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4 Urban rainwater harvesting systems: research, implementation and 5 future perspectives 6

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28 ABSTRACT

29 While the practice of rainwater harvesting (RWH) can be traced back millennia, the degree of its
30 modern implementation varies greatly across the world, often with systems that do not maximize
31 potential benefits. With a global focus, the pertinent practical, theoretical and social aspects of RWH
32 are reviewed in order to ascertain the state of the art. Avenues for future research are also identified.
33 A major finding is that the degree of RWH systems implementation and the technology selection are
34 strongly influenced by economic constraints and local regulations. Moreover, despite design protocols
35 having been set up in many countries, recommendations are still often organized only with the
36 objective of conserving water without considering other potential benefits associated with the
37 multiple-purpose nature of RWH. It is suggested that future work on RWH addresses three priority
38 challenges. Firstly, more empirical data on system operation is needed to allow improved modelling by
39 taking into account multiple objectives of RWH systems. Secondly, maintenance aspects and how they
40 may impact the quality of collected rainwater should be explored in the future as a way to increase
41 confidence on rainwater use. Finally, research should be devoted to the understanding of how
42 institutional and socio-political support can be best targeted to improve system efficacy and
43 community acceptance.

44
45
46 **Keywords:** Rainwater harvesting, stormwater management, sustainable urban water systems, water

47 conservation, water efficiency.

48 **1. Introduction**

49 Rainwater Harvesting (RWH) is probably the most ancient practice in use in the world to cope with
50 water supply needs. In recent decades, as a result of new technological possibilities, many countries
51 are supporting updated implementation of such practice to address the increase in water demand
52 pressures associated with climatic, environmental and societal changes (Amos et al., 2016).

53 In urban areas, RWH consists of the concentration, collection, storage and treatment of rainwater from
54 rooftops, terraces, courtyards, and other impervious building surfaces for on-site use. Civil uses of
55 collected rainwater are disparate (e.g. toilet flushing, laundry, garden irrigation, terrace cleaning, and
56 other sporadic out-door uses such as car washing), but all aim to reduce consumption of drinking
57 water from centrally supplied sources. GhaffarianHoseini et al. (2016) suggest these uses can globally
58 account for 80-90% of overall household water consumption, and highlight the significant water
59 conservation benefits associated with RWH implementation. Consequently, installation of RWH
60 systems increases water self-sufficiency of cities and can help delay the need to construct new
61 centralized water infrastructures (Steffen et al., 2012).

62 Water scarcity and need for water supply augmentation are not the only reasons that have motivated
63 municipalities to boost RWH system installation. In fact, consolidated scientific and grey literature of
64 the last twenty years shows that RWH belongs to the large family of detention-based Low Impact
65 Development (LID) or Sustainable Drainage System (SuDS) approaches and can be adopted as a
66 complementary measure to reduce frequency, peaks and volumes of urban runoff if systems are
67 appropriately designed. The increase of urban-catchment distributed detention by tank-based RWH
68 systems (and other at-source technologies) may reduce the impacts of urbanization growth on the
69 stormwater drainage system (Brodie, 2008; Burns et al., 2015) and possibly contribute to the
70 mitigation of environmental impacts on receiving water bodies (e.g. Hamel and Fletcher, 2014). For
71 example, studies from Australia show that the installation of rainwater tanks at the allotment scale
72 could return the rainfall-runoff response of the impervious roof close to pre-development levels
73 (Burns et al., 2012a) and reduce disturbance of the catchment water quality regimes (Burns et al.,

74 2012b). Multiple-usage demands ensure a relatively continuous use of the water, thereby maximizing
75 rainfall capture by creating room in the storage tank for upcoming rain events (Domènech and Saurí,
76 2011; Gardner and Vieritz, 2010). Incorporating demands that align with local rainfall patterns can
77 substantially increase the efficiency of the system in terms of both water conservation and stormwater
78 mitigation (Zhang et al., 2009).

79 When used in conjunction with infiltration-based solutions, excess overflow water from RWH systems
80 (that would otherwise generate street runoff or enter the storm sewer network) can be infiltrated
81 (often after preliminary treatment, as determined by national regulations) for groundwater recharge
82 (Dillon, 2005). Recent studies have shown that infiltration techniques coupled with RWH can also help
83 in modifying the urban microclimate by increasing moisture content and evapotranspiration (e.g.
84 Hamel et al., 2012), so mitigating the heat island phenomenon (Furumai, 2008; Coutts et al., 2012).

85 Environmental benefits concerning the reduction of emissions and the decreasing of consumed
86 resources with RWH system implementation have been explored in recent years (e.g. Angrill et al.,
87 2012). In this regard, the scientific literature shows that the selected use of rainwater in the building
88 and the type of implementation project (renovation or new construction) significantly affect the
89 economic viability of the system (Devkota et al., 2015; Morales-Pinzón et al., 2015).

90 The implications of RWH for energy consumption are currently contested. Parkes et al. (2010) suggest
91 that the water supplied by RWH systems typically requires greater operational energy to deliver than
92 the mains water it displaces. However, Ward et al. (2011) indicate that this is very much context
93 dependent and in fact technological innovation in pump design and in low- or no-energy RWH systems
94 makes this less of an issue going forward. Jiang et al. (2013), for example, found that RWH systems
95 may lead to a decrease of energy usage. Other projects are using harvested rainwater within houses
96 for thermal energy recovery and building cooling (An et al., 2015; Kollo and Laanearu, 2016).

97
98 The literature clearly shows that the range of applications of RWH systems in urbanized areas is very
99 large. However, the results and the perception of the extent of potential benefits are varied and
100 controversial. Additionally, methods for the evaluation of the overall efficiency of multi-objective (also

101 competing) RWH systems are still at an embryonic stage. In this light, a critical review of the state of
102 the art of application of RWH systems is carried out in this paper to clarify some key aspects that may
103 determine their successful implementation. The context addressed is that of systems in urban areas
104 already serviced by centralized water infrastructure. The paper is organized as follows. A focus on
105 types and complexities of implemented systems according to the different potential objectives of RWH
106 is firstly presented in section 2. Section 3 briefly explores the degree of application of RWH in the
107 world's continents highlighting experienced benefits and drawbacks. A review of results concerning
108 water quality aspects as well as treatment requirements of urban RWH is reported in section 4.
109 Advantages and limitations of approaches to model the RWH system behaviour and performance are
110 examined in section 5. Section 6 critically discusses financial feasibility of RWH installations while
111 section 7 explores social aspects as well as other non-technical issues associated with governmental
112 policies. Finally, section 8 explores research needs and future perspectives for the development of
113 RWH systems in urban environments.

114

115 **2. Characteristics of rainwater harvesting systems**

116 2.1. Conventional systems

117 Fig. 1 shows the configuration of a typical system for on-site RWH and the interaction of its main
118 components. Design configurations and installation protocols for RWH systems have been defined in
119 design guidance and implementation manuals across the globe (e.g. Deutsches Institut für Normung,
120 1989, Texas Water Development Board, 2005, Master Plumbers and Mechanical Services Association
121 of Australia, 2008; British Standards Institute, 2013). The core component of each RWH system is the
122 rainwater tank that allows implementation of the basic functions of storage and treatment of the
123 collected rainwater. Typically, the collection surface is the building rooftop, but other impervious
124 catchment surfaces (normally those closely associated with the building) can be connected to the tank.
125 During rain events, generated runoff is delivered to the tank via the collection system (usually a
126 system of gutters and downspouts) and temporarily stored in order to match demand for rainwater
127 for the building in-door and out-door uses. A separate piping network is usually required to connect

128 the rainwater tank to appliances and/or taps for rainwater use. One or more pumps are commonly
129 (but not exclusively) adopted to assure appropriate pressure head for the various uses.
130 Complementary devices for quality control are first flush diverters, debris screens, and filters.
131 Diverters separate and convey the more polluted part of the runoff volume to the sewer system, while
132 screens and filters are used to intercept solids (sediment, debris, leaves, etc.) and particulate matter to
133 prevent them from entering the tank (Abbasi and Abbasi, 2011).

134 A critical point of the design of domestic RWH systems is the type of tank to use for rainwater storage.
135 Although non-potable use is expected in the large majority of cases, the demand type plays an
136 important role in tank selection. The technology offers a range of tanks from above-ground “rain
137 barrels” (normally plastic or metal containers of a few cubic meters capacity) typically used for
138 irrigation purposes and runoff control in single-household residential buildings, to above- or below-
139 ground concrete cisterns (of larger size) oriented to multi-storey buildings and multi-purpose RWH
140 including large demanding in-door and out-door uses. Field experience has shown that, although high
141 capacity storage tanks may increase the benefits of RWH systems, limited space can often prevent
142 their installation (GhaffarianHoseini et al., 2016).

143

144 2.2. New systems

145 Innovation in system configuration is ongoing globally with systems ranging from fractioning of
146 storage by use of interrelated modular systems and collapsible tanks (Dao et al., 2009) to gutter-based
147 collection and storage (Hardie, 2010) or other high-level, low-energy systems (Melville-Shreeve et al.,
148 2016), each aiming to fit with the pressures of different contexts.

149

150 Recent projects have considered the incorporation of dual storage facilities into RWH system
151 installations (Brodie, 2008) with separate tank units designated for both stormwater detention and
152 retention storage objectives. The retention storage volume is designed to meet user demands and the
153 detention storage volume (normally comprising the top portion of the storage tank) serves as a
154 temporary holding space for runoff control. The two storage volumes may be connected by a small

155 orifice that allows the water in the detention portion to slowly drain out and leave space in the tank
156 prior to the next rain event (Gee and Hunt, 2016).

157 The need to address objectives that often mutually conflict (i.e. maximizing water saving, maximizing
158 empty tank volume for runoff control, minimizing costs, etc.) requires customizing RWH systems in
159 order to maximize their return on investment. More complex systems than illustrated in Fig. 1 can
160 incorporate the combined use of the RWH module with other system facilities (i.e. infiltration systems,
161 rain gardens, bio-retention cells, etc.). Such facilities can allow management of tank overflows, first
162 flush diversion or dual storage release (Herrmann and Schmida, 2000; Kim and Yoo, 2009).

163
164
165 **Fig. 1.** here
166

167
168 More advanced technological options and ICT can also be implemented by adding sensors to the tank
169 system equipment. Though increasing system complexity, such Supervisory Control And Data
170 Acquisition system (SCADA)-based devices can improve the automation and control of RWH systems
171 for optimal management of stored rainwater resources (Han and Mun, 2011; Gee and Hunt, 2016).

172

173 **3. Degree of application in various countries**

174 3.1. Africa

175 In addition to the use of harvested rainwater by communities/individuals in large cities, RWH in Africa
176 includes experience gained in small urban settlements where communal RWH systems have been
177 developed in areas which ordinarily would be considered rural.

178

179 Gould (1993) provides a comprehensive overview of RWH in Africa and the state of the art up until
180 1994. Whilst little has changed in the last 20 years, there is evidence of the continued and increasing
181 role of Non-Governmental Organisations (e.g. UNESCO, SIDA, UNEP), and research organisations in
182 promoting and supporting the use of RWH through a range of activities - typically focused,

183 understandably, on the poor. A number of studies (e.g. Handia et al., 2003; Fisher-Jeffes, 2015) have
184 shown that RWH could provide a substantial water source across the continent. Large survey projects
185 making use of GIS tools have shown opportunities for RWH in selected countries of Africa such as
186 Botswana, Ethiopia, Kenya, Malawi, Mozambique, Rwanda, Tanzania, Uganda, Zambia, and Zimbabwe
187 (Mati et al., 2006).

188

189 This has led to the spread of RWH across Africa, and the formation of Rainwater Harvesting
190 Associations in a number of countries. In many parts of the continent RWH is practised as a result of
191 economic rather than physical water scarcity – meaning there is adequate water available for use, but
192 a lack of infrastructure to store, treat and transport it to where it is needed. Furthermore, while
193 governments are generally supportive of RWH, it is evident that this support (from all sectors) is
194 overwhelmingly for rural and poor communities.

195

196 Small-scale communal RWH (i.e. where a pond/storage tank is used to collect runoff and provide
197 water for a number of households, or for a large public building) is probably the most diffused level of
198 application of RWH in Africa (e.g. Dobrowksy et al., 2014). Recently, commercial/industrial companies
199 have taken an interest in alternative water resources, including RWH, at industrial site scale for a
200 variety of end-uses including irrigation and cooling. Conversely, research has indicated that domestic
201 RWH is only economically viable for a minority in urban areas – with large roofs and high demand or
202 for isolated households without other water sources (Fisher-Jeffes, 2015).

203

204

205 3.2. Asia

206 RWH plays an important role in many Asian countries. For example, much work has been done in
207 Japan where, from the early 1980s, local governments started promoting the introduction of water
208 recycling systems as an effective mitigation countermeasure for large cities facing both water scarcity

209 and urban flood problems. Since then, RWH has been actively introduced in large public and private
210 buildings also thanks to the support by local municipalities promoting special finance programmes.

211

212 Fig. 2 shows the results of a survey providing the number of public facilities and office buildings using
213 RWH systems in Japan over the last four decades (MLIT, 2014); it indicates the number of RWH
214 systems increases significantly after the introduction of the governmental financial support, with 10
215 times more installations recorded at the end of 2012 as compared with 1990. However, significant
216 improvements are expected, given that rainwater usage (7,8 Mm³/year) was estimated to about 0.01%
217 of the water usage throughout the country.

218

219

220 **Fig. 2.** here

221

222

223 The detailed analysis of a sample of over 250 different RWH facilities at national level revealed a large
224 variety of installed tank systems. Almost 30% of the systems are installed in schools and university
225 buildings with tank sizes ranging between 8-1000 m³. Another 15% is installed in public offices with
226 maximum tank storage capacity of the tank of 1500 m³. Small-size RWH facilities placed in individual
227 houses (storage capacity less than 1m³) are wide-spread in Japan. Although statistical data on the use
228 of small tanks is not available nationwide, the Great East Japan Earthquake in March 2011 caused a
229 sudden rise in the number of households that installed tanks to store rainwater for emergency.

230

231 In recent decades, RWH is being revisited also in South Korea as an adaptation strategy for coping with
232 climate extremes, especially in highly developed urban areas. Emphasis is being given to large-scale
233 RWH projects (Han and Mun, 2011). Ongoing discussion in South Korea to support RWH concerns the
234 development of incentive tools/schemes to reimburse the energy saved from using rainwater in
235 private houses.

236

237 The low-cost implementation of RWH systems has also been supported in Thailand. The Thai
238 government embarked on an extensive national program for RWH, using jar tank systems of various
239 capacities (from 0.1 to 3 m³). These have been installed in many villages for drinking water purposes
240 and have been shown to provide sufficient harvested rainwater for household use during the dry
241 season, lasting up to six months (Wirojanagud and Vanvarothorn, 1990).

242

243 In the Gansu province, China, a demonstration project on RWH has been carried out with very positive
244 results in the recent decades (Gould et al., 2014). Up to the year 2000, the project has led to building
245 more than 2 million rainwater tanks with a total capacity of more than 73 million m³ supplying
246 drinking water for almost 2 million people and supplementary irrigation for more than 230,000 ha of
247 land. Based on these results, seventeen provinces have adopted RWH systems starting from the year
248 2001 and built more than 5.5 million tanks for drinking water and supplemental irrigation throughout
249 China.

250 In 2009, the Taiwan Water Resources Agency included RWH in the Taiwanese Water Law as
251 alternative source for domestic water supply. The new policy (MI, 2013) requires, for example, that all
252 new buildings with a total floor area larger than 10,000 m² must install domestic RWH equipment to
253 supply at least 5% of the total water required by the building.

254

255 3.3. Australia

256 Australia has one of the highest degrees of the implementation of RWH systems. According to the
257 results of a survey by the Australian Bureau of Statistics (ABS, 2015), about 1.7 million households had
258 fitted rainwater tanks to their households. These tanks provided approximately 156 GL of water –
259 approximately 8% of household water use - during 1 July 2013 to 30 June 2014 (one year period),
260 which is equivalent to AU\$507 million. As of March 2013, approximately 34% of Australian
261 households that could fit a rainwater tank had a tank as compared to 32% in 2010 and 24% in 2007.
262 The increase is attributed to water restrictions imposed by water authorities, rebates provided by
263 government authorities, favourable water regulations and water pricing factors (ABS, 2015).

264 Interestingly, out of all the households fitted with a rainwater tank, households outside of the state
265 capitals had the highest rate (44%) of implementing RWH compared to households in the state
266 capitals (only 28%). Across both rural and urban areas, around half of the RWH systems were
267 connected to indoor end-uses. Finally, the survey found that the biggest motivator to install a RWH
268 system was to save potable water (49% of the people fall in this category).

269

270 RWH seems to have been successfully implemented across Australia. For example, 77% of the
271 households did not have any problem with their RWH system in the 12 month period reported on in
272 the survey; though in general, pump malfunctioning was reported to be the most common problem
273 (41% of reported problems). The maintenance of RWH systems was undertaken by 58% of all the
274 tank owners, which typically included cleaning of roof gutters.

275

276 Field performance of RWH systems in reducing potable water demand in Australia was quantified in a
277 study by Burns et al. (2015). The study reports observed potable water reductions in the range of 10-
278 100% from continuous monitoring of twelve household-scale RWH installations. Not surprisingly, the
279 largest such reductions were associated with households featuring tanks connected to multiple indoor
280 demands (toilet flushing, cloth-washing, and hot water usage). Similar field experiments by Umapathi
281 et al. (2012) revealed potable water savings of 1-67% (mean equal to 31%) for 20 allotments in
282 Queensland and multiple in-door demands and external demand for garden watering.

283

284 Beyond the household scale, there is limited data on RWH system use in Australia. Experience shows
285 that RWH systems are also used in public areas for the irrigation of gardens and sporting ovals. Such
286 systems tend to be installed, operated and maintained by local government. The prevalence of these
287 more large-scale systems increased markedly in the 2000s because of severe water restrictions as a
288 consequence of extreme drought conditions that persisted in south-eastern Australia for around 10
289 years.

290

291 3.4. Europe

292 The status of implementation of RWH systems in European countries is varied. Several countries in
293 Western Europe use RWH systems to conserve municipal water supplies. In the UK, traditionally
294 people have collected and stored rainwater for household use (laundry, washing up and other cleaning
295 operations). However, modern RWH systems have only been introduced relatively recently. One of the
296 reasons is that suitable codes and standards for RWH (including BS 8515:2013 and BS 8595:2013)
297 have only relatively recently become available and anticipated incentives and adaption mechanisms
298 for charging for harvested rainwater have not been forthcoming from governing, regulatory or water
299 management organisations in the UK (Ward et al., 2014). Commercial-scale systems, such as those
300 installed in supermarkets, schools and office buildings, are currently more widespread due to their
301 greater financial viability than household-scales systems, though innovation in smaller systems may
302 see the latter increase in the future (Melville-Shreeve et al., 2016). The UK community for sustainable
303 drainage, 'Susdrain', has compiled an inventory of case studies ([http://www.susdrain.org/case-](http://www.susdrain.org/case-studies/)
304 [studies/](http://www.susdrain.org/case-studies/)).

305

306 Currently, Germany is a leader in promoting the widespread use of this technology for domestic use.
307 As a consequence of the promotion (by grants and subsidies) of household RWH at the local
308 government level (Schuetze, 2013), today almost one third of new buildings built in Germany are
309 equipped with a rainwater collection system. Due to serious industrial air pollution and strict
310 regulations regarding drinking water standards, household rainwater supplies are fundamentally
311 limited to non-potable uses focusing mainly on irrigation, toilet flushing, and laundry use. Spain has
312 undertaken a programme of incentives and subsidies for new buildings (Domènech and Saurí, 2011).
313 While, in the year 2008, France enacted a regulatory framework (De Gouvello et al., 2014) to
314 encourage the use of rainwater through tax credit (although this is now abolished). Technical
315 guidelines for RWH have also been issued in Italy (UNI, 2012). Since then, several communities
316 promote RWH as complementary technology to improve urban runoff control and irrigation of public
317 and private green spaces. The popularity of installing RWH systems is also increasing in other

318 countries such as Austria, Switzerland, Belgium and Denmark, with the potable water price being the
319 main driver (Godskesen et al., 2013; Ringelstein, 2015). A good example of RWH practices within
320 water sensitive and sustainable urban development is Hammarby Sjöstad in Stockholm, Sweden,
321 which incorporates RWH as well as street runoff collection (Iveroth et al., 2013).

322 3.5. Americas

323 The level of application of RWH in the Americas varies depending on the country, even state,
324 considered. More than 100,000 residential RWH systems are in use in the USA (Lye, 2002) in the form
325 of simple rain barrels for garden irrigation at the end of roof downspouts, or of complex large-scale
326 multiple end-use systems including potable use. Texas is probably the state with the highest level of
327 implementation. Harvested rainwater in Texas helps a number of water-scarce communities to reduce
328 the gap between supply and demand (Texas Water Development Board, 2005). The State of Texas
329 offers financial incentives for RWH systems exempting RWH equipment from sales tax. Cities of Austin
330 and San Antonio use local subsidy-based tools to encourage construction of RWH systems as a
331 measure to conserve water. Rainwater harvesting from roof surfaces is allowed also in other states
332 (e.g. Oregon, New Mexico) with strict requirements needed for the uses of rainwater. Thousands of
333 systems have been installed in these areas going from “do-it-yourself” rain cistern for watering food
334 gardens to tanks for fire suppression at the scale of community.

335

336 Research results from the field (Debusk et al., 2013) have been based on monitoring different RWH
337 systems in south-eastern U.S.A. Two of the systems monitored - which supplied water for flushing
338 animal kennels and the irrigation of greenhouses - reduced potable water demand by 100 and 61%
339 respectively. Conversely, Jones and Hunt (2010) showed minimal potable water reductions obtained
340 from three different RWH systems supplying rainwater for toilet flushing, irrigation and car washing.

341

342 The potential benefits of RWH in South America have been assessed, and pilots implemented, in a
343 number of places. For example, in 2001, the “One Million Cistern” RWH programme was launched in

344 Brazil. It aimed to benefit about two million people (more than 350,000 cisterns constructed) living in
345 semi-arid rural settlements with no source of potable water nearby (De Moraes and Rocha, 2013).
346 Gomes et al. (2012) assessed such a programme by surveying 623 beneficiaries. The survey
347 highlighted the main problems that prevented adequate functioning of the RWH units (e.g. the poor
348 quality of the roof, the small storage capacity of cisterns, and the absence of automatic devices for the
349 first flush diversion). In Brazil, Marcynuk et al. (2013) highlight that households with access to
350 rainwater from cisterns were associated with a minor risk of infections compared to households
351 supplied by other water sources – typically sources with no sanitary protection, including rivers,
352 springs and dams. However, there is still debate over the ways to incentivise and charge for the use of
353 RWH in Brazil (Ward et al., 2014).

354

355 In Central America, the Isla Urbana initiative in Mexico City has enabled the harvesting of 170 ML of
356 roof runoff to alleviate water scarcity and local flood problems (Isla Urbana, 2016). The initiative
357 allowed displacement of “pipas” (water trucks widely used to supply water to households) and is now
358 expected to be a boost for future development of specific regulations regarding RWH across Mexico.
359 Further, in the Bahamas, Bermuda, and other Caribbean islands, rainwater cisterns must be included
360 in all new constructions under governmental economical support. For instance, rebates of \$0.50 per
361 gallon of installed tank capacity are offered as an incentive by the Barbados Water Authority. In other
362 areas of South and Central America, RWH implementation is mainly at the stage of research/planning
363 evaluation (Waller et al., 2001; Lizárraga-Mendiola et al., 2015).

364

365 **4. Quality assessment of harvested rainwater**

366 4.1. Metals and nutrients

367 The quality of harvested rainwater depends largely upon the materials used to construct the RWH
368 system and the environment in which it is located (Lee et al., 2010). Despite rooftop surfaces being
369 comparatively cleaner than parking lots, sidewalks and other impervious surfaces, rooftop runoff can
370 contain substantial amounts of heavy metals and nutrients (Chang and Crowley, 1993; Hamdan, 2009).

371 Sources of pollutants in rooftop runoff include precipitation (i.e. wet deposition), atmospheric
372 deposition (i.e. dry deposition) and materials used in the construction of the roof (Abbasi and Abbasi,
373 2011).

374 One of the most prominent issues with the quality of the collected rainwater is the phenomenon of
375 acid rain, which can result in low pH levels in areas characterized by high vehicle traffic volumes, high-
376 density residential development and industry (Olem and Berthouex, 1989; Melidis et al., 2007). In
377 addition, numerous other pollutants have been measured in rainwater due to their presence in the
378 atmosphere. In East Texas, U.S.A., rainwater concentrations of copper (Cu) and zinc (Zn) exceeded
379 U.S.A. Environmental Protection Agency (USEPA) freshwater quality standards of 0.013mg/l and
380 0.12mg/l, respectively, due to industrial emissions from petroleum refining, petrochemical production
381 and forest products production (Chang et al., 2004). Elevated total suspended sediment (TSS)
382 concentrations in rainwater sampled by Adeniyi and Olabanji (2005) in Nigeria were most likely
383 caused by agricultural bush burning and dust mobilized by vehicle traffic. Constituents in collected
384 rainwater that have been linked to dry deposition include TSS, Pb (due industrial emissions), chloride
385 (Cl) (due to application of de-icing salts in the winter), Cu, nitrates (due to agricultural fertilizer
386 applications), nitrites, Zn, Al, Fe and Ca (Morrow et al., 2010; Mendez et al., 2011).

387 Wash off of the particulates that have accumulated on the roof surfaces since the prior precipitation
388 event is another important sources of constituents. The antecedent dry period plays a role in the
389 accumulated deposition and, thus, in the concentration of pollutants in runoff (Quek and Förster,
390 1993; Thomas and Greene, 1993; Förster, 1999). Yufen et al. (2008) reported an increase in total
391 nitrogen (TN) and total phosphorus (TP) concentrations as the number of preceding dry days without
392 precipitation increased. Numerous studies have also confirmed that roof runoff exhibits a first flush
393 effect in which the majority of the matter collected on a roof surface is washed off during the
394 beginning (1-2 mm of runoff) of a precipitation event (Quek and Förster, 1993; Yufen et al., 2008; Kus
395 et al., 2010a). Concentrations usually decrease as rainfall continues (e.g. Kus et al., 2010b).

396 In addition to wet and dry deposition, roofing materials can serve as a significant source of
397 contaminants in roof runoff (Melidis et al., 2007; Despins et al., 2009; Clark et al., 2008; Akoto et al.,

398 2011). Roof materials contribute dissolved and particulate matter to roof runoff due to weathering
399 processes and chemical and physical reactions occurring between the rainwater and the materials
400 (Zobrist et al., 2000). Several studies have shown that rough roofing surfaces, such as asphalt shingles,
401 trap and retain particles and pollutants more so than smooth materials and can have a detrimental
402 effect on harvested water quality (Bradford and Denich, 2007; Despins et al., 2009, Farreny et al.,
403 2011). Thus, materials that contain constituents prone to leaching, such as zinc or copper, should be
404 avoided in case of implementation of a RWH system (Bradford and Denich, 2007).

405 In addition to the roofing materials, gutters (i.e. drainage system) have been identified as major
406 contributors of heavy metals to roof runoff, especially Zn and Al (Förster, 1999; Lee et al., 2010).
407 Protective coatings are often applied to the outside of metal downspouts to protect the material from
408 corrosion; however, runoff water comes into contact with the unprotected inside. Applying protective
409 coatings to the inside of downspouts may be a way of preventing metal contamination of harvested
410 rainwater from gutters and downspouts (Ward et al., 2010).

411 Several studies have identified distribution piping as another significant contributor of contaminants
412 within RWH systems (Morrow et al., 2010; Martin et al., 2010). Simmons et al. (2001) also observed
413 higher concentrations of Cu in water that had passed through copper piping. Aging galvanized iron
414 piping could also contribute to elevated Fe concentrations in tap water (Martin et al., 2010). Ward et
415 al. (2010) suggest that the selection of plumbing materials be determined by the hardness of
416 rainwater in the given area to minimize the potential leaching of metals and the consequent
417 deterioration of harvested rainwater.

418

419 4.2. Microbial quality of rainwater

420 The microbial quality of harvested rainwater is an important factor affecting the possibilities of using
421 the water for both in-door and out-door purposes.

422 The microbial populations in collected and stored rainwater may exhibit substantial variations
423 between different locations (Table 1), depending on climatic conditions (e.g. wind speed and direction,
424 regime of rainfall events), existence of first-flush, and the type of wild life (e.g. birds, cats or foxes) that

425 may come in contact with the collection surface. While it is recognised that birds act as a major source
426 of pathogens, other sources include dry deposition (of particles large enough to carry
427 microorganisms) or by wet deposition (during rain events). Another factor that affects the microbial
428 quality of rainwater is the length of antecedent dryness. Most studies report that longer periods of
429 dry-weather are linked to higher microorganism levels due to increased deposited animal faeces on
430 the roof surface (e.g. Yaziz et al., 1989).

431

432

433 **Table 1** here

434

435

436 The design of the roof and the rainwater harvesting system, as well as material selection also appear
437 to affect the microbial quality. Literature indicates that inappropriate design and material selection
438 promote contributions from avian sources and inhibit cleaning activities, thus resulting in lower
439 microbial quality of harvested rainwater. The two most detected pathogens, as reported in a review by
440 Fewtrell and Kay (2007a, 2007b), were *Salmonella* spp. and *Campylobacter* spp. (Table 1). These
441 authors further report that many of the pathogens isolated from roof-harvested rainwater may not be
442 infective to humans. Albrechtsen (2002) investigated the microbial quality of rainwater collected in
443 seven Danish rainwater harvesting from roofs supplying water for toilet flushing. The study found that
444 the microbial quality of the water was similar to that of tap water used in the cistern, but in 44% of the
445 samples one or more pathogen specie was observed, meaning that untreated rainwater potentially
446 introduced pathogenic microorganisms into the households which would normally not be found in
447 toilets supplied with water from the distribution system.

448

449 4.3. Rainwater treatment

450 The storage tank provides an opportunity for water quality improvement due to increasing pH,
451 sedimentation of particulates and precipitation of heavy metals (Despins et al., 2009; Olem and
452 Berthouex, 1989).

453 Sedimentation plays a primary role in the reduction of contaminant loads within the tank, as
454 particulates settle out rather quickly once water enters the storage tank (Sung et al., 2010). In addition
455 to sedimentation, water quality improvement occurs via sorption and precipitation, especially when
456 pH is neutral or alkaline (Olem and Berthouex, 1989). These treatment processes are most likely the
457 cause of a generally better quality of stored water compared to roof runoff, and, in many cases, led to
458 compliance with potable water guidelines and standards (Ward et al., 2010; Sazakli et al., 2007).

459

460 The potential of water quality contamination throughout RWH systems necessitates the use of
461 different treatment options to produce water of suitable quality for potable and non-potable uses. As
462 discussed in section 2, potential treatment options for RWH systems include both pre-storage (debris
463 screens and filters and first-flush diversion) and post-storage measures (post-storage filtration,
464 clariflocculation and disinfection). The majority of studies on harvested rainwater quality
465 acknowledge that first-flush diversion can significantly improve the quality of collected rainwater and
466 recommend this as a staple in RWH system design (Abdulla and Al-Shareef, 2009; Despins et al., 2009).
467 Diverting the first flush can retard the build-up of particulates and sediments within storage tanks,
468 prevent odour and aesthetic problems (e.g. coloration, visible organic matter) and improve overall
469 water quality (Lee et al., 2010; Abbasi and Abbasi, 2011). It is also highly recommended as a method
470 for decreasing the concentrations of pesticides and other organic compounds that enter the storage
471 tank (Zhu et al., 2004). The diversion volume recommendation varies greatly. Some examples of
472 recommended first flush amounts provide from 40L per 80-90m² of rooftop (about 0.5 mm rainfall), to
473 200L per 100m² of rooftop (2 mm rainfall) (Abbasi and Abbasi, 2011).

474 Abbasi and Abbasi (2011) recommend the following three characteristics to maximize the
475 effectiveness of debris capture when employed by a RWH system: i) Filters should be easy to clean; ii)
476 Filters should not clog easily and clogging should be easy to detect and rectify; and iii) Filters should
477 not provide an entrance for additional contamination (e.g. corrodible materials, openings large enough
478 to allow animals to access the system. etc.). Recent low-cost technology in this specific field includes
479 new gravity-based self-cleaning filters for installation before the tank storage (Vieira et al., 2013).

480 Post-storage treatment can consist of in-line sediment filters on pumps, slow sand filtration, clari-
481 flocculation and/or disinfection. Particle filtration (sediment filters, sand filtration, other types of
482 filters), have been shown to remove particulates and heavy metals and improving turbidity (Despins
483 et al., 2009). Adding a flocculent such as alum or calcium hydroxide to the storage tank promotes
484 flocculation and settling of suspended fine particulate matter (Abbasi and Abbasi, 2011). Finally,
485 disinfection methods include bleaching powder, potassium permanganate, iodine, heat (boiling water),
486 chlorine, ultraviolet light and ozonation. A recent study from the UK by Ward et al. (2017) investigated
487 the use of a novel treatment train combining filtration, UV and ozonation in a compact point-of-use
488 device. Water quality monitoring across three international field trial locations demonstrated the
489 point-of-use (POU) device could successfully treat harvested rainwater to potable standard. Each of
490 these options has pros and cons to its use; however, disinfection is predominantly used to improve
491 microbiological quality of water. Various low-cost treatment options have also been proposed in water
492 scarce areas of developing countries. For example, treatment of rooftop rainwater by combination of
493 plant coagulant use (*Moringa stenopetala* seed), sand filter and boiling showed to reduce coliforms
494 and turbidity for potable water supply in Ethiopia (Taffere et al., 2016).

495 Although first flush diversion and pre-storage filtration can substantially improve the quality of water
496 stored in a rainwater harvesting system, frequent maintenance of these systems is just as important.
497 Numerous studies have found that regular maintenance improves water quality (Magyar et al., 2007;
498 Abdulla and Al-Shareef, 2009). Tasks that should be performed regularly include cleaning the
499 catchment surface, gutters and storage tank, cleaning filters, first flush diverters and debris screens,
500 and inspecting the system for possibly points of entry for mosquitoes and vermin (Kus et al., 2010b).

501

502 **5. Current trends in rainwater harvesting systems modelling**

503 Modelling tools and methodologies have been developed over the last 20 years to facilitate the
504 evaluation (and design) of RWH systems. Key studies have focussed on objectives associated with
505 matching water availability (e.g. rainfall) with water demand (Dixon et al., 1999; DeBusk and Hunt,
506 2014; Melville-Shreeve et al., 2016). As both rainfall and water demand are temporally variable, RWH

507 evaluation models are frequently used as a design tool to calculate the volume of storage required to
508 balance these inflows and outflows, such that the water demand is adequately met for a specific
509 building or location.

510

511 Tank design approaches include methods based on the use of empirical relationships (Ghisi, 2010;
512 Palla et al., 2011), stochastic analysis (Cowden et al., 2008; Basinger et al., 2010), and continuous mass
513 balance simulation of the tank inflow and outflow (Fewkes and Butler, 2000; Liaw and Tsai, 2004;
514 Campisano and Modica, 2012; Sample and Liu, 2014). Mass balance models combine simplicity of
515 application with appropriate description of rainfall and water demand dynamics at a variety of spatial
516 and temporal scales (Campisano and Modica, 2015; Melville-Shreeve et al., 2016) with the possibility
517 to account also for uncertainty (Mitchell, 2007; Lash et al., 2014). Typically RWH mass balance models
518 combine a set of interrelated modules which include the following:

- 519 1) a behavioural model, to represent rainwater demand (D). Demand can be taken from literature,
520 historic meter data or real-time metering data;
- 521 2) a rainwater (R) inflow model to represent available water. This is based on synthetic rainfall series
522 or rain gauge data. Temporal datasets range from minutes to months with spatial proximity ranging
523 from on-site rain gauges to regional averages;
- 524 3) a calculation module which enables tank mass balance simulations to be performed whilst
525 accounting for losses at each time step (such as roof runoff losses, first flush losses, filter losses, tank
526 overflows);
- 527 4) an output module which logs, summarises and presents data from each simulation.

528 The *rainwater demand model* represents user behaviour and this aspect is arguably the hardest aspect
529 to accurately quantify. Empirical datasets illustrate the stochastic nature (with high variability) of
530 water demands. Demand profiles can vary between seemingly identical households in similar
531 locations due to various socio-technical factors including varying work patterns, household
532 demographics and deployment of different water fittings (e.g. low-flush WCs). Behavioural model
533 tools have also been extended to include multiple concurrent demand patterns (e.g. toilet flushing,

534 garden irrigation, etc.) (Campisano and Lupia, 2017). However, RWH evaluators frequently need to fix
535 the demand as an average value (usually average daily or monthly values) to enable simulations to be
536 carried out (Parker and Wilby, 2012; Ward et al., 2012; Melville-Shreeve et al., 2016). Sensitivity
537 analyses are required where behavioural models are based on a limited or uncertain data (Fewkes and
538 Butler, 2000). High resolution demand data may be needed to assure accurate outputs (Campisano
539 and Modica, 2015) depending on the objective of the analysis.

540 The *rainwater inflow model* must also account for significant input variability, which can be overcome
541 somewhat by using low resolution (spatially and temporally) regional averages. Model output
542 accuracy can be improved by running simulations at higher frequencies (daily or sub-daily time steps),
543 especially where site specific rainfall datasets are available (Ward et al., 2012). The accuracy of the
544 results is also affected by the length of the available precipitation series. Although accuracy level is
545 case-sensitive (i.e. affected by the local precipitation regime), various studies (e.g. Liaw and Tsai, 2004;
546 Mitchell, 2007) agree that a 30-year long series should provide statistically reliable results. *Calculation*
547 *modules* make use of various mass balance simulation schemes. Basic modelling approaches of “yield
548 after spillage” (YAS) and “yield before spillage” (YBS) (Fewkes and Butler, 2000) have been used in
549 many models in the context of RWH. Research studies have been devoted to the selection of the
550 appropriate simulation time step to enable realistic representation of results of mass balances. Several
551 authors (e.g. Fewkes and Butler, 2000; Mitchell, 2007;) analysed water saving efficiency by modelling
552 a RWH system at a range of time intervals (hourly, daily and monthly) with the YAS and YBS operating
553 rules tested. General conclusions support the use of the YAS operating algorithm for design purposes
554 as it results in a more conservative estimate of water saving efficiency. With an increased focus on
555 stormwater control, there is now an opportunity to revisit this work to evaluate the most conservative
556 scenario under a dual purpose objective.

557 Water efficiency modelling approaches within RWH tools have been widely shown to give accurate
558 representations when daily time step intervals are used (e.g. Fewkes and Butler, 2000; Campisano et
559 al., 2013). However, RWH tools can be manipulated to use a wide range of time steps with selection
560 based on the resolution of data available. Recent work by Campisano and Modica (2015, 2016) has

561 further exemplified the opportunity for high resolution (sub-hourly time steps) data to drive accurate
562 simulations, with specific emphasis on stormwater retention.

563 A range of studies which provide further details of existing RWH evaluation tools is described in Table
564 2. The selection of the most appropriate modelling tool and the simulation parameters depends on the
565 objective of the analysis. Studies described in Table 2 suggest a trend towards increasing complexity
566 and detail within RWH models. For example, Zhang et al. (2010) and a recent development within
567 Campisano et al.'s (2012) tool enable stormwater management metrics to be generated. In addition,
568 research identifying RWH water saving efficiencies in a wide range of international settings continues
569 apace (Kim and Yoo, 2009; Ghisi and Schondermark, 2013; Karim et al., 2015; Unami et al., 2015).

570 In addition to satisfying local water demand, RWH is increasingly being considered as an option for
571 contributing to stormwater management. Consequently, RWH evaluation tools have been further
572 extended to enable stormwater management metrics to be evaluated (Kellagher and Maneiro Franco,
573 2007; Campisano and Modica, 2015; DeBusk et al., 2013). Gerolin et al. (2010) illustrated the ability of
574 single tank RWH systems to capture stormwater runoff during extreme storms, noting that this was
575 especially valid when $Q/D < 1.0$, where Q and D are the yearly tank inflow volume and rainwater
576 demand, respectively (see Fig. 1). Kellagher (2011) investigated these findings which contributed to
577 revised stormwater source control guidance (now integrated within the British Standard BS8515)
578 based on specifying oversized RWH tanks for properties where $Q/D < 0.95$. Jensen et al.,(2010) have
579 also shown that water saving and stormwater control are not conflicting objectives of RWH systems;
580 however, different tank sizes are usually needed to obtain the optimal benefit for each objective.

581

582 **Table 2** here

583

584

585 Melville-Shreeve et al. (2014) illustrated the opportunity for dual purpose “retention and throttle”
586 RWH systems to be designed and evaluated within proprietary drainage software. These findings
587 showed that RWH systems for UK houses could be developed that provide 95% of the user’s non-
588 potable water demand whilst also maintaining sufficient attenuation capacity to control stormwater
589 runoff during the 1 in 100 year design storm. Mugume et al. (2016) extended this work to show how

590 systems of this type can be deployed at a city scale to meet both stormwater and water efficiency
591 objectives.

592 Using life cycle analysis (LCA), Morales-Pinzón et al. (2015) have shown that the introduction of
593 environmental objectives (associated with emissions and the materials used) may impact significantly
594 on tank sizing, depending on the type of the building in which the RWH system is installed.

595

596 **6. Financial viability**

597 There have been many studies that assessed the financial viability of RWH systems. Many of these
598 studies make use of simple tools to match costs and benefits of system implementation. More recent
599 tools based on an analysis of the system life cycle (Ward et al., 2012; Neto et al., 2012; Loubet et al.,
600 2014; Morales-Pinzón et al., 2015) have also been used to assess benefits of RWH technologies
601 compared with alternative water supply strategies. Zhang et al. (2009) assessed the feasibility of RWH
602 in high-rise buildings in four capital cities in Australia and noted that Sydney has the shortest payback
603 period (about 10 years) followed by Perth, Darwin and Melbourne. Analysis by Rahman et al. (2010)
604 showed that payback in Sydney can be achieved for multi-storey buildings under some favourable
605 scenarios and conditions (e.g. a low discount rate and a large number of users). Imteaz et al. (2011)
606 showed that for large tanks connected to commercial roofs in Melbourne, the capital cost can be
607 recovered within 15 to 21 years depending on the tank size and future water price increase rate.
608 Various results have been obtained on the different level of viability of RWH systems with regard to
609 the system size. Domènech and Saurí (2011) examined the efficiency of a RWH system for two main
610 types of buildings (single and multi-family housing units) in Barcelona (Spain). They found that in
611 single-family households the payback period is in between 33 to 43 years depending on the tank size,
612 while for a multi-family building, it is larger than 60 years for a 20 m³ tank. Ghisi and Schondermark
613 (2013) found that domestic RWH in Santa Catarina State, Southern Brazil would be economically
614 feasible for most cases and generally the higher the rainwater demand, the higher the financial return.
615 In contrast, Roebuck et al. (2011) noted that domestic RWH systems in the UK are unlikely to deliver
616 any realistic payback period given the assumptions made at the time. Ward et al. (2012) estimated,

617 using empirical monitoring data, capital payback periods of between 6 and 11 years for a commercial-
618 scale office-based RWH system serving a building occupancy of 110 people.

619 It appears that a significant portion of researchers have found that RWH systems are not financially
620 viable, depending on scale (Kumar, 2004; Roebuck et al., 2011; Rahman et al., 2011). However, in
621 many cases, differences in the way maintenance and operational costs have been taken into account
622 (e.g. pump replacement, electricity bill and cleaning of roof catchment system) led to controversial
623 conclusions. For example, Ward et al. (2011) mentioned that using different evaluation methods can
624 determine differences up to 60% for energy consumption costs. Besides, most of the approaches
625 utilised are simplistic as they do not holistically assess all potential benefits achievable with RWH
626 systems. Indirect benefits such as savings due to delaying the upgrade of a major water infrastructure
627 (water supply, sewer or treatment facility) (Coombes and Kuczera, 2003) or improved control of
628 combined sewer overflows (Gwenzi and Nyamadzawo, 2014) are only two examples of benefits that
629 should be included for a more comprehensive and realistic analysis of the system return on
630 investment. Interestingly, Melville-Shreeve et al. (2014; 2016), using a Multiple Criteria Analysis,
631 demonstrated additional benefits of RWH such as energy savings and environmental benefits due to
632 reduced raw water abstraction, pumping, and water treatment. Other benefits may come from
633 increased agricultural efficiency in urban residential (food gardens) and rural contexts (Lupia and
634 Pulighe, 2015). Ngigi et al. (2005) found that a 50 m³ water tank for irrigation can increase the yield of
635 a 0.2 ha cropped land by 1000 kg/ha. Conversely, Fisher-Jeffes (2015) showed that implementing
636 RWH for water conservation and stormwater retention at the same time in a catchment would
637 negatively impact the economic viability of the system. Zhang et al. (2015) using Hedonic Price
638 Method showed that there is likely to be an increase in the real estate value of the homeowner's
639 property having a RWHS. Not least, hard water if replaced by rainwater (which is soft in nature) could
640 save washing costs (e.g. by reducing washing powder quantity) as noted by Morales-Pinzon et al.
641 (2014).

642

643 Water price is one of the main governing factors of financial analysis of RWH systems (Morales-Pinzon
644 et al., 2015). To calculate benefit-cost ratio and payback periods, future water price needs to be
645 predicted. In this regard, future water price is expected to rise at a much faster rate than the general
646 interest rate. For example, during 2013-14, New South Wales and Victoria States in Australia
647 experienced 27% and 24% increases in household water prices respectively (ABS, 2015). During this
648 period, the inflation rate in Australia was in the range of 2.25 to 3% (TE, 2016). It is predicted that
649 Melbourne's potable water price will increase by 100% within the next 5 years' time (Khastagir and
650 Jayasurya, 2011). The second most important element in the financial analysis of a RWH system is the
651 capital cost in relation to plumbing. For example, Amos et al. (2016) noted that plumbing cost may
652 make the RWH system financially non-viable.

653

654 Finally, financial viability of RWH should also take into account that mains water in most countries is
655 subsidized through direct and indirect measures (e.g. large capital funding of water supply reservoir
656 construction by government money). Consequently, analogous subsidy/rebate based measures should
657 be considered for appropriate comparative analysis with harvested rainwater, though approaches to
658 this vary internationally (Ward et al., 2014).

659

660 **7. Social acceptance, benefits, institutional support and community participation**

661 Historically, challenges to the social acceptance of RWH (and indeed wider water reuse) have focused
662 on water quality, risk perception and health risk, including the so-called 'yuck factor' (Fewtrell and
663 Kay, 2007b; Ward et al., 2010; Rozin et al., 2015), as well as financial viability (Roebuck et al., 2011).
664 As sections 4 and 6 of this paper highlight, knowledge to reduce the impact of these challenges has
665 been generated and for water quality at least, confidence built by recommendations to use risk
666 assessments and water safety plans (Gwenzi et al., 2015). Despite some households being resistant to
667 using rainwater indoors (Mankad et al., 2011), it is now acknowledged that RWH is an acceptable
668 source of non-potable water compared to other types of water reuse for non-potable purposes
669 (Dobrowksy et al., 2014; Egyir et al., 2016). The focus on acceptability and financial returns to date has

670 often detracted attention from wider challenges. These include evaluating social as well as financial
671 benefits to engender wider institutional support and reflexive analysis of the international RWH niche
672 to enable greater consideration of system efficacy and community participation, both of which will
673 enhance the hydrosocial contract and diffusion of RWH into wider society (Stenekes et al., 2006;
674 Getnet and MacAlister, 2012). Moving away from a rhetoric around perceptions and costs enables the
675 RWH sector to move towards a more positive and innovative space – where challenges are redefined
676 and responded to by policy-makers, businesses and communities.

677 678 7.1. Increasing institutional support through diverse benefit identification

679 As with approaches to water quality and quantity monitoring, government policy relating to and
680 institutional support for RWH is internationally variable. Brown and Keath (2008) assert (from an
681 Australian perspective) that facilitation of changes in practice can only occur if they are supported at
682 institutional and socio-political levels. For RWH in Australia, this would appear to be the case, as
683 growing water demand but restricted water availability catalysed State and Local Government funding
684 for RWH and, as a result, system penetration rates increased (White, 2011). As discussed in Section 3,
685 a similar shift has occurred in Japan after promotional supporting measures were introduced from the
686 early 1980s. The opposite case is demonstrated in the UK context by Parsons et al. (2010) who
687 highlight, through use of a questionnaire with house builders, that whilst knowledge about RWH has
688 increased, installation in practice, as well as institutional and regulatory gaps remain a challenge, as
689 does the lack of incentive schemes. The need to consider different charging mechanisms has been
690 highlighted, but to date no water service provider in England or Wales has adopted such a mechanism
691 (Ward et al., 2014).

692
693 Domènech and Saurí (2011) report that incentives coupled with complementary strategies are utilised
694 in Spain to stimulate installation, such as the introduction of local regulations (to mandate RWH in
695 new buildings) and partial subsidies (for new build and retrofit) requiring a voluntary contribution.
696 Consequently, it was hypothesized that citizens appreciating the benefits of RWH would be more likely

697 to invest and apply for a subsidy, rather than the wider public - though it was found that the citizens
698 that did install RWH with a subsidy would have done so without.

699

700 The case is similar in the U.S.A., though different states have variable policies towards RWH as already
701 discussed in Section 3. In Texas since 1993 six propositions or bills have passed through the legislative
702 process directly pertaining to, in support of and incentivising RWH (such as manuals, awards, tax
703 relief, exemptions, RWH committee establishment, state facilities directive, mandates and subsidies)
704 (Ward et al., 2014). In a sub-catchment-scale example from the state of Ohio, the US Environmental
705 Protection Agency implemented a novel reverse-auction incentive program to encourage citizens to
706 install rain barrels and rain gardens in the Shepherd Creek watershed, Cincinnati. Enthusiasm for
707 participation was generated by asking volunteers to bid and the lowest bidders would win and be
708 offered compensation at that level. 174 rain barrels and 85 rain gardens were installed in two
709 tranches, which were then subsequently monitored for hydrologic, water quality, ecological and end-
710 user parameters, the latter of which was used to better understand the practices of rain barrel owners
711 (Shuster et al., 2013).

712

713 In Brazil the regulatory situation is somewhere in the middle, with some states imposing an obligation
714 to include RWH in all new construction projects and others only imposing such a requirement if a roof
715 area exceeds a certain level. However, in some areas RWH is unpopular due to resistance from water
716 service providers citing lost revenue as their objection (Ward et al., 2014).

717

718 Inevitably different contexts require different approaches, but combinations of support actions are
719 arguably more likely to enhance success. For example 'smart regulation' has been trialled and
720 represents (for the German market) the interaction of three incentive schemes (water abstraction fees,
721 water supply and effluent fees and subsidies), rather than their implementation in isolation (Partzsch,
722 2009).

723

724 More recently, a range of methods, such as hedonic pricing and stated preference questionnaires, have
725 aimed to identify the social benefits RWH provides other than water savings, potential financial
726 savings and environmental kudos. Additional benefits may include feeling independent from the mains
727 water system, increasing property value and improving the life expectancy of local centralised
728 infrastructure (Zhang et al., 2015). However, further exploration of the applicability of other economic,
729 social-psychological and cultural methods is required to enable a more comprehensive identification
730 of other less tangible benefits. Highlighting these multiple benefits could represent a more
731 comprehensive approach to analysing the global status of RWH when combined with consideration of
732 the RWH niche as a whole, alongside technical relevance (system efficacy) and the extent to which
733 end-users are engaged in the RWH process. These aspects are considered in the next section.

734

735 7.2. Reflexive niche analysis to improve system efficacy and community participation

736 The application of a range of methods from outside the engineering toolkit, such as those previously
737 mentioned, provides a stepping stone for the novel application of other techniques such as social
738 network analysis (SNA). For example, to interrogate the UK RWH niche, Ward and Butler (2016) used
739 SNA to develop a RWH network interaction model by mapping RWH actors and their relationships.
740 The analysis showed that RWH infrastructure innovators were addressing challenges such as reducing
741 energy use/carbon emissions and improving stormwater control by increasing the technical efficacy of
742 their RWH products. This is in line with past research, such as that by White (2011) in the Australian
743 context and Ward et al. (2011) for the UK, which highlighted the physical compatibility of the RWH
744 with the household as a main issue for adoption suggesting a need for a broader portfolio of products
745 addressing system configuration and increased flexibility. This gap was addressed by Melville-Shreeve
746 et al. (2016) through a multi-criteria analysis of different system configurations representing a set of
747 nine novel typologies developed by RWH businesses to increase efficacy.

748

749 Despite these technical innovations, innovation in service and social innovation by RWH infrastructure
750 innovators and other organisations has been limited to date. This is beginning to change, however, as

751 the effect of daily water-using practices of individuals on water availability comes into focus. This is
752 particularly true in developing countries where issues of gender arise, as water collection and
753 management at the household level is often designated a female responsibility, whereas the
754 construction of RWH storage tanks (cisterns) and community-level management of water often
755 considered the domain of men (De Moraes and Rocha, 2013). By empowering women in the strategic
756 and physical construction of water management in Brazil (One Million Cisterns RWH programme),
757 they became both decision-makers and beneficiaries in relation to RWH (De Moraes and Rocha, 2013).
758 Adler et al. (2014) emphasizes that community participation and leadership are also essential for the
759 success of RWH programmes.

760

761 Three other social enterprise initiatives from across the globe include Mexico's Isla Urbana, India's
762 public-community-private-partnership scheme Aakash Ganga and the UK's emerging RainShare (Isla
763 Urbana, 2016; Sustainable Innovations, 2014). These initiatives support community participation in
764 RWH by facilitating the installation of RWH systems to collectively share roof runoff from nearby
765 houses. The households keep a proportion for their own use and the rest is channelled to a communal
766 storage tank for various end-uses such as crop irrigation or household use. Each project has
767 encountered a range of organisational and bureaucratic challenges to implementation. Some orientate
768 around the layers of involvement of different organisations and groups concerned and others to the
769 rigidity of institutional structures relating to existing infrastructure. Research into such issues that
770 continues the theme of the application of novel methods is certainly warranted.

771

772 **8. Lessons learned and future research challenges**

773 Uptake from field application and experience gained from results of research in the recent decades
774 have provided some important lessons as well as identifying some areas of future research that would
775 contribute to advance the field of RWH.

776 Rainwater harvesting shows potential (to a varying extent) for applicability as an alternative approach
777 to source water in cities across the world. In contrast to water-abundant developed countries, where

778 RWH is prevalently considered as a backup supply source (Cook et al. 2013), very often systems for
779 rainwater harvesting are a primary source of fresh water in several developing and drought-prone
780 developed countries. Constraints such as local regulations and costs of implementation and
781 maintenance play a key role in the system penetration rates and used technology in the various
782 continents.

783 Consolidated confidence about the effectiveness of design protocols and water quality risk deriving
784 from implementation of RWH systems has been achieved in recent decades. However, existing
785 recommendations and guidelines typically consider system design in the perspective of water
786 conservation/water saving objectives only, without taking into account a number of acknowledged
787 additional benefits potentially achievable with RWH implementation. Increased research efforts in this
788 direction are expected in the future in order to develop reliable multi-purpose model tools with
789 greater connectivity to real systems for improved evaluation of RWH system global performance.
790 Research challenges could aim at including stormwater management metrics in RWH evaluators and
791 at investigating interactions between RWH and the wider urban stormwater infrastructure. Although
792 there has been a substantial amount of research internationally focused on RWH at a site scale, results
793 concerning impacts at the regional scale in urban areas are very sparse. New approaches to focus on
794 how to best represent RWH at larger scales need to be tested in different countries with different
795 climatic conditions. Furthermore, more field data on RWH systems is required. There is a particular
796 need to dedicate additional efforts to the monitoring of available pilot installations in order to improve
797 quantification and types of rain water uses (sensu Umapathi et al., 2012). Evidence shows in fact that,
798 new collective/private uses compatible with rainwater quality (e.g. irrigation for urban agriculture,
799 fire suppression, infiltration for heat island mitigation, etc.) are quickly emerging with increased
800 pressure on the available urban water budget.

801 Technology selection and regular maintenance are factors of paramount importance for the correct
802 functioning and the success of these systems as they assure appropriate water quality and improve
803 safety perception by users. In future, modelling should take into account the maintenance aspects of
804 RWH systems as such impacts could impact the quality of collected rainwater and its use. Indeed,

805 research is required to better understand how tank maintenance can be encouraged. At the household
806 scale, Mankad et al. (2015) point to the use of information to empower tank owners to undertake
807 maintenance. Such information could take the form of pamphlets or be delivered through onsite
808 inspections, though further research into how building occupants actually live with RWH systems is
809 warranted in order to develop materials to best-engage end-users.

810 Financial viability of RWH systems seems far from being acceptable with payback periods still too high
811 to provide a suitable return on investment. However, actual financial models usually consider only
812 advantages in terms of drinking water conservation/saving, forgetting a number of non-secondary
813 benefits including system retention capability to reduce urban runoff. Consequently, future research is
814 expected to provide the streamlining of financial analysis of RWH systems including multiple
815 beneficial aspects under complex engineering, hydrological, economic and social settings. In this
816 context, a challenging task will be the development of approaches to quantify and include “soft” or less
817 tangible benefits such as amenity, placemaking, urban greening, urban cooling and the broad call for
818 water sensitive cities. Wider global environmental benefits or costs also need to be considered. It is
819 recognised that developments in technology and abundant uptake may reduce unit costs.

820 The development at a wider scale of RWH as sustainable approach for alternative water resource and
821 stormwater control requires improved support at institutional and socio-political levels aimed at
822 increasing incentive tools, awareness and societal acceptance.

823 In this sense, interdisciplinary research including socio-technical analysis to improve system efficacy
824 and community participation is required.

825

826 **9. Conclusions**

827 Based on the critical analysis developed in this paper, the following main conclusions may be drawn:

- 828 • Many existing RWH systems are focussed solely on the objective of conserving water without
829 considering other potential benefits associated with the multi-purpose nature of RWH.

- 830 • There is a lack of high quality datasets associated with the multiple objectives of RWH
831 including especially: water saving, stormwater management, energy consumption and
832 greenhouse gas emissions.
- 833 • There is a need for improved modelling of these multiple benefits.
- 834 • The role of satisfactory maintenance in system performance has been noted indicating the
835 need for further research into how system reliability can be improved leading to increased
836 system uptake.
- 837 • The financial evaluation of RWH shows widely varying results, mostly giving long payback
838 figures. Greater consideration needs to be given to developing new, low-cost systems,
839 especially for retrofit purposes.
- 840 • Incorporating multiple environmental benefits into the evaluation process, such as through
841 Life Cycle Analysis, can improve overall economic viability of RWH depending on the specific
842 context.
- 843 • The importance and influence of government policy and regulations has been highlighted,
844 indicating the need for further research on how institutional and socio-political support can be
845 best targeted to improve system efficacy and community acceptance.

846

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851

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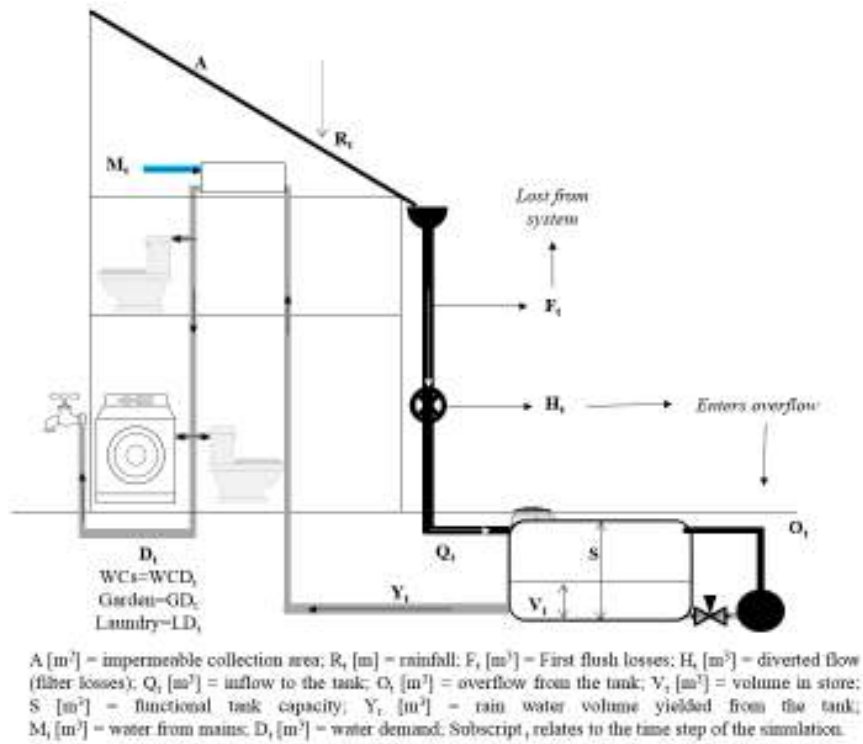
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Fig. 1. Components of a typical RWH system. Arrows indicate water fluxes (adapted from Melville-Shreeve et al., 2016).

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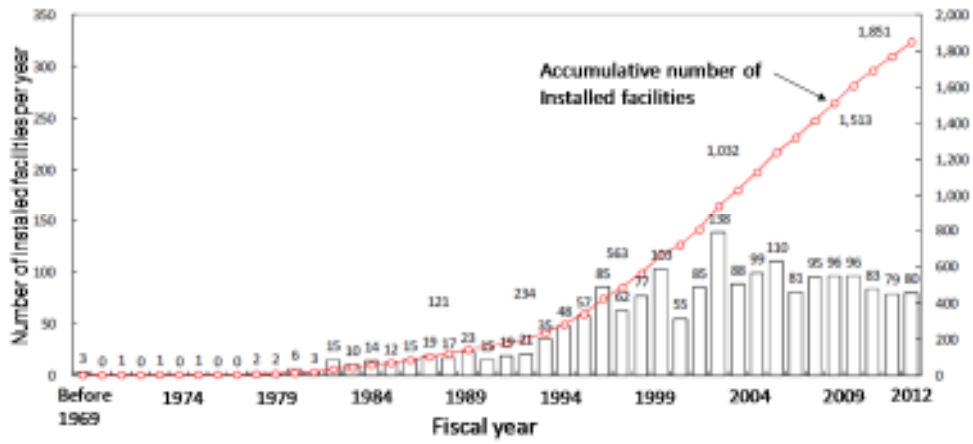


Fig. 2. Rainwater harvesting systems in public facilities and office buildings in Japan. An increasing trend is observed starting from early 1980s (adapted from MLIT, 2014)