This is the post-peer review final draft of a paper published in *Water Research*. The final publication is available at IWA Publishing http://www.iwaponline.com (DOI:10.1016/j.watres.2017.02.056)

Urban rainwater harvesting systems: research, implementation and future perspectives

Alberto Campisano [a*], David Butler [b], Sarah Ward [b], Matthew J. Burns [c], Eran Friedler [d], Kathy DeBusk [e], Lloyd N. Fisher-Jeffes [f], Enedir Ghisi [g], Ataur Rahman [h], Hiroaki Furumai [i], Mooyoung Han [j]

[a*] Department of Civil Engineering and Architecture, University of Catania, Viale A. Doria, 6, 95125, Catania, Italy, corresponding author, email: acampisa@dica.unict.it
[b] Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, EX4 4QF, UK
[c] Waterway Ecosystem Research Group, School of Ecosystem and Forest Sciences, University of Melbourne, Burnley, Australia
[d] Department of Environmental, Water & Agricultural Engineering, Faculty of Civil and Environmental Engineering, Technion–Israel Institute of Technology, Haifa 32000, Israel
[e] Biological and Agricultural Engineering, North Carolina State University, Campus Box 7625, Raleigh, NC 27695, USA
[f] Department of Civil Engineering, University of Cape Town, Private Bag X3, Rondebosch, South Africa
[g] Federal University of Santa Catarina, Department of Civil Engineering, Laboratory of Energy Efficiency in Buildings, Florianópoli, SC, Brazil
[h] School of Computing, Engineering and Mathematics, University of Western Sydney, Sydney, Australia
[i] Research Center for Water Environment Technology, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[j] Department of Civil and Environmental Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, South Korea

ABSTRACT

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

Keywords: Rainwater harvesting, stormwater management, sustainable urban water systems, water

conservation, water efficiency.

1. Introduction

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

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

Water scarcity and need for water supply augmentation are not the only reasons that have motivated municipalities to boost RWH system installation. In fact, consolidated scientific and grey literature of the last twenty years shows that RWH belongs to the large family of detention-based Low Impact Development (LID) or Sustainable Drainage System (SuDS) approaches and can be adopted as a complementary measure to reduce frequency, peaks and volumes of urban runoff if systems are appropriately designed. The increase of urban-catchment distributed detention by tank-based RWH systems (and other at-source technologies) may reduce the impacts of urbanization growth on the stormwater drainage system (Brodie, 2008; Burns et al., 2015) and possibly contribute to the mitigation of environmental impacts on receiving water bodies (e.g. Hamel and Fletcher, 2014). For example, studies from Australia show that the installation of rainwater tanks at the allotment scale could return the rainfall-runoff response of the impervious roof close to pre-development levels (Burns et al., 2012a) and reduce disturbance of the catchment water quality regimes (Burns et al., 2012b). Multiple-usage demands ensure a relatively continuous use of the water, thereby maximizing rainfall capture by creating room in the storage tank for upcoming rain events (Domènech and Saurí, 2011; Gardner and Vieritz, 2010). Incorporating demands that align with local rainfall patterns can substantially increase the efficiency of the system in terms of both water conservation and stormwater mitigation (Zhang et al., 2009).

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

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

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

The literature clearly shows that the range of applications of RWH systems in urbanized areas is very large. However, the results and the perception of the extent of potential benefits are varied and controversial. Additionally, methods for the evaluation of the overall efficiency of multi-objective (also competing) RWH systems are still at an embryonic stage. In this light, a critical review of the state of the art of application of RWH systems is carried out in this paper to clarify some key aspects that may determine their successful implementation. The context addressed is that of systems in urban areas already serviced by centralized water infrastructure. The paper is organized as follows. A focus on types and complexities of implemented systems according to the different potential objectives of RWH is firstly presented in section 2. Section 3 briefly explores the degree of application of RWH in the world's continents highlighting experienced benefits and drawbacks. A review of results concerning water quality aspects as well as treatment requirements of urban RWH is reported in section 4. Advantages and limitations of approaches to model the RWH system behaviour and performance are examined in section 5. Section 6 critically discusses financial feasibility of RWH installations while section 7 explores social aspects as well as other non-technical issues associated with governmental policies. Finally, section 8 explores research needs and future perspectives for the development of RWH systems in urban environments.

2. Characteristics of rainwater harvesting systems

2.1. Conventional systems

Fig. 1 shows the configuration of a typical system for on-site RWH and the interaction of its main components. Design configurations and installation protocols for RWH systems have been defined in design guidance and implementation manuals across the globe (e.g. Deutsches Institut für Normung, 1989, Texas Water Development Board, 2005, Master Plumbers and Mechanical Services Association of Australia, 2008; British Standards Institute, 2013). The core component of each RWH system is the rainwater tank that allows implementation of the basic functions of storage and treatment of the collected rainwater. Typically, the collection surface is the building rooftop, but other impervious catchment surfaces (normally those closely associated with the building) can be connected to the tank. During rain events, generated runoff is delivered to the tank via the collection system (usually a system of gutters and downspouts) and temporarily stored in order to match demand for rainwater for the building in-door and out-door uses. A separate piping network is usually required to connect the rainwater tank to appliances and/or taps for rainwater use. One or more pumps are commonly (but not exclusively) adopted to assure appropriate pressure head for the various uses. Complementary devices for quality control are first flush diverters, debris screens, and filters. Diverters separate and convey the more polluted part of the runoff volume to the sewer system, while screens and filters are used to intercept solids (sediment, debris, leaves, etc.) and particulate matter to prevent them from entering the tank (Abbasi and Abbasi, 2011).

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

2.2. New systems

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

Recent projects have considered the incorporation of dual storage facilities into RWH system installations (Brodie, 2008) with separate tank units designated for both stormwater detention and retention storage objectives. The retention storage volume is designed to meet user demands and the detention storage volume (normally comprising the top portion of the storage tank) serves as a temporary holding space for runoff control. The two storage volumes may be connected by a small orifice that allows the water in the detention portion to slowly drain out and leave space in the tank prior to the next rain event (Gee and Hunt, 2016).

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

Fig. 1. here

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

3. Degree of application in various countries

3.1. Africa

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

Gould (1993) provides a comprehensive overview of RWH in Africa and the state of the art up until 1994. Whilst little has changed in the last 20 years, there is evidence of the continued and increasing role of Non-Governmental Organisations (e.g. UNESCO, SIDA, UNEP), and research organisations in promoting and supporting the use of RWH through a range of activities - typically focused, understandably, on the poor. A number of studies (e.g. Handia et al., 2003; Fisher-Jeffes, 2015) have shown that RWH could provide a substantial water source across the continent. Large survey projects making use of GIS tools have shown opportunities for RWH in selected countries of Africa such as Botswana, Ethiopia, Kenya, Malawi, Mozambique, Rwanda, Tanzania, Uganda, Zambia, and Zimbabwe (Mati et al., 2006).

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

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

3.2. Asia

RWH plays an important role in many Asian countries. For example, much work has been done in Japan where, from the early 1980s, local governments started promoting the introduction of water recycling systems as an effective mitigation countermeasure for large cities facing both water scarcity and urban flood problems. Since then, RWH has been actively introduced in large public and private buildings also thanks to the support by local municipalities promoting special finance programmes.

Fig. 2 shows the results of a survey providing the number of public facilities and office buildings using RWH systems in Japan over the last four decades (MLIT, 2014); it indicates the number of RWH systems increases significantly after the introduction of the governmental financial support, with 10 times more installations recorded at the end of 2012 as compared with 1990. However, significant improvements are expected, given that rainwater usage (7,8 Mm^3/year) was estimated to about 0.01% of the water usage throughout the country.

Fig. 2. here

The detailed analysis of a sample of over 250 different RWH facilities at national level revealed a large variety of installed tank systems. Almost 30% of the systems are installed in schools and university buildings with tank sizes ranging between 8-1000 m^3. Another 15% is installed in public offices with maximum tank storage capacity of the tank of 1500 m^3. Small-size RWH facilities placed in individual houses (storage capacity less than 1m^3) are wide-spread in Japan. Although statistical data on the use of small tanks is not available nationwide, the Great East Japan Earthquake in March 2011 caused a sudden rise in the number of households that installed tanks to store rainwater for emergency.

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

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

In the Gansu province, China, a demonstration project on RWH has been carried out with very positive results in the recent decades (Gould et al., 2014). Up to the year 2000, the project has led to building more than 2 million rainwater tanks with a total capacity of more than 73 million m^3 supplying drinking water for almost 2 million people and supplementary irrigation for more than 230,000 ha of land. Based on these results, seventeen provinces have adopted RWH systems starting from the year 2001 and built more than 5.5 million tanks for drinking water and supplemental irrigation throughout China.

In 2009, the Taiwan Water Resources Agency included RWH in the Taiwanese Water Law as alternative source for domestic water supply. The new policy (MI, 2013) requires, for example, that all new buildings with a total floor area larger than 10,000 m^2 must install domestic RWH equipment to supply at least 5% of the total water required by the building.

3.3. Australia

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

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

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

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

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

3.4. Europe

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

Currently, Germany is a leader in promoting the widespread use of this technology for domestic use. As a consequence of the promotion (by grants and subsidies) of household RWH at the local government level (Schuetze, 2013), today almost one third of new buildings built in Germany are equipped with a rainwater collection system. Due to serious industrial air pollution and strict regulations regarding drinking water standards, household rainwater supplies are fundamentally limited to non-potable uses focusing mainly on irrigation, toilet flushing, and laundry use. Spain has undertaken a programme of incentives and subsidies for new buildings (Domènech and Saurí, 2011). While, in the year 2008, France enacted a regulatory framework (De Gouvello et al., 2014) to encourage the use of rainwater through tax credit (although this is now abolished). Technical guidelines for RWH have also been issued in Italy (UNI, 2012). Since then, several communities promote RWH as complementary technology to improve urban runoff control and irrigation of public and private green spaces. The popularity of installing RWH systems is also increasing in other countries such as Austria, Switzerland, Belgium and Denmark, with the potable water price being the main driver (Godskesen et al., 2013; Ringelstein, 2015). A good example of RWH practices within water sensitive and sustainable urban development is Hammarby Sjöstad in Stockholm, Sweden, which incorporates RWH as well as street runoff collection (Iveroth et al., 2013).

3.5. Americas

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

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

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

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

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

4. Quality assessment of harvested rainwater

4.1. Metals and nutrients

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

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

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

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

In addition to wet and dry deposition, roofing materials can serve as a significant source of contaminants in roof runoff (Melidis et al., 2007; Despins et al., 2009; Clark et al., 2008; Akoto et al., 2011). Roof materials contribute dissolved and particulate matter to roof runoff due to weathering processes and chemical and physical reactions occurring between the rainwater and the materials (Zobrist et al., 2000). Several studies have shown that rough roofing surfaces, such as asphalt shingles, trap and retain particles and pollutants more so than smooth materials and can have a detrimental effect on harvested water quality (Bradford and Denich, 2007; Despins et al., 2009, Farreny et al., 2011). Thus, materials that contain constituents prone to leaching, such as zinc or copper, should be avoided in case of implementation of a RWH system (Bradford and Denich, 2007).

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

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

4.2. Microbial quality of rainwater

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

The microbial populations in collected and stored rainwater may exhibit substantial variations between different locations (Table 1), depending on climatic conditions (e.g. wind speed and direction, regime of rainfall events), existence of first-flush, and the type of wild life (e.g. birds, cats or foxes) that may come in contact with the collection surface. While it is recognised that birds act as a major source of pathogens, other sources include dry deposition (of particles large enough to carry microorganisms) or by wet deposition (during rain events). Another factor that affects the microbial quality of rainwater is the length of antecedent dryness. Most studies report that longer periods of dry-weather are linked to higher microorganism levels due to increased deposited animal faeces on the roof surface (e.g. Yaziz et al., 1989).

Table 1 here

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

4.3. Rainwater treatment

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

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

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

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

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

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

5. Current trends in rainwater harvesting systems modelling

Modelling tools and methodologies have been developed over the last 20 years to facilitate the evaluation (and design) of RWH systems. Key studies have focussed on objectives associated with matching water availability (e.g. rainfall) with water demand (Dixon et al., 1999; DeBusk and Hunt, 2014; Melville-Shreeve et al., 2016). As both rainfall and water demand are temporally variable, RWH evaluation models are frequently used as a design tool to calculate the volume of storage required to balance these inflows and outflows, such that the water demand is adequately met for a specific building or location.

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

1) a behavioural model, to represent rainwater demand (D). Demand can be taken from literature, historic meter data or real-time metering data;

2) a rainwater (R) inflow model to represent available water. This is based on synthetic rainfall series or rain gauge data. Temporal datasets range from minutes to months with spatial proximity ranging from on-site rain gauges to regional averages;

3) a calculation module which enables tank mass balance simulations to be performed whilst accounting for losses at each time step (such as roof runoff losses, first flush losses, filter losses, tank overflows);

4) an output module which logs, summarises and presents data from each simulation.

The *rainwater demand model* represents user behaviour and this aspect is arguably the hardest aspect to accurately quantify. Empirical datasets illustrate the stochastic nature (with high variability) of water demands. Demand profiles can vary between seemingly identical households in similar locations due to various socio-technical factors including varying work patterns, household demographics and deployment of different water fittings (e.g. low-flush WCs). Behavioural model tools have also been extended to include multiple concurrent demand patterns (e.g. toilet flushing, garden irrigation, etc.) (Campisano and Lupia, 2017). However, RWH evaluators frequently need to fix the demand as an average value (usually average daily or monthly values) to enable simulations to be carried out (Parker and Wilby, 2012; Ward et al., 2012; Melville-Shreeve et al., 2016). Sensitivity analyses are required where behavioural models are based on a limited or uncertain data (Fewkes and Butler, 2000). High resolution demand data may be needed to assure accurate outputs (Campisano and Modica, 2015) depending on the objective of the analysis.

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

Water efficiency modelling approaches within RWH tools have been widely shown to give accurate representations when daily time step intervals are used (e.g. Fewkes and Butler, 2000; Campisano et al., 2013). However, RWH tools can be manipulated to use a wide range of time steps with selection based on the resolution of data available. Recent work by Campisano and Modica (2015, 2016) has further exemplified the opportunity for high resolution (sub-hourly time steps) data to drive accurate simulations, with specific emphasis on stormwater retention.

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

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

Table 2 here

Melville-Shreeve et al. (2014) illustrated the opportunity for dual purpose "retention and throttle" RWH systems to be designed and evaluated within proprietary drainage software. These findings showed that RWH systems for UK houses could be developed that provide 95% of the user's non-potable water demand whilst also maintaining sufficient attenuation capacity to control stormwater runoff during the 1 in 100 year design storm. Mugume et al. (2016) extended this work to show how systems of this type can be deployed at a city scale to meet both stormwater and water efficiency objectives.

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

6. Financial viability

There have been many studies that assessed the financial viability of RWH systems. Many of these studies make use of simple tools to match costs and benefits of system implementation. More recent tools based on an analysis of the system life cycle (Ward et al., 2012; Neto et al., 2012; Loubet et al., 2014; Morales-Pinzón et al., 2015) have also been used to assess benefits of RWH technologies compared with alternative water supply strategies. Zhang et al. (2009) assessed the feasibility of RWH in high-rise buildings in four capital cities in Australia and noted that Sydney has the shortest payback period (about 10 years) followed by Perth, Darwin and Melbourne. Analysis by Rahman et al. (2010) showed that payback in Sydney can be achieved for multi-storey buildings under some favourable scenarios and conditions (e.g. a low discount rate and a large number of users). Imteaz et al. (2011) showed that for large tanks connected to commercial roofs in Melbourne, the capital cost can be recovered within 15 to 21 years depending on the tank size and future water price increase rate. Various results have been obtained on the different level of viability of RWH systems with regard to the system size. Domènech and Saurí (2011) examined the efficiency of a RWH system for two main types of buildings (single and multi-family housing units) in Barcelona (Spain). They found that in single-family households the payback period is in between 33 to 43 years depending on the tank size, while for a multi-family building, it is larger than 60 years for a 20 m^3 tank. Ghisi and Schondermark (2013) found that domestic RWH in Santa Catarina State, Southern Brazil would be economically feasible for most cases and generally the higher the rainwater demand, the higher the financial return. In contrast, Roebuck et al. (2011) noted that domestic RWH systems in the UK are unlikely to deliver any realistic payback period given the assumptions made at the time. Ward et al. (2012) estimated, using empirical monitoring data, capital payback periods of between 6 and 11 years for a commercial-scale office-based RWH system serving a building occupancy of 110 people.

It appears that a significant portion of researchers have found that RWH systems are not financially viable, depending on scale (Kumar, 2004; Roebuck et al., 2011; Rahman et al., 2011). However, in many cases, differences in the way maintenance and operational costs have been taken into account (e.g. pump replacement, electricity bill and cleaning of roof catchment system) led to controversial conclusions. For example, Ward et al. (2011) mentioned that using different evaluation methods can determine differences up to 60% for energy consumption costs. Besides, most of the approaches utilised are simplistic as they do not holistically assess all potential benefits achievable with RWH systems. Indirect benefits such as savings due to delaying the upgrade of a major water infrastructure (water supply, sewer or treatment facility) (Coombes and Kuczera, 2003) or improved control of combined sewer overflows (Gwenzi and Nyamadzawo, 2014) are only two examples of benefits that should be included for a more comprehensive and realistic analysis of the system return on investment. Interestingly, Melville-Shreeve et al. (2014; 2016), using a Multiple Criteria Analysis, demonstrated additional benefits of RWH such as energy savings and environmental benefits due to reduced raw water abstraction, pumping, and water treatment. Other benefits may come from increased agricultural efficiency in urban residential (food gardens) and rural contexts (Lupia and Pulighe, 2015). Ngigi et al. (2005) found that a 50 m^3 water tank for irrigation can increase the yield of a 0.2 ha cropped land by 1000 kg/ha. Conversely, Fisher-Jeffes (2015) showed that implementing RWH for water conservation and stormwater retention at the same time in a catchment would negatively impact the economic viability of the system. Zhang et al. (2015) using Hedonic Price Method showed that there is likely to be an increase in the real estate value of the homeowner's property having a RWHS. Not least, hard water if replaced by rainwater (which is soft in nature) could save washing costs (e.g. by reducing washing powder quantity) as noted by Morales-Pinzon et al. (2014).

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

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

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

Historically, challenges to the social acceptance of RWH (and indeed wider water reuse) have focused on water quality, risk perception and health risk, including the so-called 'yuck factor' (Fewtrell and Kay, 2007b; Ward et al., 2010; Rozin et al., 2015), as well as financial viability (Roebuck et al., 2011). As sections 4 and 6 of this paper highlight, knowledge to reduce the impact of these challenges has been generated and for water quality at least, confidence built by recommendations to use risk assessments and water safety plans (Gwenzi et al., 2015). Despite some households being resistant to using rainwater indoors (Mankad et al., 2011), it is now acknowledged that RWH is an acceptable source of non-potable water compared to other types of water reuse for non-potable purposes (Dobrowksy et al., 2014; Egyir et al., 2016). The focus on acceptability and financial returns to date has often detracted attention from wider challenges. These include evaluating social as well as financial benefits to engender wider institutional support and reflexive analysis of the international RWH niche to enable greater consideration of system efficacy and community participation, both of which will enhance the hydrosocial contract and diffusion of RWH into wider society (Stenekes et al., 2006; Getnet and MacAlister, 2012). Moving away from a rhetoric around perceptions and costs enables the RWH sector to move towards a more positive and innovative space – where challenges are redefined and responded to by policy-makers, businesses and communities.

7.1. Increasing institutional support through diverse benefit identification

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

Domènech and Saurí (2011) report that incentives coupled with complementary strategies are utilised in Spain to stimulate installation, such as the introduction of local regulations (to mandate RWH in new buildings) and partial subsidies (for new build and retrofit) requiring a voluntary contribution. Consequently, it was hypothesized that citizens appreciating the benefits of RWH would be more likely to invest and apply for a subsidy, rather than the wider public - though it was found that the citizens that did install RWH with a subsidy would have done so without.

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

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

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

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

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

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

Despite these technical innovations, innovation in service and social innovation by RWH infrastructure innovators and other organisations has been limited to date. This is beginning to change, however, as the effect of daily water-using practices of individuals on water availability comes into focus. This is particularly true in developing countries where issues of gender arise, as water collection and management at the household level is often designated a female responsibility, whereas the construction of RWH storage tanks (cisterns) and community-level management of water often considered the domain of men (De Moraes and Rocha, 2013). By empowering women in the strategic and physical construction of water management in Brazil (One Million Cisterns RWH programme), they became both decision-makers and beneficiaries in relation to RWH (De Moraes and Rocha, 2013). Adler et al. (2014) emphasizes that community participation and leadership are also essential for the success of RWH programmes.

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

8. Lessons learned and future research challenges

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

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

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

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

Technology selection and regular maintenance are factors of paramount importance for the correct functioning and the success of these systems as they assure appropriate water quality and improve safety perception by users. In future, modelling should take into account the maintenance aspects of RWH systems as such impacts could impact the quality of collected rainwater and its use. Indeed, research is required to better understand how tank maintenance can be encouraged. At the household scale, Mankad et al. (2015) point to the use of information to empower tank owners to undertake maintenance. Such information could take the form of pamphlets or be delivered through onsite inspections, though further research into how building occupants actually live with RWH systems is warranted in order to develop materials to best-engage end-users.

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

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

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

9. Conclusions

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

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

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

Acknowledgments

The authors would like to thank Dr. Peter Melville-Shreeve for his contribution to the paper. The authors also thank Dr. Hiroyuki Okui and Dr. Masahiro Imbe for contributing information concerning the state of the art of implementation of RWH systems in Japan.

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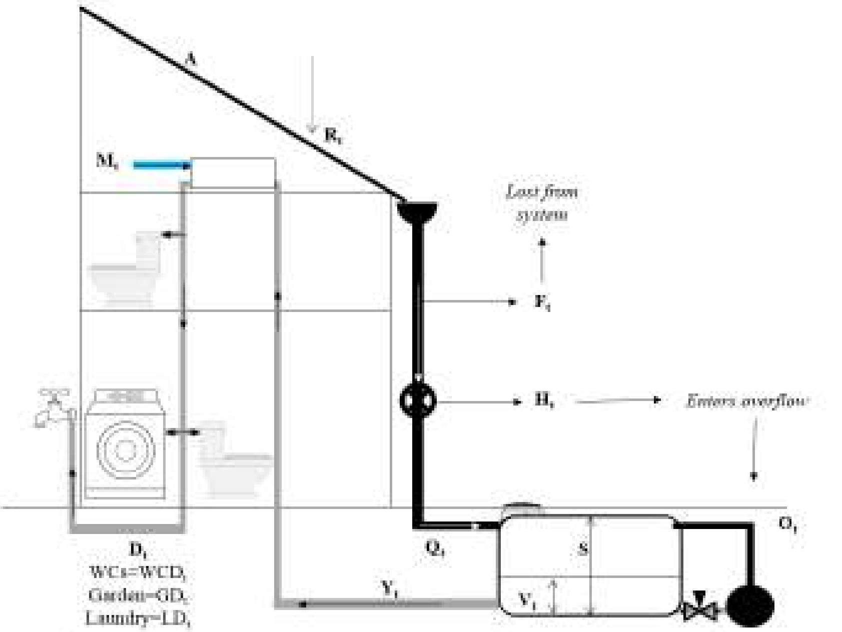

A [m^2] = impermeable collection area; R_t [m] = rainfall; F_t [m^3] = First flush losses; H_t [m^3] = diverted flow (filter losses); Q_t [m^3] = inflow to the tank; O_t [m^3] = overflow from the tank; V_t [m^3] = volume in store; S [m^3] = functional tank capacity; Y_t [m^3] = rain water volume yielded from the tank; M_t [m^3] = water from mains; D_t [m^3] = water demand; Subscript $_t$ relates to the time step of the simulation.

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

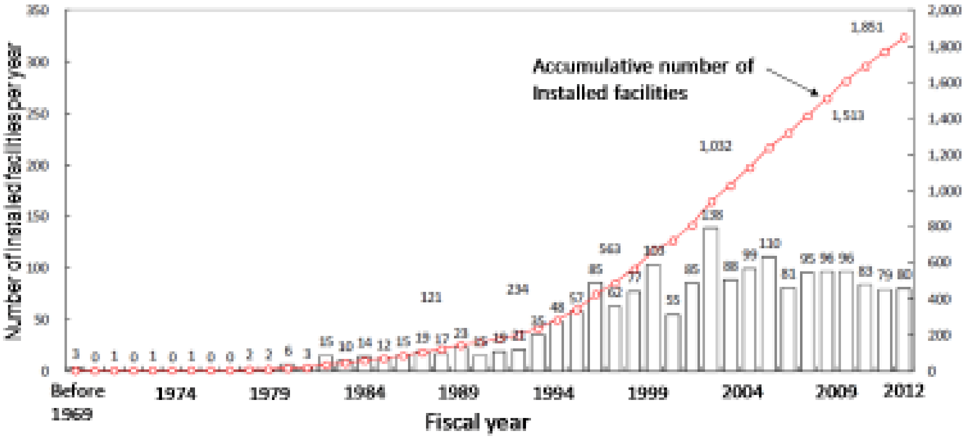

Fig. 2. Rainwater harvesting systems in public facilities and office buildings in Japan. An increasing trend is observed starting from early 1980s (adapted from MLIT, 2014)