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Can smart rainwater harvesting schemes result in the improved performance of integrated urban water systems?

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1 **Can Smart Rainwater Harvesting Schemes result in the improved**
2 **performance of Integrated Urban Water Systems?**
3

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13 **Can Smart Rainwater Harvesting Schemes result in the improved** 14 **performance of Integrated Urban Water Systems?** 15

16 **Abstract**

17 Although rainwater harvesting (RWH) schemes have gradually gained more credibility and popularity
18 in recent times, efficient utilisation and larger scale implementation of multi-purpose RWH is still a
19 challenging task. This paper aims to explore the potential of using smart RWH schemes and their impact
20 on the efficiency improvement in integrated urban water systems (UWS). The smart RWH scheme
21 analysed here is capable of proactively controlling the tank water level to ensure sufficient spare storage
22 is maintained at all times that accommodates the runoff from storm events. The multi-purpose RWH tank
23 can mitigate local floods during rainfall events and supply harvested rainwater to non-potable residential
24 water consumption. Optimal design parameters of the smart RWH scheme is also identified to achieve
25 the best operational performance of the UWS. WaterMet² model is used to assess the performance of the
26 UWS with smart RWH schemes. The efficiency of the proposed methodology is demonstrated through
27 modelling a real case of integrated UWS. The results obtained indicate that utilisation of smart RWH
28 with an optimally-sized tank, compared to the corresponding conventional RWH, is able to significantly
29 improve the UWS efficiency in terms of mitigation of local flooding and reliability of water supply from
30 harvested rainwater.

31
32 *Keywords:* Flood mitigation, rainwater harvesting, smart technologies, urban water systems.
33

34 **Introduction**

35 Strategic planning of integrated urban water systems (UWS) needs to evaluate a combination of potential
36 intervention options to identify the most appropriate strategies which provide long-term sustainability of
37 these systems. Previous assessment of sustainability-based performance of integrated UWS indicates that
38 highly ranked intervention strategies are those supporting both (a) efficient water abstraction, supply and
39 reduced consumption and (b) stormwater/wastewater collection and controlled release, i.e. strategies
40 such as rainwater harvesting (RWH) and other water recycling options (Behzadian and Kapelan 2015a).
41 In particular, the application of rainwater harvesting in urban water management has gained considerable
42 attention in recent decades as a new alternative resource given increasingly severe droughts, increased
43 water demands and limited potable water resources (Tchobanoglous et al. 2003). In particular, RWH can

44 result in both potable water saving in water supply systems and reduction of stormwater runoff discharge
45 into the wastewater systems.

46

47 Performance assessment of different RWH schemes has been frequently carried out in the literature. The
48 focus of those studies has been either on water supply only (Rozos et al. 2010) or on more integrated
49 aspects (Behzadian et al. 2014a). Some studies analysed RWH schemes for non-potable water use only
50 and hence water supply reliability (e.g. Eroksuz and Rahman 2010; Khastagir and Jayasuriya 2010;
51 Imteaz et al. 2011; Ward et al. 2012) and resilience in the context of distribution systems (Basupi et al.
52 2014) were mainly investigated. As a result of these analyses, a wide range of potable water saving
53 efficiencies have been reported in the literature ranging from 21.6% by Chiu et al. (2009) in Taipei and
54 59% by Zaizen et al. (1999) in Japan to 70% by Nodle (2007) in Germany. However, other studies applied
55 multi-purpose RWH analysis in which non-potable domestic water use and stormwater control were
56 considered simultaneously (e.g. Partzsch 2009; and Jones and Hunt 2010). In the UK context, the British
57 Standard for RWH (BS8515:2013) gives recommendations primarily for non-potable water use but also
58 recommends the integrated sizing approach for multi-purpose RWH in situations where the potential of
59 the average runoff for harvesting is greater than the average non-potable demand supplied by harvested
60 rainwater (BSI 2013).

61

62 A RWH scheme is typically implemented as a tank that harvests rainwater from impermeable surfaces
63 (e.g. building roof) and supply for non-potable water consumptions (e.g. toilet flushing) which are
64 complemented with a mains water top-up (Ward et al. 2012). The performance of RWH schemes under
65 different climates (e.g. dry and wet) has also been investigated in the literature to either evaluate the
66 system reliability (Rozos et al. 2010) or to determine the tank size (Imteaza et al. 2011). More recently,
67 Bouziotas et al. (2015) investigated the flood attenuation performance of RWH schemes under different
68 urban densities.

69

70 The most common (i.e. conventional) type of RWH schemes is characterised as a passive or reactive
71 system where filling, emptying and spilling a tank is a function of rainfall, demand and storage capacity,
72 respectively (BSI 2013). More specifically, the general functionality of a conventional RWH scheme is
73 described as follows: it harvests rainwater during rainfall events typically from impermeable surfaces

74 (e.g. roofs, roads and pavements) and fills the tank as long as there is enough room in the storage capacity
75 (Fig. 1a). This process continues irrespective of any subsequent rainfall events. Once the tank is full
76 specifically during extreme or frequent rainfall events, the tank overflows runoff into the wastewater
77 system. The conventional approach has been used to investigate the operation of RWH schemes by many
78 researches (e.g. Rozos et al. 2010, Eroksuz and Rahman 2010, Imteaz et al. 2011 and Ward et al. 2012).
79 However, the conventional approach can be a major disadvantage for RWH schemes especially when
80 stormwater management is crucial. This drawback has also been reported in the literature by Jones and
81 Hunt (2010) that logged frequent overflows in their monitored RWH tank during most rainfall events.
82 One general solution to diminish this negative impact is to simply enlarge the storage capacity of the
83 tank to provide more spare storage for stormwater management during large storms (Jones and Hunt
84 2010). However, an over-sized tank is unlikely to be a cost-effective and desirable option (Ward et al.
85 2012).

86

87 Unlike the above passive configuration, an active RWH (called smart RWH henceforth) scheme can be
88 envisaged in which the storage volume is proactively managed to ensure spare storage is maintained
89 especially during large storm events to effectively store runoff at all times (BSI 2013). More specifically,
90 the smart RWH scheme can be designed that provides adequate spare storage in a timely manner. This
91 is achieved through pre-empting the storage volume and standby for collecting stormwater runoff hence
92 efficiently attenuating potential urban flooding while harvested water is supplied based on available
93 storage. On the other hand, provision of spare storage in this way is in conflict with the efficiency of
94 potable water saving. More specifically, this implies that some available harvested runoff needs to be
95 discharged without being used by any water demand and therefore a compromise exists. Despite a
96 plethora of investigations exploring various aspects of the RWH performance, to the best of the authors'
97 knowledge, none of the previous works has examined the performance of smart RWH schemes (as
98 outlined above) in the context of integrated UWS. Hence, the primary aim of this paper is to explore
99 whether and how the smart RWH can be beneficial for integrated UWS and explore how efficient a smart
100 RWH scheme can be in integrated UWS for reducing excess stormwater while supplying to non-potable
101 domestic water use. This paper is also aimed at identifying the optimal range of design parameters that
102 the smart RWH can achieve the best performance of stormwater control in integrated UWS and then
103 compare it with corresponding conventional RWH schemes.

104

105 **Methodology**

106 This paper presents a new approach for smart RWH schemes that assist the integrated UWS in mitigating
107 urban flood and hence improve performance of UWS with smart RWH. All this is examined through a
108 conceptual WaterMet² model. The optimal performance of the smart RWH schemes with different
109 *operational* and *design* parameters is also identified and compared with conventional RWH for an
110 integrated UWS over a specified planning horizon. The suggested smart RWH is briefly described below
111 followed by formulation of the optimisation model and description of the UWS model used in the paper.

112

113 *Smart RWH*

114 The concept of the smart RWH scheme defined here is inspired by the active RWH introduced by the
115 British Standard for RWH in BS8515 (BSI 2013). More specifically, the British standard recommends
116 two storage management approaches for actively control stormwater runoff using RWH: 1) approach
117 based on rainfall forecasting and 2) approach based on water level control. The smart RWH suggested
118 here is following the second approach, i.e. it proactively manages/controls the water volume/level in the
119 tank to ensure spare capacity is maintained at all times to collect the runoff during rainfall events. Such
120 a smart system can perform this function by using sensors to measure rainfall depth and water volume in
121 the tank. These data can be used by the smart system in order to trigger actuators (i.e. valves/pumps)
122 releasing specific amount of storage volume based on a pre-specified timetable across the year. The
123 released water needs to be discharged into permeable surfaces in a time of no rain such that it has no
124 contribution to exacerbating flooding in the sewer networks downstream (BSI 2013). Such a scheme for
125 pre-emptying specific volume of the tank as shown in Fig. 1b is the basis for the smart RWH used in this
126 paper.

127

128 **Fig. 1** Structure of the conventional and smart RWH

129

130 The operational policy of the RWH tank requires to specify water release of the tank for each time step
131 according to water availability in the tank and water demands (Rozos and Makropoulos 2013). One of
132 the commonly used types of operational policy is regression formula which was used in water resources
133 systems (Karamouz et al. 2003) and urban water supply systems (Rozos and Makropoulos 2013). A

134 general form of non-linear regression formula based on the total available water storage (i.e. volume plus
 135 inflow) is suggested in this paper. In other words, the suggested smart RWH scheme considers improving
 136 the operational policy of the RWH tank based on the measurement of tank inflow and volume by using
 137 related sensors. Actuators then release a specific water volume (R_t) from the tank at time step t as a
 138 function of water volume (V_t) at time step (*instance*) t and inflow volume into the tank (I_t) at time *interval*
 139 t (i.e. between time steps t and $t-1$), i.e. as follows:

$$141 \quad R_t = a_i \times (V_t + I_t)^{b_i} \quad i=1, \dots, 12 \quad (1)$$

142
 143 where a_i and b_i are two *operational* parameters of RWH tank that are assumed to be constant for each
 144 calendar month. The released water (R_t), which is assumed to be discharged into permeable surfaces,
 145 allows the tank to keep some space free and on standby for extreme rainfall and therefore mitigate
 146 potential local flooding. It should be noted that the RWH simulation is based on daily time step for the
 147 duration of a specified planning horizon (at least one year to include seasonal variations). However, the
 148 operational parameters in Eq. (1) need to be specified for each calendar month such that the long-term
 149 performance of the smart RWH tank in the integrated UWS can lead to both maximising local flood
 150 attenuation and minimising water usage from the mains over a specified planning horizon. This can be
 151 obtained from a multi-objective optimisation model which is described below.

152 153 *Multi-objective optimisation model*

154 A two-objective optimisation model is developed here to identify the optimal values of *operational*
 155 parameters in Eq. (1) that will lead to optimal operation of the smart RWH scheme in an integrated UWS.
 156 The total number of decision variables is equal to 24 (the number of calendar months, i.e. 12, multiplied
 157 by the number of operational parameters in each month, i.e. 2). The two objectives are to minimise total
 158 water demand supplied from the potable water mains (i.e. conventional distribution pipes) and to
 159 minimise the total urban flooding (i.e. total volume of stormwater and sanitary sewage exceeding the
 160 storage capacity of a combined sewer network). The objective functions can be written as the following
 161 normalised quantities:

$$162 \quad \text{Potable water supplied} = \min \frac{\sum_{t=1}^T V_t^{SP}}{\sum_{t=1}^T V_t^{NSP}} \times 100 \quad (2)$$

163 Total Excess stormwater = $\min \frac{\sum_{t=1}^T V_t^{SEx}}{\sum_{t=1}^T V_t^{NSEx}} \times 100$ (3)

164
$$V_t^{(N)SEx} = \begin{cases} V_t^{SW} + V_t^{TO} + V_t^{SS} - Cap_{WS} & \text{if } (V_t^{SW} + V_t^{TO} + V_t^{SS}) > Cap_{WS} \\ 0 & \text{if } (V_t^{SW} + V_t^{TO} + V_t^{SS}) \leq Cap_{WS} \end{cases}$$
 (4)

165

166 where V_i^{SP} and V_i^{NSP} are volume of water demands supplied from the mains at time step t if smart RWH
 167 and no RWH exist, respectively; V_t^{SEx} and V_t^{NSEx} are excess volume of stormwater (i.e. flood) at time
 168 step t if smart RWH and no RWH exist, respectively; V_t^{SW} is volume of stormwater runoff discharged
 169 into the combined sewer networks at time step t ; V_t^{TO} is volume of the smart RWH tank overflow
 170 discharged into the combined sewer networks at time step t ; V_t^{SS} is volume of sanitary sewage at time
 171 step t ; Cap_{WS} is storage capacity of the combined sewer networks; T is number of analysed time steps. In
 172 other words, the first objective states the proportion of the water demands supplied from the potable
 173 water of the mains when smart RWH exists relative to the conditions that the potable water of the mains
 174 supplies the entire water demands without smart RWH. Thus, the ratio between potable water demands
 175 in these two conditions is expressed as a percentage in the first objective. The same relation is in place
 176 for the second objective which is expressed as a percentage of the ratio between local floods in the same
 177 two conditions. It should also be noted that Eq. (4) states that excess volume of stormwater happens in a
 178 time step when the total discharge of that time step exceeds the capacity of the combined sewer network
 179 (Fig. 2).

180

181 The multi-objective evolutionary algorithm of NSGA-II is used to solve the above optimisation problem
 182 (Deb et al. 2002). NSGA-II (Non-dominated Sorting Genetic Algorithm II) is a multi-objective
 183 evolutionary algorithm (MOEA) optimisation model that could alleviate the difficulties of previous
 184 MOEAs such as non-elitism approach and considerable computational effort (Behzadian et al. 2009).
 185 Comparison of several popular MOEAs in the problems of water distribution systems shows that NSGA-
 186 II with minimum parameters tuning remains a good choice that can achieve the best spread of optimal
 187 solutions (Wang et al. 2014).

188

189 The values of two objective functions shown in Eq. (2) and (3) are calculated using the simulation model
 190 of the integrated UWS. The model used here is the WaterMet² model (Behzadian and Kapelan 2015b)
 191 which is described in more detail in the next section.

192

193 *WaterMet² simulation model*

194 WaterMet² is a mass-balanced-based simulation model which assesses the performance of integrated
195 UWS over a specified planning horizon (Behzadian and Kapelan 2015a). The WaterMet² model with
196 daily time step tracks down different flows and fluxes (e.g. water, energy, greenhouse gas emissions and
197 materials) within an integrated UWS. WaterMet² adopts a simplified but distributed approach for
198 conceptual modelling of the main physical UWS components in the main infrastructures of water supply
199 and wastewater including separate/combined sewer networks. WaterMet² inherited the mass-balanced
200 and distributed modelling approach from some tools such as *UVQ* (Mitchell and Diaper, 2010) and
201 *UWOT* (Makropoulos et al., 2008) and combined it with industrial ecology based modelling approach
202 from *DMM* (Venkatesh et al. 2015). All this has led WaterMet² to be made up of an arbitrary number of
203 conveyance and storage components which are connected to each other through the sub-catchments (Fig.
204 2).

205

206 The main consecutive components of the water supply infrastructure modelled in WaterMet² are water
207 resources, water supply conduits, Water Treatment Works (WTW), trunk mains, service reservoirs and
208 distribution mains. Sewer networks and Wastewater Treatment Works (WWTW) are also two
209 components which constitute the wastewater infrastructure. All these components are also connected
210 with water sources (i.e. water inflows and rainfalls) and sinks (i.e. receiving water bodies) that form the
211 water boundaries. The clean water, transported by the water supply infrastructure, is converted into
212 sanitary sewage by water demand profiles in the WaterMet² sub-catchments and then collected by the
213 wastewater infrastructure. The water demand profiles cover six types of indoor (household) appliances
214 and fittings (i.e. kitchen sink, hand basin, washing machine, shower, toilet and dish washer) plus
215 commercial and other outdoor demands including frost tapping and household irrigation (e.g. garden
216 watering). WaterMet² also simulates rainfall-runoff modelling and the overland runoff collected by the
217 wastewater infrastructure. All this enables WaterMet² to simulate rainwater harvesting potential which
218 is used for water demand profiles in sub-catchments. Each WaterMet² sub-catchment comprises a group
219 of neighbouring local areas which cover water demands profiles and total surface area for rainfall-runoff
220 modelling. As a result of the daily simulation of all UWS components, WaterMet² is able to calculate
221 daily water supplied from different sources (e.g. water mains and RWH tanks) as well as excess

222 stormwater overflowed (i.e. flood) in wastewater infrastructures as defined in Eq. (4) over a specified
223 time horizon. Further details of WaterMet² modelling processes and assumptions can be found in
224 Behzadian and Kapelan (2015a).

225

226 **Fig. 2** Main UWS components of WaterMet² including RWH tank
227

228 **Case Study**

229 The suggested methodology is validated and demonstrated on a real-world UWS of a northern European
230 city which was taken from Venkatesh et al. (2015) and Behzadian and Kapelan (2015a, 2015b). Based
231 on the world map of The Köppen Climate Classification (Peel et al. 2007), the case study is located under
232 "Dfb" climate (warm summer humid continental climate). The WaterMet² model is calibrated by using
233 a manual, trial and error approach for historical daily measurements in both water and wastewater
234 production. This approach is used here as it can lead to reasonably good prediction accuracy and has
235 been successfully employed in similar models such as UVQ (Mitchell and Diaper 2010). The calibrated
236 WaterMet² model of the real-world UWS is used here to examine the capabilities of the smart RWH. The
237 real-world case study is an integrated UWS which contains both subsystems of water supply and
238 wastewater including combined sewer networks. More specifically, the water supply subsystem
239 comprises two existing water resources, each connected to one WTW and then the distribution mains.
240 The wastewater subsystem is characterised by a largely combined sewer network feeding two WWTWs.
241 A single WaterMet² subcatchment with two associated local areas, one with RWH and the other without
242 RWH, is used to define water consumption and rainfall-runoff modelling. The main input data for
243 modelling runoff and water demands at local area and household scales are given in Table 1. All water
244 demand categories except household irrigation and frost tapping are necessary during the whole year.
245 Household irrigation (i.e. garden) is carried out between mid-May and the end of August (4.5 months)
246 while frost tapping (water flowing through the main pipelines to prevent freezing) is required from
247 November until the end of March (5 months). The rainfall-runoff modelling and evaporation are
248 calculated in WaterMet² based on the Rational Method and the Preferred method, respectively (Maidment
249 1992). The above integrated UWS is simulated in WaterMet² with a daily time step over one year to
250 identify the optimal operational parameters of the smart RWH. Based on the recommendations of
251 conventional designs, the storage capacity of each household RWH tank is assumed to be predefined at
252 3 m³ (Behzadian and Kapelan 2015b). This tank size is calculated based on the specifications of

253 households and climate in the case study given in Table 1 and recommendations made by BSI (2013)
254 and Ward et al. (2012). A single RWH scheme is used to represent many small domestic RWH units
255 across the city. The key characteristics of the UWS and the model calibration procedure can be found in
256 Behzadian and Kapelan (2015b).

257

258 **Table 1** Input data related to water demands and runoff modelling

259

260 **Results and discussion**

261 The above methodology is first applied and discussed on the case study for four constant tank capacities
262 (i.e. sizes) in proportion to the full-size of the RWH storage capacity, i.e. 3m^3 for each household (see
263 the above section), separately. Thus, the total sum of the tank capacities analysed here for all households
264 with RWH are: 1) 12.5% of full capacity, i.e. 0.06 million cubic metres (MCM) (equal to
265 $0.125 \times 3\text{m}^3 \times 160,000$ households); 2) 25% of full capacity, i.e. 0.12 MCM; 3) 50% of full capacity i.e.
266 0.24 MCM and 4) full (100%) capacity i.e. 0.48 MCM. The objective here is to analyse the long-term
267 performance of the smart RWH for different tank capacities and levels of tank releases and then compare
268 all this with conventional RWH. It is assumed that the RWH tank collects runoff from impermeable
269 surfaces (i.e. roofs, roads and pavements) and supplies to flushing toilet and household (i.e. garden)
270 irrigation only.

271

272 The NSGA-II parameters, used for all multi-objective optimisation models, are obtained after a limited
273 number of trial runs and are as follows: population size of 84, tournament selection, random-by-gene
274 mutation with the probability of 0.0417 (equal to the inverse of the number of genes, i.e. $1/24$), single
275 point crossover with the probability of 0.9. The stopping criterion of the algorithm is mainly dominated
276 by the number of generations which is set to 1,000 for each optimisation run.

277

278 Fig. 3 illustrates the Pareto fronts (PFs) obtained by the two-objective optimisation models for the
279 analysed tank capacities. Each PF, representing one specific tank size, shows the trade-off between the
280 two conflicting objectives of the RWH tank (i.e. reduction of potable water use versus attenuation of
281 urban flood). Each PF provides decision makers with a set of non-dominated optimal solutions (i.e. there
282 is no solution in which both objectives are better than other solutions). The following can be noted from
283 the figure: (1) The optimal solution with the minimum local flood attenuation and maximum reduction

284 of potable water supply from the mains on each PF, i.e. the most left hand side point (e.g. point A),
285 represents the performance of the UWS with conventional RWH. This performance is due to the fact that
286 the harvested rainwater is not released from the tank according to Eq. (1), i.e. operational parameter a is
287 zero for all months (not shown here); (2) On the other hands, the optimal solution with the maximum
288 local flood attenuation on each PF (e.g. point C) shows the performance of the UWS with smart RWH;
289 (3) This trend (i.e. from conventional to smart RWH) can also show the impact of smart technologies on
290 the improved flood attenuation while compromising potable water supply in the four different tank sizes.
291 For instance, flood attenuation for the smallest storage capacity (i.e. 0.06 MCM) is only 2.3% (i.e. from
292 91.3% to 89.0%) whereas volumetric flood attenuation for larger RWH capacities (i.e. 0.24 and 0.48
293 MCM) is considerably larger, approximately 7%. This can be attributed to the increased flexibility of
294 larger capacities which cover both a higher number of floods and larger flood events; (4) Each PF shows
295 that the larger the release of water from the smart RWH tank, further local flood mitigation can be
296 expected although the less potential of the harvested rainwater can also occur. The generated PFs can be
297 useful for stakeholders in a case study and help them make more informed decisions based on their
298 preferences to the objectives of RWH; (5) Finally note that the improved RWH performance with
299 increased tank size (for both objectives) which is demonstrated by the fact that PF for larger tanks are
300 closer to the ideal point (0,0). This will be analysed and discussed further in the next section.

301

302 **Fig. 3** Pareto optimal solutions for different tank sizes of the smart RWH

303

304 The performance of the UWS with smart RWH can be further explored in the time analysis of the RWH
305 tank over the analysed period. Hence, the monthly average performance of the RWH tank for the three
306 solutions of A, B and C in the PF associated with the total storage capacity of 0.24 MCM (Fig. 3) are
307 analysed here as shown in Fig. 4(b)-(d). Fig. 4(a) also shows the stormwater runoff after deducing
308 evaporation, infiltration and depressions of permeable and impermeable surfaces for each local area.
309 These solutions represent the performance of three types of RWH including a maximum water supply
310 from RWH (i.e. solution A as conventional RWH), smart RWH with maximum flood reduction (solution
311 C) and finally solution B which compromises the above two objectives. When comparing the overall
312 performance of conventional and smart RWH in Fig. 4, three time periods (months 3-4, 5-7 and 9-11)
313 can be distinguished based on the stormwater runoff in Fig. 4a and water demand from RWH (i.e. toilet
314 flushing and household irrigation). Note that the daily water demand of toilet flushing, which is required

315 all over the year, accounts for about 40% of the total water demand from the RWH tank while the
316 remaining 60% is needed for household irrigation which is required only between months 4.5 and 8. In
317 the first time period (months 3-4) with a relatively high rainfall (Fig. 4a) but a low water demand from
318 the RWH tank (i.e. about 40% of the total demand), the tank volume and inflow into conventional RWH
319 (i.e. solution A) are relatively high and thus the average overflow is high (due to the aforementioned low
320 water demand). However, the smart RWH (e.g. solution C) keeps the most of the tank volume empty,
321 i.e. an average 88% of storage capacity is free as shown in Fig. 4b, in order to attenuate more flood and
322 therefore the average overflow in this solution is trivial. In the second period (months 5-7) which is
323 characterised as being both high rainfall and high water demand, the performance of all RWH types are
324 quite similar. However, in the third time period (months 9-11) characterised by high rainfall in Fig. 4a
325 and low water demand (i.e. again about 40% of the total demand), the smart RWH keeps storing small
326 water volumes to increase the spare storage for capturing larger inflows. As a result, the tank overflow
327 in this scheme is considerably smaller compared to much larger overflows in the conventional RWH.
328 Note that in all of the above time periods, the performance of solution B lies between solution A and C,
329 i.e. represents a compromise of these two solutions.

330

331 **Fig. 4** Monthly aggregated results of three solutions for (a) stormwater runoff in each local area; (b)
332 average RWH volume; (c) average RWH overflow and (d) average RWH inflow
333

334 The above results discussed so far shows the performance of the suggested method only for specified
335 values of design parameters in RWH such as tank storage size and fixed collection surface areas (see the
336 case study section). Therefore, determination of the most efficient design parameters of RWH to achieve
337 the best performance of the suggested smart technologies is explored below.

338

339 *Optimal design parameters of smart RWH schemes*

340 The above results only consider the optimal operational parameters of smart RWH. This section considers
341 analysing the combined optimal operational and design parameters of smart RWH simultaneously for
342 local flood mitigation in the integrated UWS. The design parameters analysed here are storage tank size
343 and collection surface area which are explicitly considered as new objective functions. To that end, two
344 new two-objective optimisation models similar to those presented above are first analysed with new first
345 objectives instead of the objective in Eq. (2) (i.e. percent of potable water supplied from the mains). This

346 replacement is due to the fact that the objectives in Eqs. (2) and (3) are indirectly correlated and only the
347 second objective (i.e. percent of total excess stormwater) can implicitly consider the other one.

348

349 In the first two-objective optimisation model, the new first objective is to minimise the storage capacity
350 of the RWH tank. The model also assumes the collection surface for harvesting rainwater include all
351 impermeable surfaces (i.e. roof, pavement and road). The first two-objective optimisation model results
352 in the PF of the optimal solutions for the smart RWH as shown in Fig. 5. The performance of local flood
353 mitigation in the conventional RWH for the corresponding tank capacities is also simulated in the UWS
354 and shown in the same figure. As it can be seen from the figure, the best conventional RWH solution that
355 leads to the maximum flood mitigation (i.e. approximately 85% of total excess stormwater) needs to have
356 at least 0.22 MCM storage capacity (around 46% of full-size tank capacity of conventional design) while
357 a smart RWH scheme with 0.09 MCM storage capacity (19% of full-size tank capacity of conventional
358 design) can provide the similar level of flood mitigation. This corroborates the advantage of the active
359 (i.e. smart) RWH scheme that design storage capacities of smart RWH are generally smaller than those
360 of passive (i.e. conventional) one (BSI 2013). In addition, the similar performance of flood reduction for
361 both smart and conventional RWH for the tank sizes smaller than 0.05 MCM (equivalent to around 10%
362 of full-size tank capacity of conventional design) indicates that there is no sensible point to develop the
363 suggested smart method for small tank RWH capacities. This can be likely attributed to the very low
364 ratio of runoff yield (due to the small storage capacity) to the water demand, which empties the storage
365 volume very quickly. On the other hand, for the tank sizes greater than 0.05 MCM, there is an increasing
366 trend for the improvement of the flood reduction performance with the smart RWH relative to the
367 conventional RWH. This improvement gradually becomes significant with a maximum of 7.4% for the
368 storage capacity of about 0.24 MCM from which point the difference of the two approaches for larger-
369 sized tanks is slightly similar. This can be indicative of the full potential of flood reduction when using
370 smart approach in RWH and also provides the best tank size which leads to the maximum local flood
371 mitigation.

372

373 **Fig. 5** Impact of the storage capacity of the RWH tank on flood mitigation in the UWS

374

375 In the second two-objective optimisation model, the first objective is defined as to minimise percentage
376 of the collection surface for harvesting rainwater in the second optimisation model. It assumes that both

377 permeable and impermeable surfaces are considered for harvesting rainwater in the second optimisation
378 model. Collection of rainwater from permeable surfaces assumes that they are converted to impermeable
379 surfaces and hence the infiltration rate, i.e. 30%, would reduce to only 5% to account water detention
380 related to the runoff coefficient of impermeable surfaces according to the surface properties in Table 1.
381 The storage capacity of the RWH tank in the second model is constant and equal to 0.24 MCM.

382

383 Fig. 6 shows the PF of the optimal solutions in the smart RWH as a result of the second two-objective
384 optimisation model to address the influence of the collection surface area. Similarly, the performance of
385 the local flood mitigation with the conventional RWH for the corresponding surface areas of harvesting
386 rainwater is also shown in the figure. Similar to the sensitivity analysis of the storage capacity, there is
387 no benefit of applying smart RWH for small surface areas for harvesting rainwater (i.e. about 10% of the
388 total surface areas). This can also be due to the fact that small surface areas for harvesting rainwater
389 would result in the small ratio of the small average runoff yield to the large non-potable water demand
390 from the harvested rainwater. This also corroborates the BSI (2013) that recommends for the small above
391 ratio, the pre-emptying process happens relatively rare which is in fact the opposite to the basic function
392 of the smart RWH. In addition, as it can be seen from Fig. 6, enlarging the area for harvesting rainwater
393 in the smart RWH can have a substantial impact on local flood mitigation as the RWH tank can affect
394 larger surface areas and hence more floods can be prevented or mitigated. As the percentage of the total
395 impermeable surface areas in the case study is 16% (see Table 1), those percentages greater than this in
396 the figure need the inclusion of permeable surface area for harvesting rainwater. As this assumes that
397 those included permeable surface areas are converted to impermeable surface areas, this results in the
398 increase of runoff as it reduces the water loss due to the infiltration rate of smaller permeable surface
399 area. The resultant impact of combining this conversion with larger surface areas for harvesting rainwater
400 is negative for the conventional RWH (i.e. increasing flood) while the performance of flood reduction
401 with the smart RWH have been improved even more for those percentages of surface areas.

402

403 **Fig. 6** Impact of percentage of the total surface area for harvesting rainwater on local flood mitigation
404

405 A combination of the design parameters analysed above can be envisaged in a three-objective
406 optimisation model (i.e. objectives of flood reduction, storage capacity and surface area for harvesting
407 rainwater) which is analysed here. Fig. 7 shows the result of this three-objective optimisation model as a

408 PF of the optimal solutions for smart RWH and the concurrent impact of both design parameters (storage
409 capacity and percentage of the total surface area for RWH) on flood mitigation. Similarly, the
410 performance of conventional RWH for the corresponding design parameters is also shown in the figure.
411 As can be seen, the larger tank capacities and the surface area for harvesting rainwater would result in
412 substantial mitigation of local floods in the smart RWH (maximum to the level of about 32%) whereas
413 the conventional RWH can only decline the UWS flood to about 77% among all values defined for these
414 parameters. Provision of such a three-objective PF can be very useful specifically for long-term planning
415 of both smart and conventional RWH. Apart from these two design parameters, other parameters such as
416 precipitation and various water demands (Rozos et al. 2010, Imteaz et al. 2011) may have a substantially
417 influence on the main performance indicators (e.g. water supply reliability and flood peak attenuation)
418 of the UWS.

419

420 **Fig. 7** Three-objective PF for the impact of both design parameters of storage capacity and percentage
421 of the total surface area for harvesting rainwater
422

423 The smart RWH analysed here is mainly based on the second approach suggested by BS8515 (BSI 2013)
424 i.e. the control of water level using the operational policy as defined in Eq. (1). According to this policy,
425 the amount of water released from the tank is specified based on what is currently stored and current
426 inflow in different months. However, it should also be based on what is likely to arrive soon (i.e. future
427 rainfall/inflow) as suggested in the first approach of the British Standard (BSI 2013). The impact of the
428 rainfall forecasting on operation of smart RWH can be quite significant in cases that there is no rainfall
429 forecasted in the near future and even though the tank is fairly full, the water can supply non-potable
430 water demands only, i.e. not release any extra water. On the other hand, if weather forecast shows a lot
431 of rainfall will happen soon, the policy orders to release all of the stored water even though the tank is
432 fairly full. The analysed smart RWH here strive to highlight the primary advantages of water level control
433 but this cannot overcome the need to forecast rainfall. Therefore, integration of the suggested operational
434 policy with a rainfall forecast module in smart RWH schemes needs to be further investigated in the
435 future researches.

436

437 Furthermore, climatic conditions can be a determining factor to identify the effectiveness of key
438 performance indicators (KPI) in smart RWH schemes. The impact of this factor on KPIs has been

439 analysed for conventional RWH schemes in previous research works (e.g. design robustness of RWH
440 schemes by Rozos et al. 2010). The climatic conditions analysed in this paper is humid continental
441 climate with an annual average rainfall of 803 mm. Hence, all the findings obtained in the results can
442 only be considered for similar climatic conditions. For climates with more annual rainfall (e.g. equatorial
443 regions), the smart RWH can be even more effective than the analysis conducted in here due to larger
444 potential for flood peak attenuation. On the other hand, this effectiveness may decline for regions with
445 less annual rainfall (e.g. semi-arid regions) due mainly to the reasons explained for small tank capacities
446 in Fig. 5 and small surface areas of harvesting rainwater in Fig. 6. However, further investigation may
447 be required to analyse different climatic conditions for smart RWH and obtain compelling evidence for
448 this statement.

449

450 **Conclusions**

451 The new methodology for smart RWH schemes was developed and analysed here and their impact on
452 the performance of an integrated UWS was explored. The smart RWH considered the optimal operational
453 policy of the tank to proactively control water tank level based on the current storage volume and inflow
454 in the analysed case study. The integrated UWS performance was evaluated by using the WaterMet²
455 model. Optimal design parameters of smart RWH (i.e. tank size and the surface area for rainwater
456 harvesting) were also identified and its performance in the integrated UWS was compared with
457 conventional RWH. As a result of the application of the proposed approach in the real-world UWS, the
458 following key findings can be concluded:

- 459 1. The proposed smart RWH methodology can provide optimal operation of the tank throughout
460 the year for variable rainfall and water consumption conditions. This is due to the fact that the
461 smart RWH tank operation can maximise the efficiency of storage usage during rainfall events
462 (resulting in improved local flood attenuation) whilst, at the same time, efficiently harvesting
463 rainwater to complement water supply from the mains.
- 464 2. Choosing optimal operational and design parameters for multi-purpose RWH is important for
465 both smart and conventional RWH schemes in order to achieve optimal performance of the
466 integrated UWS. The results obtained in the paper suggest that there is no meaningful difference
467 in the UWS performance between smart and conventional RWH schemes for small-sized tanks
468 (i.e. less than about 10% of full-size tank capacity of conventional design) and small surface

469 harvesting areas (i.e. less than about 10% of the total surface areas). Opposite of this, as the
470 RWH tanks and surface harvesting areas increase in size, substantial improvement in the UWS
471 performance with smart RWH schemes can be seen when compared to the conventional
472 alternative. This further emphasises the importance of choosing optimal operational/control and
473 design parameters of smart RWH schemes.

474 3. The Pareto fronts obtained for smart RWH schemes provide essential information regarding key
475 trade-offs involved between given competing objectives. These fronts could and should be used
476 by decision makers for the improved planning of UWS and ultimately assessing the potential of
477 RWH schemes against other water demand management (i.e. water saving) technologies and
478 other flood attenuation options (e.g. other types of sustainable drainage systems).

479

480 The analyses and subsequent results presented here represent only a first step in using smart RWH
481 schemes. Although there seems to be considerable potential for their application in integrated UWS,
482 further investigations are required to validate the effectiveness of smart technologies in RWH under
483 different climates and uncertain rainfall. Moreover, other parameters (e.g. prediction of precipitation and
484 various water demands) and technologies/modules (e.g. smart household irrigation and rainfall forecast)
485 should be included in future analyses of smart RWH.

486

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491 Readers interested to use WaterMet² software tool for research purposes may contact the authors.

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