reduction in biodiversity and ecosystem services (Bunn & Arthington, 2002;
55 King et al., 2005; Poff et al., 1997; Walsh et al., 2012).

56 Rainwater harvesting systems (RWH) are widely used as a traditional source of primary
57 or supplementary water supply (Gardner & Vieritz, 2010; Mikkelsen et al., 1999; Ward et al.,
58 2012). They also act as a Stormwater Control Measure (SCM), capturing and storing the runoff
59 from impervious surfaces (e.g. roofs) which is then diverted to supply household end-uses.
60 Such a design provides complementary retention to reduce the volume, frequency and peak of
61 urban runoff, which can reduce stormwater network overflows and mitigate urban flooding
62 risks (Burns et al., 2015; Jamali et al., 2019; Schubert et al., 2017). Such systems offer benefits
63 in potentially delaying the upgrade of water supply and drainage infrastructure (Coombes &
64 Kuczera, 2003), although the extent of benefit depends strongly on their storage capacity and
65 characteristics of the household water demand (Campisano & Modica, 2016).

66 Application of Real-time Control (RTC) technology has the potential to enhance RWH
67 performance in relation to both water supply and flood mitigation (Roman et al., 2017; Xu et
68 al., 2020a). Real-time control is a collection of software, sensors, communication devices and
69 actuators (Bennett, 1994), which can be combined to provide RWH systems with digital
70 information (e.g. rainfall forecast) and adapt its operation in real-time in response to operating
71 conditions. Doing so allows RWH systems to evolve from their conventional static nature to
72 highly adaptive (Kerkez et al., 2016). Real-time controlled RWH systems generally release
73 stored rainwater prior to a rainfall event (termed here as '*pre-storm releases*'), through a
74 remotely controlled discharge structure, to proactively create sufficient capacity for the
75 predicted inflows, thus minimizing the magnitude and frequency of uncontrolled overflows. A
76 range of modelling and empirical studies have demonstrated that RTC outperforms
77 conventional RWH systems in stormwater retention and peak flow reduction (Gee & Hunt,
78 2016; Oberascher et al., 2019; Roman et al., 2017), with no meaningful impact on water supply
79 performance (Melville-Shreeve et al., 2016; Xu et al., 2018).

80 Real-time control application to rainwater has advanced in recent times to include the
81 use of longer rainfall forecast windows. Xu et al. (2020b) modelled three different RTC
82 strategies using a 7-day lead precipitation forecast. They found that increasing the rainfall
83 forecast window, which extends the predictive horizon of the pre-storm releases, resulted in a
84 better attenuation of the peak flow. This approach also reduced overflow frequency and
85 extended the recession time, leading to an RTC outflow regime much closer to that of natural
86 streams (Xu et al., 2020b). Such an approach could potentially counteract the negative
87 hydrologic impacts caused by urbanisation (Leopold, 1968; Poff et al., 2010).

88 The focus of RTC application to RWH systems, to date, has mainly been on the
89 effectiveness at the land parcel, leaving its impacts on stormwater networks largely untested
90 (Xu et al., 2020a). Understanding whether the benefits gained at each parcel can be

91 accumulated and translated to a larger scale such as the catchment, is vital to understand the
92 potential cost-effectiveness of RTC RWH systems for adapting to a changing climate. This
93 requires explicit consideration of the behaviour of a distributed network of RTC RWH systems
94 and the hydraulic behaviour of the stormwater network.

95 In this study, we evaluated the impact of at-source RTC RWH systems on the behaviour
96 of a stormwater network. We adopted two different RTC strategies, to (i) mitigate floods and
97 (ii) deliver a more natural overall flow regime (for further details see Xu et al., 2020b), and
98 modelled their impact on a stormwater network across a range of system settings, under two
99 different climate scenarios (i.e. current and future climates), during a 7-month simulation
100 period. Network flooding volume and peak flow reduction were characterised, with a more
101 detailed analysis on the network outflow regime.

102 We hypothesised that operating RWH systems using RTC could reduce flooding
103 volume and peak flow for a stormwater network in both current and future climates, which
104 could mitigate the risks of urban flooding, while providing a decentralised supplementary water
105 supply. Our results demonstrated that implementing higher proportions of RTC systems
106 provided larger benefits than simply increasing the storage capacity, potentially avoiding or
107 deferring expensive upgrades for stormwater infrastructure. Our work provides useful insights
108 for application of at-source RTC RWH systems in future smart stormwater management.

109 **2. Methods**

110 To predict the impact of RTC RWH systems on the performance of a stormwater
111 network, we used a modelling approach which combined outputs from a volumetric RTC RWH
112 behaviour model coded in R software (version 4.1; R Core Team, 2021), with the 1-D hydraulic
113 model in the Stormwater Management Model (SWMM version 5.1 executed by PCSWMM 7.4;
114 Rossman, 2015). A similar modelling tool is also available in Python as an integrated library

115 'pyswmm' (McDonnell et al., 2020). The steps are illustrated in Figure 1 and details are given
116 below. The analysis was undertaken on a stormwater network located in a city in the province
117 of Quebec, in Canada, for which the SWMM model was adapted from Shishegar et al. (2021).
118 RWH systems were assumed to only connect to roofs, while stormwater runoff from other
119 surfaces (e.g. pavement) was conveyed directly to the drainage network.

120 2.1 RTC Strategies

121 We adopted two RTC strategies, as per Xu et al. (2020b): Strategy S1 (*'Flood*
122 *Mitigation'*) was designed to minimise storage overflows and Strategy S2 (*'Longest*
123 *Discharge'*) was designed to attenuate the flashiness and magnitude of pre-storm releases, to
124 return to a more natural flow regime. In Strategy S1, overflows predicted to occur within the
125 next seven days are released uniformly over the next 24-hr window. In contrast, Strategy S2
126 aims to achieve the longest possible duration for each pre-storm release (i.e. the pre-storm
127 releases start seven days in advance and finish before the predicted rain). Both RTC strategies
128 are based on 7-day lead rainfall forecast, with the forecast assumed to be perfect (i.e. no forecast
129 error was modelled), as the forecast error has little impact on overall system performance when
130 a 7-day rolling horizon is applied (see more details in section 2.2.2; Shishegar et al., 2021).

131 2.2 Modelling procedure

132 A modelling procedure (Figure 1) was developed to test the performance of the
133 proposed RTC system. This procedure includes three different modules: rainfall-runoff module
134 (M1), RTC module (M2) and drainage simulation module (M3). M1 utilises a hydrological
135 model, providing the 6-min catchment runoff and daily runoff forecast as input to M2. M2
136 generates the outflow from each at-source RTC system using the pre-defined control strategies
137 (as explained in section 2.1), which is then used by M3 to model the flow dynamics in the

138 stormwater network. M1 and M3 were enabled by SWMM, while M2 was computed by a
139 custom-written RTC algorithm in R software.

140 2.2.1 M1 Rainfall-Runoff Module

141 In M1, two distinct runoff sources were generated: the roof runoff, used as the inflow
142 to the RWH system, and the surface runoff from the remaining surfaces of the catchment. Both
143 were simulated by the rainfall-runoff model in SWMM (see more details in section 2.3 Study
144 Catchment) using real rainfall data. Roof runoff was modelled separately from other land uses
145 (i.e. pavement and pervious areas), because the RTC RWH behaviour cannot be implemented
146 directly in SWMM: the prediction and control of the RTC systems were therefore run in the
147 RTC module (M2). Roof areas were obtained by mapping each individual household and were
148 grouped by each catchment boundary (i.e. each catchment had one integrated roof area). The
149 imperviousness of roofs was assumed to be 100% and with a depression storage of 1.5 mm
150 (American Society of Civil Engineers, 1992). The imperviousness of each catchment for other
151 surfaces (e.g. pavement and pervious area) was then recalculated to exclude the area of roof
152 catchment, based on the mapping of the study catchment.

153 2.2.2 M2 Real-Time Control Module

154 The RTC module (M2) determines the pre-storm releases through control variables and
155 simulates the performance of RTC systems under different strategies. It consists of three steps.
156 In the first step, RWH Prediction, operating at a daily time-step, anticipates system overflows
157 for RTC decision-making using the Rainwater Harvesting Behaviour Model (Equations 1-3).
158 Yield-after-spillage rules were applied to provide a more accurate estimation of yield (Fewkes
159 & Butler, 2000; Equation 1). System inflow was predicted prior to the actual events using a 7-
160 day runoff forecast extracted from the output of M1. The forecast is updated every 24 hours.
161 Overflows are considered as unregulated — i.e. they occurred whenever the maximum capacity

162 is exceeded. First flush diversion system was excluded from the model, given that the use, type
 163 and volumetric behaviour of filtration devices, if present, is highly variable.

$$Q_{oi,t} = \max\left\{V_{i,t-1} + Q_{ai,t} - S_i, 0\right\} \quad (1)$$

$$Y_{i,t} = \min\left\{V_{i,t-1} - Q_{bi,t}, D_{i,t}\right\} \quad (2)$$

$$V_{i,t} = \min\left\{V_{i,t-1} + Q_{ai,t} - Y_{i,t} - Q_{bi,t}, S_i - Y_{i,t} - Q_{bi,t}\right\} \quad (3)$$

164 where $V_{i,t}$ and $V_{i,t-1}$ are the volume (L) in system i ($i \in N_T$) at the end of time step t (current) and $t - 1$ (previous)
 165 respectively, $Y_{i,t}$ is the rainwater yield in system i at t (L/timestep), $Q_{bi,t}$ is the RTC pre-storm release (control
 166 variable) from system i at t (L/timestep), $Q_{oi,t}$ is tank overflow from system i at t (L/timestep), S_i is tank storage
 167 capacity (L) of system i , $D_{i,t}$ is the demand (L/timestep) from tank i at time t , $Q_{ai,t}$ is the system i inflow at time t
 168 (L/timestep), N_T represents the set of tanks

169 In the second step, pre-storm release plans are developed to minimize the system
 170 overflows, based on the developed strategies. The overflow volume predicted for the RTC
 171 system corresponds to all roof surfaces connected to RTC RWH systems (see more details in
 172 section 2.3).

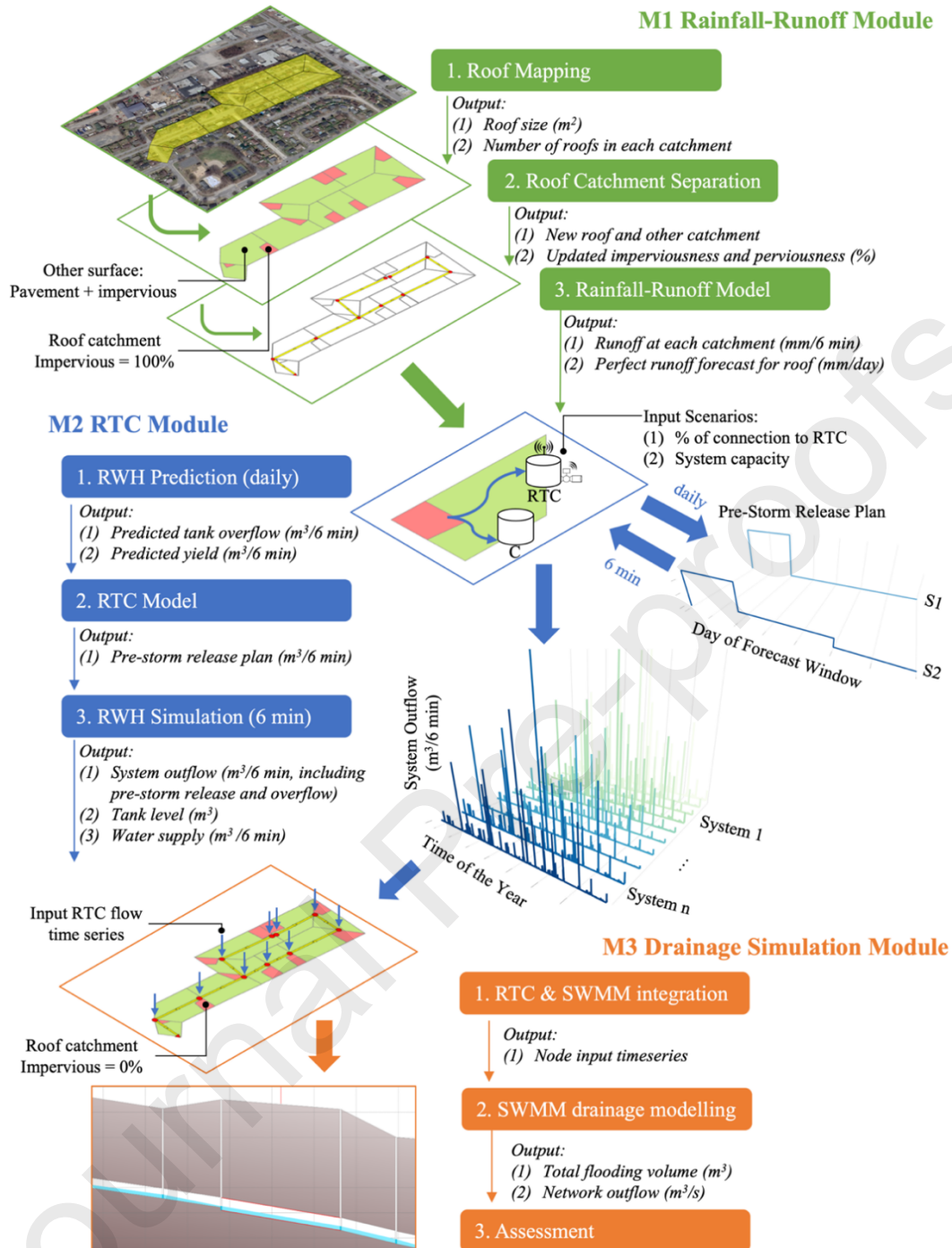
173 In the third step, the RWH Simulation (Figure 1) models the performance of defined
 174 controls using the RWH behaviour model (Equations 1-3). While the process is similar to RWH
 175 Prediction, this step is run on a 6-min time step, to capture system inflow and outflow dynamics.
 176 It utilised continuous simulation, assuming that all systems were empty at the beginning of the
 177 entire simulation period, meaning that this initial condition will not reset at each event. Finally,
 178 outflows (i.e. pre-storm releases and any overflows) from each system are summed and fed
 179 into the Drainage Simulation Module (M3).

180 Prediction and simulation components are operated on a 7-day rolling horizon. This
 181 setting, also known as receding horizon, has been used in the Model Predictive Control of urban

182 drainage systems (Lund et al., 2018). RWH Prediction decides the RTC plan for the next 7-day
183 period, given its ability to inform controlled releases long before the actual event (Xu et al.,
184 2020b). However, only the actions in the first 24-hour period of that rolling horizon are
185 implemented in the RWH Simulation component, which is then renewed recursively, on a daily
186 basis, when forecast information is updated. This approach creates the possibility to account
187 for forecast errors (which typically decrease as the forecast window decreases), to minimise
188 the impact of these errors on system performance.

189 2.2.3 M3 Drainage Simulation Module: combining R and SWMM model

190 The Drainage Simulation Module (M3), based on SWMM, aims to model the impact
191 of RTC and RWH systems on flow dynamics in stormwater networks. Outflow time-series data
192 from M2 are fed into each catchment node as external inflow, representing the flow from roof
193 areas. Each roof area is set to be 0% imperviousness with depression storages of 99 mm to
194 ensure zero runoff is produced in the hydrological model (as the roof runoff is being modelled
195 by M1). Finally, model results, such as total flooding volume and network outflow, are stored
196 and evaluated using a range of assessment metrics (see section 2.4).



197

198 **Figure 1.** Conceptual representation of modelling procedure, including three modules: (1) M1 Rainfall-Runoff
 199 Module, (2) M2 RTC Module, and (3) M3 Drainage Simulation Module. RTC represents for Real-Time Control
 200 systems, while C represents for Conventional RWH systems.

201

2.3 Study catchment

202

The study area is a small urban district, with primarily residential land use, located in a

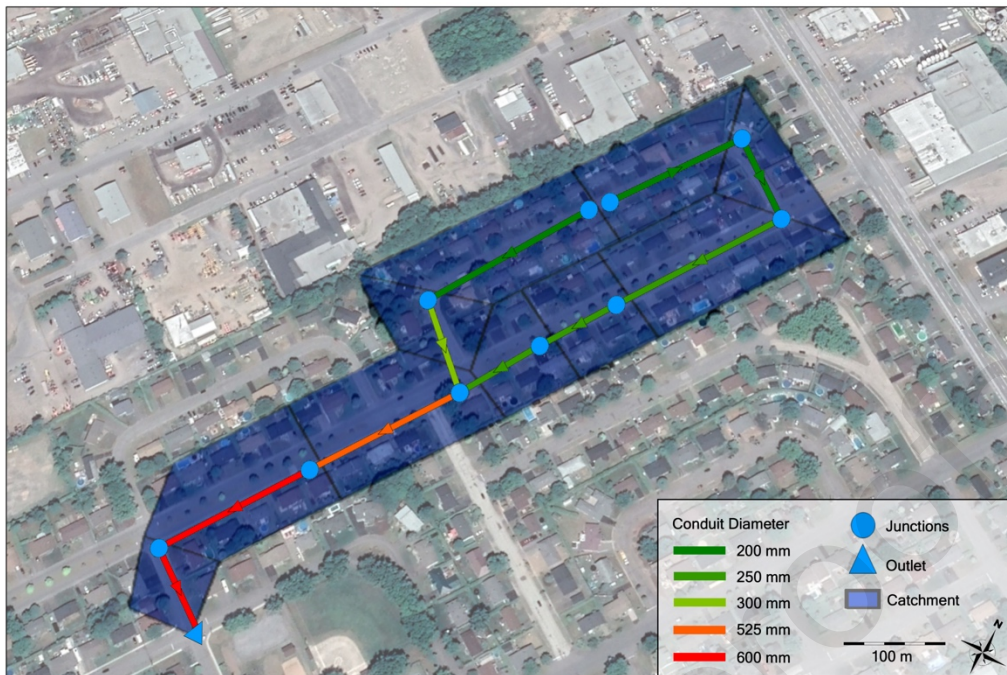
203

mid-size municipality in the province of Quebec, Canada. It is approximately 7.3 ha in area,

204 with an average imperviousness of 45.9% and includes 70 houses with an average roof area of
205 188.8 m². The SWMM model of the drainage network was adapted from Shishegar et al. (2021)
206 (Figure 2). The study catchment is drained to a combined sewer system with limited capacity,
207 with recorded flooding issues in upstream nodes. For this study, a separate stormwater system
208 is assumed by excluding the wastewater flow (i.e. set as zero). The study catchment consists
209 of 10 subcatchments (with an average slope of 2%), 10 nodes and 10 pipes with diameters
210 varying from 200 mm upstream to 600 mm downstream.

211 Rainfall observations, adopted from Shishegar et al. (2021), were obtained from a rain
212 gauge near the study stormwater network (Latitude: 46°01'00" N, Longitude: 71°57'00" W;
213 Environment and Climate Change Canada, 2021). An individual rain event was defined as
214 having more than 0.2 mm of rainfall with an antecedent dry period of 6 hr. In total, 77 rain
215 events were exacted from a 7-month period (i.e. 1st April to 31st Oct 2013), with total
216 precipitation of 796.4 mm.

217 A domestic water demand profile was adopted from local authority data (Ministry of
218 Municipal Affairs and Housing, 2020), which indicates a daily water consumption of 275
219 L/person/day. A population of 2.1 person per household was assumed according to the census
220 in the nearby catchment (Statistics Canada, 2017). RWH systems were assumed to supply toilet
221 flushing, which counts for 30% of the domestic demand, with two peak usages at 9 am and 7
222 pm in the diurnal pattern, leading to 173.3 L/day for each household. Although such supply
223 has not been implemented in this study catchment, it is commonly used in many countries, such
224 as Australia, Europe and America, reflecting the general use of rainwater harvesting systems
225 (Campisano et al., 2017).



226

227 **Figure 2.** Schematic illustration of study district, located in the province of Quebec, Canada.

228 2.4 Scenarios and Input Data

229 A range of scenarios were designed to test the impact of RTC system settings on
 230 network performance. We considered five rainwater storage capacities, relative to the roof
 231 areas (i.e. 5, 10, 20, 40, 80 L/m²) and five different storage capacities to which RTC is applied
 232 (e.g. 100% represents all RWH systems are operated by RTC). All of these were compared to
 233 a baseline scenario (i.e. no RWH system). Two climate conditions – *current* and *future* - were
 234 applied to evaluate the performance of the proposed RTC strategies in the context of climate
 235 change. Future rainfall is projected by adding a fixed factor of 15% to all rainfall data values.
 236 This simple approach has been adopted by previous studies in the southern Québec
 237 region (Bilodeau et al., 2018; Shishegar et al., 2021), although future increases in rainfall
 238 intensities are likely, in reality, to vary by region, season (Ouranos, 2015) and return period of
 239 rainfall events (Mailhot et al., 2012).

240 2.5 Assessment Metrics

241 Two metrics were adopted to quantitatively evaluate the impact of RTC RWH systems
 242 on the drainage network performance, namely peak flow and flooding volume reduction (Table
 243 1). These metrics were both assessed at the catchment scale, and quantify, respectively, the
 244 maximum outflow rate (m^3/s) at the network outfall and total network flooding volume (i.e.
 245 the sum of flooding volume from each node in m^3), standardised by its performance relative to
 246 the baseline scenario. The network outflow is also characterized using a flow duration curve
 247 (i.e. to better understand the distribution of the flows during the 7-month period (Quinn et al.,
 248 2021)), which compares the outflow regimes of two RTC systems with a conventional RWH
 249 system without RTC. In addition, we assessed the water supply efficiency of the RWH systems
 250 at the catchment-scale across the full range of scenarios (see Table 1 below).

251 To understand the specific performance gain resulting from RTC implementation,
 252 flooding volume at each node in one RTC scenario (e.g. 40 L/ m^2 systems operated by strategy
 253 S1) was plotted against the baseline scenario. Moreover, three of the most intense rainfall
 254 events, along with one event that has the longest duration and largest rainfall depth over the
 255 simulation period, were selected as illustrative examples to demonstrate peak flow reduction.

256

257 **Table 1.**258 *Assessment Metrics for Triple Objectives of Rainwater Harvesting*

Assessment Metrics	Equation	Description
Peak Flow Reduction (%)	$\rho_{peakflow} = \frac{Q_{out,max_{baseline}} - Q_{out,max_{RTC}}}{Q_{out,max_{baseline}}}$	Peak flow reduction of RTC strategies compared to the conventional system. Q_{out} refers to the outflow of the entire drainage network.

<p>Flooding Volume Reduction (%)</p>	$\rho_{flooding} = \frac{V_{flooding_{baseline}} - V_{flooding_{RTC}}}{V_{flooding_{baseline}}}$	<p>$V_{flooding_{baseline}}$ and $V_{flooding_{RTC}}$ are the total flooding volume of baseline (i.e. without any RWH systems) and RTC scenarios respectively.</p>
<p>Water Supply Efficiency (%)</p>	$E_{ws} = \frac{\sum_{i \in N_T} \sum_t Y_{i,t}}{\sum_{i \in N_T} \sum_t D_{i,t}} / n$	<p>$Y_{i,t}$ and $D_{i,t}$ are the rainwater yield and water demand in system i ($i \in N_T$) at time t (L/6 minutes). n is the total number of tanks (i.e. size of N_T), N_T represents the set of tanks.</p>

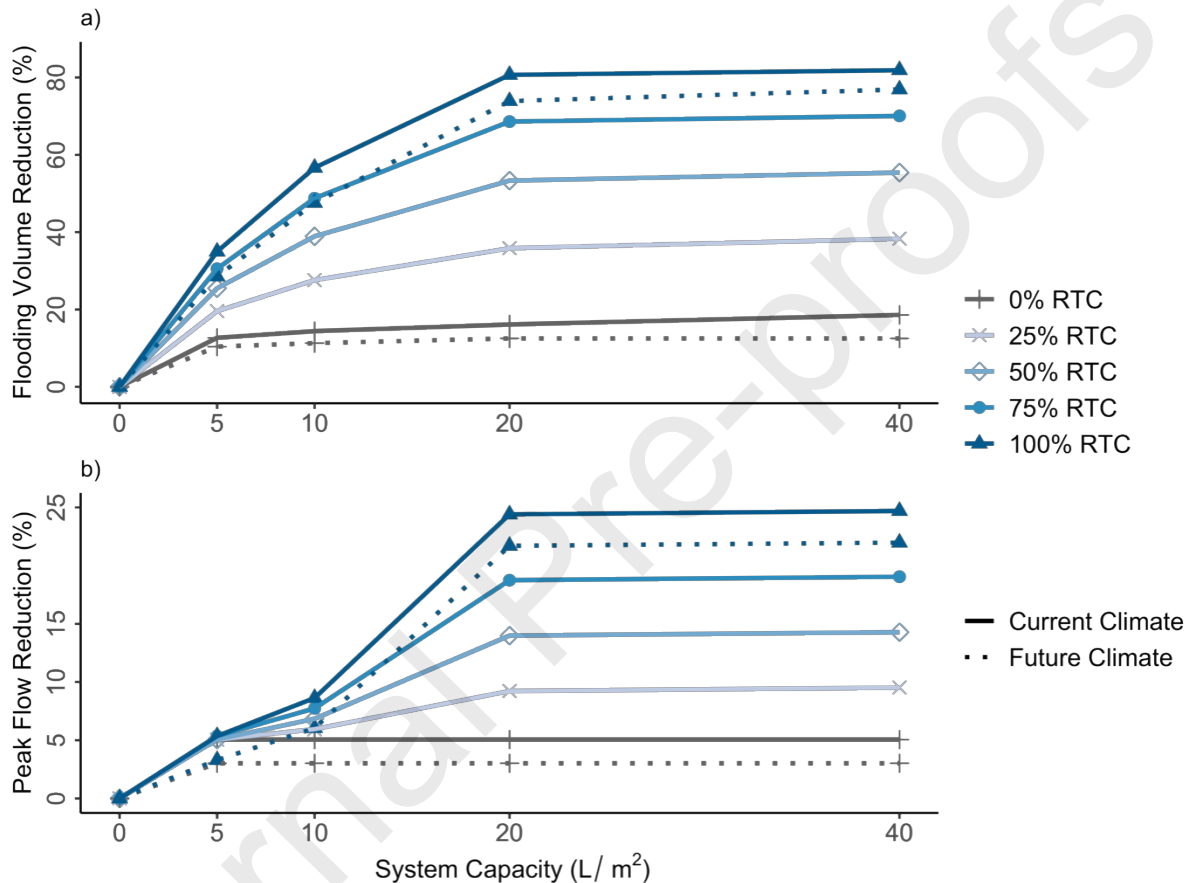
259 3. Results

260 3.1 Network Flooding Volume

261 As expected, the implementation of RWH systems reduced the total network flooding
 262 volume (Figure 3a). Conventional systems without RTC (i.e. 0% RTC) demonstrated an
 263 average of 17% flooding volume reduction compared to the baseline scenario (i.e. 0 L/m² tank
 264 size) which resulted in total flooding volume of 812 m³. The flooding volume reduction
 265 performance of these passively controlled tanks gradually increased with system capacity.

266 Increasing the use of RTC further reduced the flooding risk, by mitigating network
 267 flooding volume (Figure 3a). Operating all RWH system using RTC S1 (i.e. 100% RTC)
 268 reduced the network flooding volume up to 82%. Equipping roof areas with 10 L/m² RTC
 269 RWH systems doubled the flooding volume reduction achieved by much bigger (80 L/m²)
 270 conventional RWH systems, with total flooding volume of 352 and 609 m³, respectively. More
 271 importantly, the performance gain from increasing the proportion of controlled tanks was larger
 272 for small sized system (i.e. < 20 L/m²), decreasing in relative terms where larger rainwater
 273 storages were used.

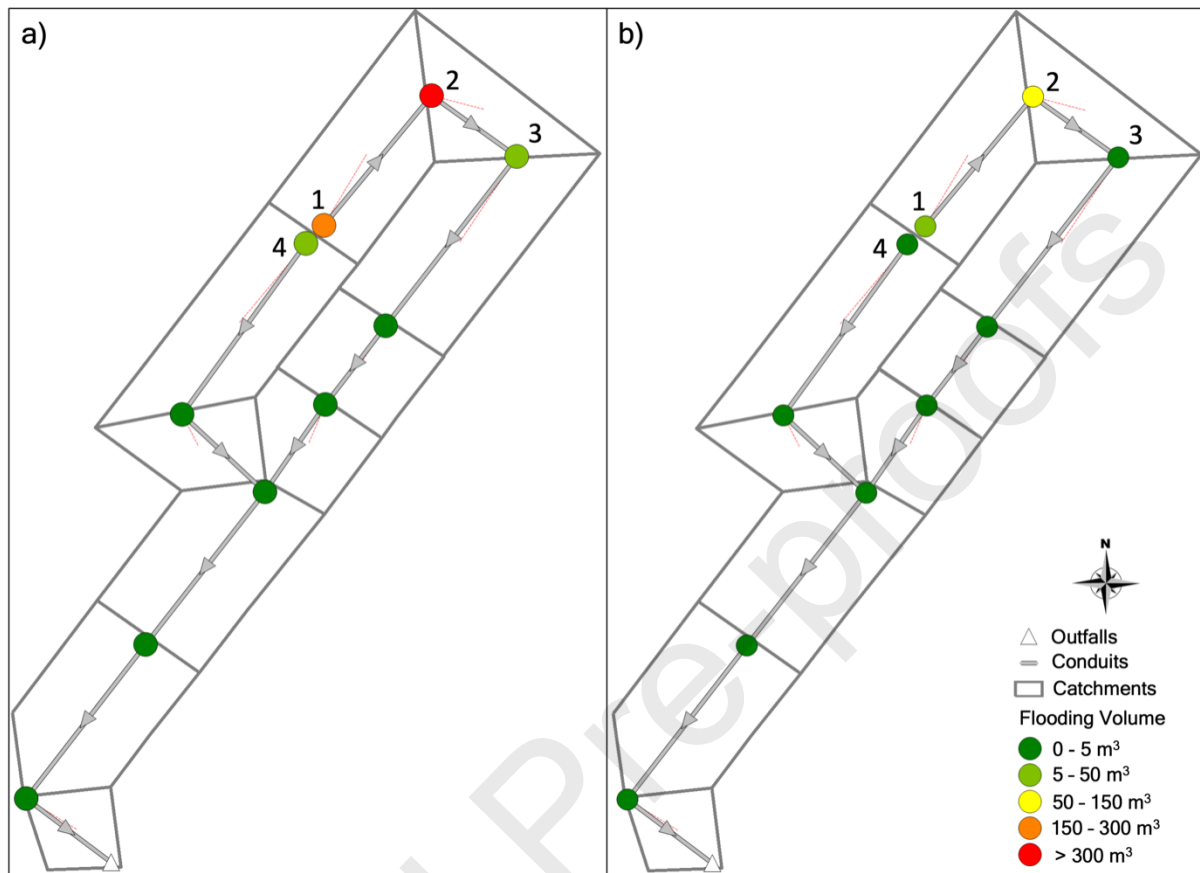
274 A similar trend in flooding volume reduction was modelled under the future climate,
 275 across all scenarios. While both the conventional and RTC demonstrated approximately 5%
 276 decrease in performance under future climate, the smallest RTC system (i.e. 5 L/m²)
 277 outperformed the largest conventional system (i.e. 80 L/m²), with 29% and 21% flooding
 278 volume reduction, respectively.



279
 280 **Figure 3.** Evaluation of a) flooding volume and b) outlet peak flow reduction performance in a range of scenarios
 281 under current and future climates under the Strategy S1 Flood Protection for the 7-month simulation period.

282 The enhanced network flooding volume reduction provided by RTC is due to the
 283 improved stormwater control at-source. This is illustrated by the presence of flooding volume
 284 in the upstream nodes within the baseline scenario (Figure 4a). Retrofitting with 40 L/m² RTC
 285 system (Figure 4b) can completely retain the flooding volume within nodes 3 and 4, while
 286 providing 88% and 77% flooding volume reduction to nodes 1 and 2 respectively, mitigating

287 a total of 665 m³ node flooding volume for the entire network during the 7-month simulation
 288 period.



289
 290 Figure 4. Flooding volume at each node of the study catchment in different scenarios during the 7-month
 291 simulation period, for a) baseline scenario and b) all the roofs connected to a 40 L/m² RTC system operated by
 292 Strategy S1 Flood Protection.

293 3.2 Flow Regime

294 3.2.1 Peak Flow Reduction

295 Operating RWH systems by RTC with S1 was shown to effectively reduce the peak
 296 flow at the drainage network outfall. Like the network flooding volume reduction, enhancing
 297 the proportion of RTC systems improved the peak flow reduction by up to 25% and 22%
 298 (Figure 3b) in the current and future climates, respectively. Increasing the storage capacity
 299 improved peak flow reduction, but the gains achieved were clearly constrained by the
 300 proportion of storages operated by RTC, with no gain in performance for systems size greater

301 than 5 L/m² for passively controlled systems. Conversely, scenarios with RTC applied to only
 302 25% of storages saw gains in performance with incrementally larger storages.

303 Real-time controlled systems were also modelled to mitigate peak flow in large rainfall
 304 events (Table 2). The Flood Mitigation strategy (S1), with a capacity of 40 L/m², for example,
 305 was shown to reduce peak flows by 25% to 40% in the most intense events (i.e. 9th August,
 306 27th June and 28th June events), while achieving a 32% peak reduction during the largest and
 307 longest rain event (i.e. 23rd May event which has total rainfall depth of 89.6 mm over 76.3 hr).
 308 This performance was also resilient against future climate, where an increasing of 15% rainfall
 309 resulted in an average loss of approximately 2% in the achieved peak flow reduction.

310 **Table 2.**

311 *Peak flow reduction at the outfall of the study catchment in four large events in 2013.*

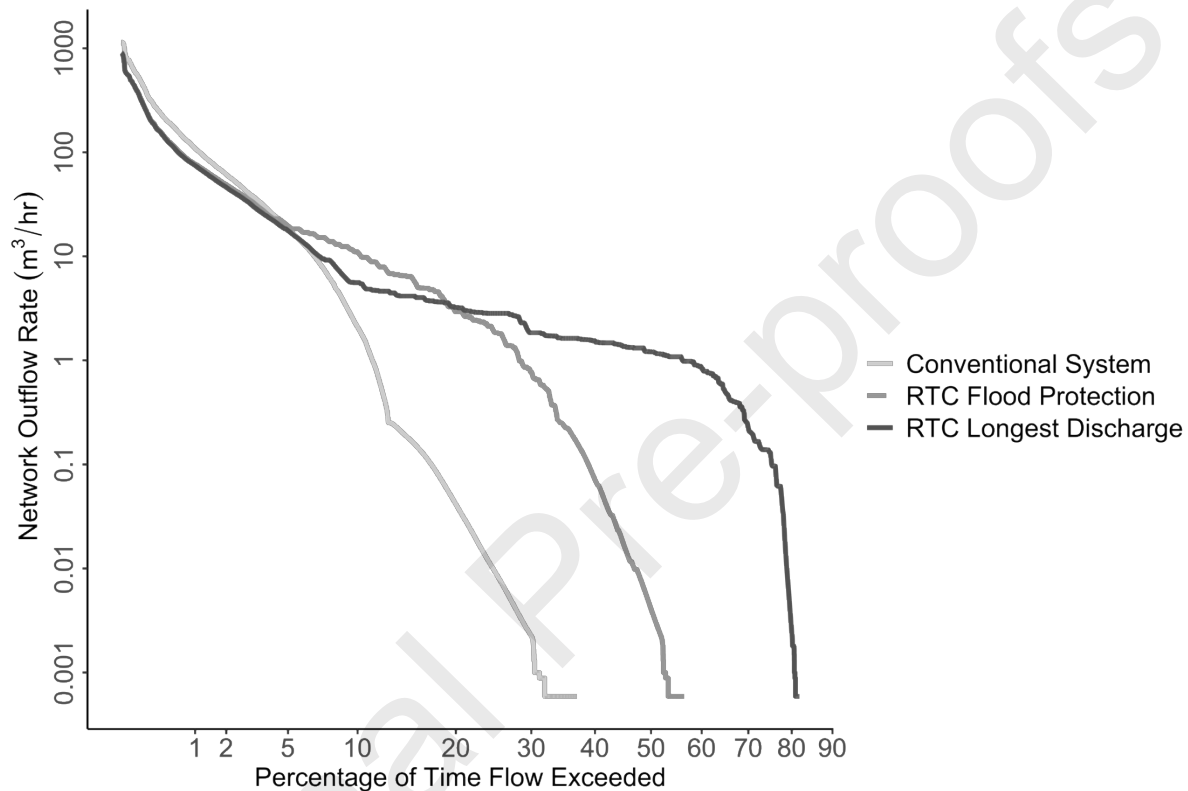
Date	Rainfall Duration (hr)	Current Climate			Future Climate		
		Rainfall	Maximum	Peak Flow	Rainfall	Maximum	Peak Flow
		Depth (mm)	6-min Intensity (mm/hr)	Reduction (%)	Depth (mm)	6-min Intensity (mm/hr)	Reduction (%)
9 August	4	21.8	63.6	25	25.1	73.1	22
27 June	2	8.4	48	40	9.7	55.2	37
28 June	3.9	21.8	39.6	33	25.1	45.5	30
23 May	76.3	89.6	30	32	103	34.5	31

312

313 3.2.2 Outflow Characterisation

314 The outflows of two of the modelled RTC scenarios were characterized, for illustration,
 315 by a flow duration curve, with a comparison to the conventional systems (Figure 5). Both RTC
 316 systems demonstrated similar performance in reducing the magnitude and flashness of high
 317 flows compared to the conventional system, especially for the highest flow Q5 (observed less
 318 than 5% of the time). However, the RTC release using S2 Longest Discharge strategy was able

319 to better attenuate the flows, especially for Q5 – Q60 (Figure 5). The Flood Mitigation strategy
 320 (S1) showed higher flows during Q5 - Q20, but with a sudden decrease towards low flow levels.
 321 In contrast, the Longest Discharge strategy (S2) generally produced more muted high flows,
 322 decreasing more gradually (i.e. lower rate of change) until the turning point occurred later at
 323 Q60. This gives a more constant overall flow regime.



324
 325 Figure 5. Outflow Duration Curve (i.e. showing percentage of the time of a given flow magnitude is exceeded)
 326 of RTC S1 Flood Protection (i.e. grey) and S2 Longest Discharge (i.e. black) compared to conventional system
 327 (i.e. light grey). The x-axis is scaled to 0 – 90% due to the cease-to-flow condition (i.e. no flow) occurring after
 328 Q90. All the roof catchments were equipped with 40 L/m² tank, while both of the RTC proportions were set as
 329 100%. Network outflow is obtained at the outlet of the study catchment, which is computed by the hydraulic
 330 model using SWMM.

331 3.3 Water Supply

332 Water supply performance was similar for both RTC strategies, being somewhat lower
 333 than that of conventional systems. Indeed, RTC Flood Protection demonstrated an average of

334 74% (\pm 21%) supply efficiency across all scenarios, compared to 94% (\pm 5.3%) in
335 conventional systems. The decrease in efficiency is relatively larger in small sized systems
336 (e.g. 5 and 10 L/m²), diminishing in large systems (e.g. 80 L/m²) where the difference is
337 generally less than 2%.

338 4. Discussion

339 4.1 Impact of RTC

340 Increasing the proportion of RWH storages controlled by RTC dramatically improved
341 the performance in terms of peak flow and flooding volume reduction. This can also be
342 achieved by increasing storage capacity, although a diminishing marginal return occurred when
343 the capacity of the RTC systems exceeded 20 L/m². The magnitude of performance gained
344 from increasing RTC proportion was relatively greater than simply increase tank capacity. This
345 observation confirmed that implementation of RTC can make the most of each RWH storage
346 through adaptive management of its capacity, improving retention of runoff, thus reducing
347 network flooding while maintaining water supply performance, although the pre-storm release
348 could reduce the security in storage for supply. RTC RWH systems have the potential to deliver
349 significant cost savings; systems operated by RTC can be built at a smaller size, while
350 delivering the same level of service as a larger conventional design. Doing so can help to reduce
351 the overall cost, especially in high-density urban environments, where space is limited (i.e.
352 insufficient space or high cost for large tanks). Similarly, retrofitting of RTC to existing RWH
353 storages will improve their performance, reducing flood risk of the stormwater network,
354 without requiring replacement of existing storages.

355 Increasing storage volume improved peak flow reduction, but in conventional storages,
356 this occurred only for increases up to around 20 L/m². Above that, any gain was very small.
357 This is because, regardless of storage volume, the limited water demand means that these tanks

358 remain near full most of the time (Jones & Hunt, 2010). Implementation of RTC overcomes
359 this limitation; the RTC systems can better mitigate the peak flow by proactively emptying the
360 storage through the pre-storm releases. It offers flexibility to create the necessary capacity in
361 real-time allowing RTC RWH systems to better reduce the storm runoff at its source, prior to
362 the pipe network, thus potentially reducing flooding risks for the downstream receiving waters.

363 This adaptive approach could also be extended to reduce the risks of combined sewer
364 overflows (CSO), which pose a major hazard to urban water environment (Ellis & Hvitved-
365 Jacobsen, 1996; Passerat et al., 2011). Real-time control can also be applied to decentralised
366 and centralised stormwater systems that include storage to create resilience in urban drainage
367 networks, and cope with increasing impervious runoff caused by changing land use and climate
368 change, allowing high-cost infrastructure upgrades to be postponed or avoided.

369 In theory, the maximum peak flow reduction in this study is approximately 40%, given
370 that the RWH storages are limited to only control the runoff from roof surfaces which occupies
371 around 40% of the total impervious areas. Therefore, the impact of RTC on the drainage
372 network is constrained by the extent of its application. This will likely occur in practical
373 implementation, given that RWH systems are generally utilised to manage roof runoff only
374 (Campisano et al., 2017), with ground-level runoff being unaffected. Future work could be
375 undertaken to test approaches to circumvent this physical constraint, for example by coupling
376 the RTC RWH systems with other stormwater control measures (SCMs; e.g. biofilters (Shen
377 et al., 2019) and detention basin (Shishegar et al., 2019)). Real-time control could be applied
378 to this network of SCMs. Indeed, RTC technology is increasingly applied in both nature-based
379 and storage-based SCMs, with growing interest in investigating the mechanisms and benefits
380 on the collaborative operation of multiple systems at a range of geographical scales (Di Matteo
381 et al., 2019; Liang et al., 2021; Mullapudi et al., 2018).

382 However, maintaining the ecological integrity of an aquatic ecosystem requires not only
383 alleviation of peak flow, but restoration of a flow regime as close as possible to its natural (pre-
384 urbanisation) state (Poff et al., 1997). Doing so requires consideration of various aspects of the
385 flow regime, including magnitude, frequency, timing, duration and flashiness. Therefore, while
386 both developed RTC strategies successfully reduced the magnitude of peak, performing the
387 pre-storm releases over a longer period at a lower rate, as occurred in S2 (Longest Discharge),
388 was far more effective in delivering a flow regime more typical of pre-urban conditions. This
389 outcome also has the benefit of minimising the hydraulic disturbance and subsequent erosion
390 of downstream channels (Hawley et al., 2013; Russell et al., 2020).

391 4.2 Implementation at catchment-scale

392 Recent advances in low-cost sensor technology enable the real-time monitoring of
393 environmental conditions (e.g. water level in stormwater networks and streamflow) and system
394 dynamics (e.g. water level in the tanks and actuator status), providing a feasible and affordable
395 solution for large-scale deployment (Cherqui et al., 2019; Montserrat et al., 2013; Shi et al.,
396 2021). The collected data can be transmitted via innovative communication technology, such
397 as Low Power Wide Area Networks (LPWAN), which is characterised by low energy
398 consumption and high transmission ranges (Silva et al., 2017). Such a technique has begun to
399 be applied in operating multiple site-scale RTC RWH systems, powered by solar panels and
400 batteries, at catchment-scale (Oberascher et al., 2021). Further gains can likely be made
401 through the integration of sensor data and online hydrodynamic models, to improve the
402 network performance of RTC RWH systems (Bartos & Kerkez, 2021).

403 One important driver of implementation relates to the costs and benefits of RTC RWH
404 systems. While the cost of such system is context specific, several studies have concluded that
405 rainwater storages retrofitted by RTC technology is a more cost-effective solution when

406 broader criteria, such as flood control and environmental benefits, are considered (Melville-
407 Shreeve et al., 2016; Parker et al., 2022). Additional benefits could also be obtained from the
408 coordinated control of multiple rainwater storages at network scale given the synergies it can
409 provide. Future research is needed to evaluate the costs and benefit of more complex RTC
410 schemes, in specific regulatory and infrastructure contexts.

411 4.3 Future research

412 Future research is required to investigate the effectiveness of control strategies which
413 permit the spatially distributed RWH systems to collaborate across the catchment. This could
414 be achieved by optimisation-based control, although doing so will require overcoming the
415 computational challenges associated with running optimisation and hydraulic models in real-
416 time. The performance of such control could also be compared with simpler rule-based control,
417 as simplicity of implementation will be helpful in opening up the benefits of RTC to a wider
418 range of actors. Future areas of research should also include a closed-loop control where real-
419 time monitoring data (e.g. water level in each drainage node) could provide feed-back to
420 improve the control strategy, minimising the impacts of uncertainties in weather forecast and
421 system dynamics. Another area of future work could be to propagate the sort of 1-D hydraulic
422 modelling carried out here with a 2-D flood model. Even more complex feedback loops could
423 be investigated if modelling both 1 and 2-D domains.

424 5. Conclusion

425 In this study, we modelled the impact of at-source RTC RWH systems on the behaviour
426 of a stormwater network, through the integration of a RTC model in R software and a 1-D
427 hydraulic model in SWMM. Two different RTC strategies, one for mitigating floods, the other
428 aimed at delivering a more natural flow regime, were tested across a range of system settings
429 under two climate scenarios—current and future climates. We concluded that the use of RTC

430 can substantially reduce the network flooding volume and peak flow in both current and future
431 climates and mitigate the risks of urban flooding, while providing a decentralised water supply.
432 Implementing higher proportions of RTC systems provided larger relative benefits than simply
433 increasing the storage capacity of RWH systems. Moreover, the RTC systems fundamentally
434 modified the flow regimes of the network outflow, which reveals a promising potential in
435 reducing erosion and restoring pre-development flow regimes in receiving waters. Our study
436 suggests that RTC storages distributed throughout a stormwater network can substantially
437 improve its performance, potentially avoiding or deferring expensive sewer network upgrades.
438 Investments in RTC technology would appear to be more promising than investments in
439 detention volume alone.

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452 7020305, <https://climate.weather.gc.ca/>). Domestic water demand data were sourced from
453 Canadian Ministry of Municipal Affairs and Housing
454 (<https://www.mamh.gouv.qc.ca/infrastructures/strategie/cartographie-et-rapports-annuels/>).

455 Average population in each household was obtained from census for the case study region from
456 Statistics Canada ([https://www12.statcan.gc.ca/census-recensement/2016/dp-
pd/prof/index.cfm?Lang=E](https://www12.statcan.gc.ca/census-recensement/2016/dp-
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685 **Highlights:**

- 686 • Impact of real-time control (RTC) rainwater harvesting systems on stormwater
687 network was modelled by coupling SWMM and RTC model in R.
- 688 • Real-time controlled rainwater harvesting systems can mitigate drainage network
689 flooding by reducing stormwater runoff at source.
- 690 • Implementing RTC in RWH storages yielded greater benefits than simply increasing
691 storage capacity.

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