Microbiological Quality of Roof-Harvested Rainwater and Health Risks: A Review

W. Ahmed,* T. Gardner, and S. Toze

Roof-harvested rainwater (RHRW) has been considered an effective alternative water source for drinking and various nonpotable uses in a number of countries throughout the world. The most significant issue in relation to using untreated RHRW for drinking or other potable uses, however, is the potential public health risks associated with microbial pathogens. This paper reviews the available research reporting on the microbial quality of RHRW and provides insight on the capacity of fecal indicator bacteria to monitor health risks and disease outbreaks associated with the consumption of untreated RHRW. Several zoonotic bacterial and protozoan pathogens were detected in individual and communal rainwater systems. The majority of the studies reported in the literature assessed the quality of rainwater on the basis of the presence or absence of specific pathogens, with little information available regarding the actual numbers of such pathogens. In addition, no information is available concerning the ongoing prevalence of different pathogens in RHRW over time. The published data suggest that the microbial quality of RHRW should be considered less than that expected for potable water and that the commonly used indicators may not be suitable to indicate the presence of pathogens in RHRW. Several case control studies established potential links between gastroenteritis and consumption of untreated RHRW. Therefore, health risks assessment models, such as those using Quantitative Microbial Risk Assessment, should be used to manage and mitigate health risks associated with drinking and nonpotable uses of RHRW.

The demands on potable water supply are escalating in line with increasing population growth, particularly in urban areas, along with increases in industrial output and commerce. This is further exacerbated by the adverse impacts of climate change on water supply sources. Consequently, water authorities around the world are keen to explore alternative water sources (AWSs) to meet ever-increasing demands for potable (i.e., drinking) water. Among the more common AWSs investigated, roof-harvested rainwater (RHRW) has been considered to be one of the most cost effective sources for both drinking and various nonpotable uses, such as irrigation, toilet flushing, car washing, showering, and clothes laundering. Countries that have investigated the potential benefits of RHRW for these uses include Australia, Canada, Denmark, Germany, India, Japan, New Zealand, Thailand, and the United States (Despins et al., 2009; Evans et al., 2006; Uba and Aghogho, 2000). For example, 10% of Australian people currently use RHRW as a major source of their drinking water, and an approximate additional 5% use RHRW as potable replacement for showering, toilet flushing, and clothes laundering (ABS 2007).

Many countries have provided subsidies to encourage the installation of RHRW systems so that such systems will provide water for drinking and nonpotable uses as a mechanism to promote the increased uptake of AWSs with the specific aim to decrease the reliance and use of scheme water (Ahmed et al., 2010; Albrechtsen, 2002). For instance, in 2006, the Queensland State Government, Australia, initiated the "Home Water Wise Rebate Scheme," which provided subsidies to Southeast Queensland residents who used rainwater for nonpotable domestics uses. More than 260,000 householders were granted subsidies by December 2008 when the scheme was concluded.

There are several advantages to using RHRW, including (i) reducing the pressure on the mains water supply, (ii) reducing stormwater runoff that can often degrade creek ecosystem health, and (iii) providing an alternative water supply during times of water restrictions. Despite these advantages, RHRW has not been widely utilized for drinking due to a lack of information on the presence and risk from chemical and microbiological pollutants. Another shortcoming is the lack of appropriate guidelines specifying the use of RHRW for both drinking and nonpotable uses and how the risk from chemical and microbiological pollutants can be managed. The most significant issue in relation to untreated

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*Corresponding author (Warish.Ahmed@csiro.au).
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5585 Guilford Rd., Madison, WI 53711 USA

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Abbreviations: AWS, alternative water source; CFU, colony forming unit; PCR, polymerase chain reaction; QMRA, Quantitative Microbial Risk Assessment; RHRW, roof-harvested rainwater; WHO, World Health Organization.

RHRW for drinking is the potential public health risks associated with microbial pathogens (Ahmed et al., 2008; Crabtree et al., 1996; Simmons et al., 2001). A wide array of pathogens could be present in the feces of birds, insects, mammals, and reptiles that have access to the roof. Consequently, following rain events, animal droppings and other organic debris deposited on the roof and gutter can be transported into the tank via roof runoff. In this scenario, if the untreated water collected from the roof is used for drinking, there is a potential for disease in people consuming this water. Only limited information is available, however, regarding the actual health risks associated with the uses of RHRW. It can be postulated that the magnitude of health risks from nonpotable uses could be lower than drinking due to lower exposure levels to pathogens. There is also a general community perception that rainwater is safe to drink without having to undergo prior treatment. In support of this perception, Dillaha and Zolan (1985) reported that the quality of RHRW is generally acceptable for drinking and household use. This was further supported by an epidemiological survey of gastroenteritis among 4- to 6-yr-old children in rural South Australia who drank rainwater or treated mains water that suggested RHRW poses no increased risk of gastroenteritis when compared with mains water (Heyworth et al., 2006). In contrast, a number of other studies on the microbial quality of RHRW have reported the presence of specific zoonotic pathogens in individual or communal RHRW systems (Ahmed et al., 2008; Birks et al., 2004; Crabtree et al., 1996; Lye, 2002; Simmons et al., 2001; Uba and Aghogho, 2000). The divergence in outcomes of studies in the quality of RHRW may be due to high variability from system to system (Lye, 1987, 2002, 2009), and therefore, legitimate questions have arisen from health regulators regarding the quality of water and consequent public health risks.

The purpose of this review is (i) to highlight research studies investigating the microbiological quality of RHRW, (ii) to provide insight on the capacity of fecal indicator bacteria to monitor health risks associated with RHRW, (iii) to highlight disease outbreaks linked to the consumption of untreated RHRW, and (iv) to provide insight on how to manage the risk of infection or gastroenteritis associated with the consumption of RHRW. It should be noted that poor microbial quality of water poses a much more acute risk of illness to consumers via exposure to pathogens compared to chemical pollutants. For this reason, the chemical quality of RHRW is not covered in this review.

Fecal Indicators and Pathogens in Roof-Harvested Rainwater

Fecal Indicators

To determine the acceptability of RHRW for drinking, it is common practice to use drinking water guidelines to monitor the microbial quality of the water. For most guidelines, this entails the nondetection of the common indicator bacteria such as *Escherichia coli* or thermotolerant coliforms (usually at numbers <1 colony forming units [CFU]/100 mL) whose presence are used to indicate potential fecal pollution of the water (NHMRC–NRMMC, 2004; WHO, 2004). Even when RHRW is not used for drinking, the assessment of the microbial quality of RHRW is usually undertaken by monitoring the presence of fecal indicators such as total coliforms, fecal coliforms, *E. coli*, enterococci and *Clostridium perfringens* (Ahmed et al., 2008, 2010; Appan, 1997; CRC for Water Quality and Treatment, 2006; Dillaha and Zolan, 1985). The World Health Organization (WHO) recommends that for drinking water, the total coliforms numbers should be <10 CFU/100 mL in 95% of samples collected from a particular water source (WHO, 2004). These guidelines also indicate that if the numbers of total coliforms are >20 CFU/100 mL water, further treatment should be undertaken prior to drinking. It should be noted that total coliforms may not be a suitable indicator of fecal contamination in RHRW. Total coliforms in water can comprise microorganisms that could be fecal in origin but also could be from other sources such as soil and vegetation, and, therefore, their presence in open systems such as rainwater tanks that can easily be contaminated with dust and plant material may not necessarily indicate fecal contamination. Fecal coliforms and enterococci are considered much better indicators of fecal contamination, and most guidelines stipulate that fecal coliforms, *E. coli*, and enterococci numbers should be zero CFU/100 mL for drinking water. Such stringent guideline values have been established for these indicators as these are commonly found in high numbers in human and animal feces. Their presence in drinking water, therefore, indicates a strong likelihood that fecal contamination has occurred and that the water is therefore not suitable for drinking (Baudisöva, 1997).

Most research studies on RHRW reported to date used fecal indicator bacteria to assess the microbiological quality of the water. Table 1 shows the percentage of positive samples for total bacteria and fecal indicator bacteria in water samples from RHRW reported in 18 research studies. In Micronesia, 155 and 176 RHRW samples were surveyed for total coliforms and fecal coliforms, respectively. Of these, 57 and 30% samples had no measurable numbers of total coliforms and fecal coliforms, respectively (Dillaha and Zolan, 1985). Thirty-nine percent of samples had total coliform numbers <10 CFU/100 mL, thus complying with the WHO drinking water guidelines. Despite the high numbers (61%) of samples not complying with the guidelines, the authors suggested that the RHRW could be reasonable for drinking. Lye (1987) also reported that RHRW could have consistently good quality in a study of the occurrence of fecal coliforms in RHRW samples in Kentucky, USA, where only one sample out of 30 had fecal coliforms numbers >10 CFU/100 mL.

In contrast, several studies reported higher numbers of fecal indicators in RHRW, which, therefore, did not comply with acceptable drinking water guideline values (Table 1). In Victoria, Australia, for example, 49 rainwater tanks surveyed for the presence of total coliforms, *E. coli*, and enterococci (Spinks et al., 2006) found that 33% were positive for *E. coli* and 73% positive for enterococci exceeding the Australian Drinking Water Guidelines of zero CFU/100 mL (ADWG, 2004). Another recent study in South Korea reported that 92 and 72% of RHRW samples were positive for total coliforms and *E. coli*, respectively (Lee et al., 2010). In all the positive samples, the numbers of these indicators were above the WHO drinking water guideline values. High numbers of *E. coli* were also found in Danish RHRW systems by Albrechtsen (2002), where *E. coli* was observed to be present in 11 out of 14 systems with numbers ranging from 4 to 900 CFU/100 mL. The conclusion made in this study was that the presence of *E. coli* indicated that the water may not be suitable for drinking (Albrechtsen, 2002). High numbers of *E. coli* (ranging from 4 to 800 CFU/100 mL) and enterococci (5 to 200 CFU/100 mL) were also reported in RHRW samples tested in Queensland, Australia (Ahmed et al., 2008). In this study, of the 27 samples tested, 63, 78, and 48% were positive for *E. coli*, enterococci, and *C. perfringens*, respectively. Ahmed et al. (2008) concluded that as *E. coli* could not be detected in a number of the water samples that were positive for other indicators of potential fecal origin such as enterococci or *C. perfringens,* RHRW should be tested for multiple indicators where possible to obtain multiple lines of evidence on the occurrence of potential fecal contamination. On the basis of these results, they concluded that *E. coli* may be of limited use to assess the microbial quality of RHRW.

Several studies also reported that enterococci are more prevalent in RHRW tanks compared with *E. coli* (Ahmed et al., 2008, 2010; CRC for Water Quality and Treatment, 2006; Spinks et al., 2006) and thus may be a better indicator for assessing fecal contamination. The greater prevalence of enterococci in RHRW may be due to the fact that enterococci persist in the water longer than *E. coli* (McFeters et al., 1974). It has also been reported that enterococci perform better in terms of indicating fecal contamination in environmental waters compared with *E. coli* (Kinzelman et al., 2003). Nonetheless, more studies on the potential sources and the relative persistence are needed that compare the usefulness of *E. coli* versus enterococci in RHRW before any recommendations can be made concerning which indicators may be the most suitable. Along with the more traditional microbial indicators, the use of alternative indicators in recent years, such as *Bacteroides* spp. and *Bifidobacterium* spp., has gained popularity to identify fecal contamination in environmental waters. To date, however, these alternative indicators have merely been used for RHRW quality monitoring. Ahmed et al. (2008) tested *Bacteroides* spp. as an alternative indicator to detect fecal contamination in water samples from RHRW in Southeast Queensland, Australia, using polymerase chain reaction (PCR). Of the 27 RHRW samples tested 2 d after rainfall events, 89% were PCR positive for *Bacteroides* spp.. On the basis of these results, it was concluded that *Bacteroides* spp. may be a more sensitive indicator for the detection of recent fecal contamination in RHRW samples due to their short survival time outside of a host, their exclusivity to the gut of warm-blooded animals, and the fact that they constitute a relatively larger portion of fecal bacteria than traditional fecal indicator bacteria (Sghir et al., 2000).

Bacterial Pathogens

To date, only a small number of studies have investigated the presence of bacterial pathogens in RHRW (Table 2). While much of the focus on bacterial pathogens in drinking water is predominantly on enteric indicators and pathogens such as *E. coli* and *Salmonella* spp., in RHRW other nonenteric pathogens such as *Legionella* and *Aeromonas* are also considered to be of concern for human health. The links between water and *Legionella* infections is well known, and a recent study by Khajanchi et al. (2010) demonstrated a link between *Aeromonas* spp. isolated from clinical and water samples, indicating a transmission from water.

In one of these studies, Simmons et al. (2001) reported the presence of *Aeromonas* spp. and *Salmonella* spp. in RHRW water samples collected in Auckland, New Zealand, with, 20 and 0.9% of the 125 samples tested as positive for *Aeromonas* spp. and *Salmonella* spp., respectively. No results on the pathogen

Table 1. Percentage of samples positive for total bacteria and fecal indicators in roof-harvested rainwater.

Country	Percentage of samples positive (>1 CFU/100 mL) for total bacteria and fecal indicators (no. of samples tested)						Reference
	Total bacteria	Total coliforms	Fecal coliforms	*E. coli*	Enterococci	*C. perfringens*	
Australia	–†	52 (100)	38 (100)	–	–	–	Verrinder and Keleher (2001)
Australia	–	90 (49)	–	33 (49)	73 (49)	–	Spinks et al. (2006)
Australia	–	–	–	63 (27)	78 (27)	48 (27)	Ahmed et al. (2008)
Australia	–	–	–	58 (100)	83 (100)	46 (100)	Ahmed et al. (2010)
Australia	100 (67)	91 (46)	78 (41)	57 (67)	82 (67)	49 (67)	CRC for Water Quality and Treatment (2006)
Australia	–	–	83 (6)	–	–	–	Thomas and Green (1993)
Australia	100 (77)	63 (81)	63 (81)	–	–	–	Evans et al. (2006)
Canada	–	31 (360)	14 (360)	–	–	–	Despins et al. (2009)
Greece	–	80 (156)	–	41 (156)	29 (156)	–	Sazakil et al. (2007)
Denmark	100 (14)	–	–	79 (14)	–	–	Albrechtsen (2002)
Micronesia	–	43 (155)	70 (176)	–	–	–	Dillaha and Zolan (1985)
New Zealand	–	–	56 (125)	–	–	–	Simmons et al. (2001)
Nigeria	100 (6)	100 (6)	ND	–	ND	–	Uba and Aghogho (2000)
South Korea	–	92 (90)	–	72 (90)	–	–	Lee et al. (2010)
Thailand	–	–	–	40 (86)	–	–	Pinfold et al. (1993)
USA	100 (30)	93 (30)	–	3 (30)	–	–	Lye (1987)
U.S. Virgin Islands	86 (45)	57 (45)	36 (45)	–	–	–	Crabtree et al. (1996)
Zambia	–	100 (5)	100 (5)	–	–	–	Handia (2005)

† – = not reported.

Table 2. Percentage of samples positive for potential pathogenic bacteria and protozoans in roof-harvested rainwater.

Country	Percentage of samples positive for potential bacterial pathogens (no. of samples tested)										Reference
	Aeromonas spp.	*Pseudomonas* spp.	*Legionella* spp.	*Campylobacter* spp.	*Mycobacterium* spp.	*Salmonella* spp.	*Shigella* spp.	*Vibrio* spp.	*Cryptosporidium* spp.	*Giardia* spp.	
Australia	15 (27)†	–	26 (27) †	45 (27)†	–	11 (27)†	–	–	–	19 (21)†	Ahmed et al. (2008)
Australia	7 (100)†	–	8 (100) †	20 (100)†		17 (100)†			ND‡	15 (100) †	Ahmed et al. (2010)
Australia	32 (56)	–	15 (67)	1.5 (67)	–	3 (67)	–	–	–	–	CRC for Water Quality and Treatment (2006)
Denmark	14 (14)	7 (14)	71 (7)	12 (17)	7 (14)	–	–	–	35 (17)	ND (17)	Albrechtsen (2002)
New Zealand	–	–	–	37 (24)†	–	–	–	–	–	–	Savill et al. (2001)
New Zealand	20 (125)	–	ND (125)	ND (125)	–	0.9 (125)	–	–	4 (125)	ND (125)	Simmons et al. (2001)
Nigeria	–	83 (6)	–	–	–	67 (6)	67 (6)	67 (6)	–	–	Uba and Aghogho (2000)
U.S. Virgin Islands	–	–	–	–	–	–	–	–	45 (45)	23 (45)	Crabtree et al. (1996)
U.S. Virgin Islands	–	–	80 (10)	–	–	–	–	–	–	–	Broadhead et al. (1988)

† Polymerase chain reaction–based methods were used for pathogen detection.

‡ ND, not detected.

number were reported in this study, however; therefore, for a health risk assessment to be undertaken for these microorganisms, an assumption needs to be made that pathogens such as *Salmonella* are present but at numbers below the detection limit of the analysis method used.

Despite this, based on the positive detections obtained, the authors concluded that RHRW was not suitable for drinking and recommended further research on the *Aeromonas* spp. because of its high prevalence and association with gastroenteritis in both adults and children. *Campylobacter* spp. has also been detected in tank water samples in New Zealand using PCR (Savill et al., 2001). In all, 37% of the samples tested were positive for *Campylobacter* spp. with numbers ranging from <0.06 to 0.56 MPN–PCR/100 mL water. In addition to *Aeromonas* spp., other microbial pathogens such as *Pseudomonas aeruginosa*, *Legionella* spp., *C. jejuni*, and *Mycobacterium* spp. have also been detected in RHRW in Denmark (Albrechtsen, 2002). On the basis of these findings, the author concluded that connecting RHRW to the drinking water systems would increase the level of risk of gastroenteritis and respiratory illness.

A recent study that used PCR to detect evidence of bacterial pathogens in tank water in Southeast Queensland, Australia, found that between 1 and 19% of the samples were positive for enteric pathogens *Aeromonas hydrophila*, *C. jejuni*, *C. coli*, and *Salmonella* spp. (Ahmed et al., 2010). In addition, 8% of the samples were positive for the respiratory pathogen *L. pneumophila*. The authors suggested that RHRW appears to decrease in microbiological quality after rain events, although the source of this reduction in microbial quality, the impact of duration between rain events on the quality of RHRW, and the time it may take after rain events before RHRW improves in quality during storage remains unknown.

Protozoan Pathogens

Despite a well-established zoonotic link, as with the presence of bacterial pathogens, the presence of protozoan pathogens in RHRW has not been extensively investigated, with only a few studies examining RHRW for the presence of *Giardia* spp. and *Cryptosporidium* spp. (see Table 2). Crabtree et al. (1996) reported that in the U.S. Virgin Islands, *Giardia* cysts and *Cryptosporidium* oocysts in tank water can be highly prevalent. They found that in 44 water samples tested from private and public rainwater systems, 45 and 23% of samples were positive for *Giardia* cysts and *Cryptosporidium* oocysts, respectively. The levels of cysts and oocysts were found to range from 1 to 10 organisms/100 L, with one sample containing 70 oocysts/100 L, and the numbers of *Cryptosporidium* oocysts in all the positive samples were well above the acceptable guidelines of zero tolerance of protozoa pathogens as described for safe drinking water in the United States. Simmons et al. (2001) also reported the presence of *Cryptosporidium* spp. in 4% of tank water samples in Auckland, New Zealand. However, unlike Crabtree et al. (1996), Simmons et al. (2001) were unable to detect any *Giardia* cysts. They concluded, however, that the prevalence of protozoan pathogens may have been underestimated because the standard analytical technique had a low detection sensitivity.

Albrechtsen (2002) similarly reported the presence of *Cryptosporidium* spp. in Danish RHRW. They tested 17 rainwater samples, of which 6 were positive for *Cryptosporidium* spp. The numbers of *Cryoptosporidium* spp. were as high as 50 oocysts/L; however, as in the study of Simmons et al. (2001), *Giardia* spp. was not detected in any of the samples. In contrast, another study in Queensland, Australia, reported the presence of *G. lamblia* in 19% of RHRW samples tested, but none of the samples were positive for *C. parvum* (Ahmed et al., 2008, 2010). One possible reason for the differences between the Australian study and those from elsewhere in the type of protozoan pathogen detected may be the different wildlife that has access to roofs. In Queensland, for example, marsupial possums are a common animal in and around urban dwellings and frequently traverse roof tops in their nocturnal movements. Possums are known to be carriers of *Giardia* cysts (Marino et al., 1992); thus, these possums could be a major source of *Giardia* spp. in RHRW in Queensland, while wild birds or other animals are the source of the *Cryptosporidium* spp. in the other studies.

Correlation between Fecal Indicators and Pathogens in Roof-Harvested Rainwater

As already indicated, RHRW can be contaminated with either traditional fecal indicator microorganisms or pathogens. To assess and monitor the quality of RHRW, it is important to know the most appropriate microorganisms that can be used to determine appropriate quality of the water. The traditional testing of water has involved the detection of fecal indicators; however, one of the significant limitations of using fecal indicators to assess the microbial quality of water is their often-poor correlation with the presence of pathogenic bacteria, protozoas, and viruses. For example, it was reported that *E. coli* and enterococci do not correlate well with pathogenic *Salmonella* spp. (Lemarchand and Lebaron, 2003), *Campylobacter* spp. (Hörman et al., 2004), *Cryptosporidium* spp., and *Giardia* spp. (Harwood et al., 2005; Hörman et al., 2004), and enteric viruses (Griffin et al., 1999; Pina et al., 1998) in environmental waters. There has been little information, however, documenting whether any correlation exists between fecal indicators and pathogens in rainwater tanks. The two studies that directly reported on links between pathogens and indicator organisms had contrasting findings. Simmons et al. (2001) reported a positive correlation between *Aeromonas* spp. and fecal indicators such as total coliforms, fecal coliforms, and enterococci. In contrast, Savill et al. (2001) reported that there was a poor correlation between *Campylobacter* spp. with total coliforms and *E. coli* in tank water. In their study, *Campylobacter* spp. was detected in the absence of *E. coli* on five occasions and in the absence of total coliforms on two occasions.

A recent study also reported the limitations of fecal indicator bacteria for the microbial assessment of RHRW quality (Ahmed et al., 2010). Of the 100 samples tested, up to 83% samples were positive for fecal indicators as determined by traditional culture-based methods. Additionally, in the samples tested, 1 to 15% samples were PCR positive for zoonotic bacterial and protozoa pathogens. Discrepancies were observed in terms of the occurrence of fecal indicators and pathogens. For example, 12% of samples had <1 CFU *E. coli*/100 mL but were positive for one or more pathogens. Similarly 6 and 19% of samples had <1 enterococci and *C. perfringens* spores, respectively, but were positive for one or more pathogens. It was determined that overall, the presence or absence of these potential pathogens did not correlate well with the detection of any of the fecal indicators.

Roof-Harvested Rainwater and Associated Health Risks

While most studies relating to RHRW have focused on the detection of microorganisms in the water, there have also been eight studies reporting on sporadic gastroenteritis associated with the consumption of untreated RHRW (Table 3). It should be noted that RHRW should only be considered a risk from zoonotic pathogens if there is a distinct source from infected animals that have access to the roof and that risks do not exist for human-specific pathogens (e.g., most viruses). Other issues that can influence the level of actual risk include the type and numbers of pathogen carried by the infected animal, the time between deposition of fecal matter on the roof and pathogens being flushed in the rainwater tank, the size of the tank and form of exposure (e.g., consumption from drinking vs. exposure to droplets in the shower or toilet flushing), and the relative environmental stability of the different pathogens.

An example of how all these factors can create a human health risk is a *Salmonella arechevalata*-related gastroenteritis outbreak reported by Koplan et al. (1978) that occurred among 83 campers in Trinidad, West Indies. Epidemiological and bacteriological studies were performed to identify the source of *S. arechevalata* infection. Through patient surveys, food items were ruled out as the source of the gastroenteritis; however, water samples collected from two kitchen taps connected to a RHRW system were found to be positive for *S. arechevalata*, although the bacterium could not be directly isolated from the tank. A sanitary survey revealed that the roof was covered with bird feces, and it was postulated

Table 3. Reported disease cases associated with the consumption of untreated roof-harvested rainwater in the research literature.

Country	Disease causing pathogens	Types of diseases	No. of people affected	Reference
Australia	*C. botulinum*	Not specified	3	Murrell and Stewart (1983)
Australia	*Campylobacter fetus*	Diarrhea, vomiting	1	Brodribb et al. (1995)
Australia	*Campylobacter* spp.	Diarrhea, abdominal pain,	23	Merritt et al. (1999)
Australia	*S.* Typhimurium phage 9	Diarrhea, abdominal pain, nausea	27	Franklin et al. (2009)
New Zealand	*S.* Typhimurium phage I	Diarrhea	2	Simmons and Smith (1997)
New Zealand	*L. pneumophila*	Legionnaires' disease	1	Simmons et al. (2008)
U.S. Virgin Islands	*L. pneumophila* serogroup I	Legionnaires' disease	27	Schlech et al. (1985)
West Indies	*S. arechevalata*	Diarrhea, headache, fever, vomiting	48	Koplan et al. (1978)

that rainwater washed off fecal matter containing *S. arechevalata* into the tank, leading to the gastroenteritis outbreak. To test this hypothesis, a number of intestinal samples were collected from local birds, rodents, and reptiles that were assumed to be the source of the contamination. However, *S. arechevalata* could not be isolated from the feces of these animals.

Another description of a potential link between pathogens and RHRW reported on an outbreak of three cases of infant botulism in New South Wales, Australia, where *Clostridium botulinum* type B was isolated from soil around one house and in the rainwater tank from another house (Murrell and Stewart, 1983). *Clostridium botulinum* type A was also present in soil, dust from a vacuum cleaner, and the rainwater tanks. The presence of *C. botulinum* spores in the rainwater tanks was suggested as possibly contributing to the occurrence of the infant botulism cases. As a result of this study, consumers with infant children were advised to disinfect water for the first 6 months of the infants lives. Another study reported the isolation of *Campylobacter fetus* from a 64-yr-old febrile neutropaenic patient, which was subsequently linked to the tank water (Brodribb et al., 1995). Three sets of blood cultures from the patient were positive for *C. fetus* using PCR. The rainwater was the only source of water supply for this particular household. To identify the source of infection, a sample of the tank water was tested and *C. fetus* was isolated from as little as 200 mL of water sample. The patient was advised to boil the tank water before consumption and had no further report of the illness.

Merritt et al. (1999) reported an outbreak of *Campylobacter* enteritis among 23 resort staff in Queensland, Australia, with untreated RHRW. Food was initially suspected as possible sources of infection. None of the food samples were positive for the *Campylobacter* spp., but four rainwater tanks were positive for total coliforms, with particularly high total coliform numbers found in one tank. The authors reported a strong association between gastroenteritis and consumption of water from a dispenser that had probably been filled from one of the contaminated tanks. It was hypothesized that the *Campylobacter* spp. that caused the outbreak may have been introduced into one or more of the tanks by contamination with the feces of wild animals. Another reported outbreak of gastroenteritis with a strong link to contaminated RHRW in Melbourne, Australia, involved an outbreak of *Salmonella* Typhimurium at a rural school camp served by a private rainwater supply (Franklin et al., 2008). The phage type strain DT9 of *Salmonella* was found in both the fecal specimens of patients and water taps supplying the untreated rainwater that were used as a drinking water source, indicating a direct link between the RHRW and the disease outbreak.

Simmons and Smith (1997) reported the isolation of *S.* Typhimurium phage type I from two of four family members who sought medical attention due to gastrointestinal symptoms. The family lived in a beach-side house and used RHRW for household use. The family reported that one of their cats, which spent much time on the roof and frequently defecated on it, had loose stools for several years. An investigation was undertaken to identify whether the infection was food borne or if it originated from the cat feces. However, the infection could not be related to food or the cat feces. *Salmonella* Typhimurium phage type I and fecal coliforms were isolated from the houses tap water, leading the authors to conclude that RHRW was the possible source of infection, although the original contamination source could not be determined.

An outbreak of Legionnaires' disease in an isolated suburb of Auckland, New Zealand, was linked to RHRW using PCR, demonstrating that the isolates of *L. pneumophila* from patient's clinical specimens were identical to the high levels of *L. pneumophila* present in the nozzle of a local marina water blaster used to clean boats. Sampling of nearby rainwater collection systems revealed that contaminated water spray from the water blaster had been carried and deposited on roof surfaces in the local area. The *L. pneumophila* within the spray were washed into rainwater tank, and users were exposed through bathroom showers (Simmons et al., 2008).

Since 1978, there have been eight reports of gastroenteritis associated with the consumption of RHRW cited in the literature (Brodribb et al., 1995; Franklin et al., 2009; Koplan et al., 1978; Merritt et al., 1999; Murrell and Stewart, 1983; Schlech et al., 1985; Simmons and Smith, 1997; Simmons et al., 2008). These studies suggest that the untreated rainwater may be a contributing factor for gastroenteritis; little is known, however, regarding the actual health risks from drinking the rainwater. Several authors highlighted the need for evaluating the actual health risks from drinking RHRW (Ahmed et al., 2008; Lye, 1992; Simmons et al., 2001). An epidemiological study to identify the risk of gastroenteritis among 4- to 6-yr-old children who drank RHRW compared with children who drank treated mains water in South Australia noted that the consumption of RHRW did not increase an observed level of gastroenteritis relative to mains water consumption (Heyworth et al., 2006). The authors concluded, however, that their data could also have reflected a level of acquired immunity among regular users of RHRW and therefore may not reflect the actual risk to the new users. In New Zealand, numerous cases of campylobacteriosis have been associated with the rainwater collection systems (Eberhart-Phillips et al., 1997). A case control study found strong association with gastrointestinal diseases caused by *Campylobacter* spp. with the consumption of RHRW. It was hypothesized that the rainwater systems in this study had been contaminated by birds roosting on the roofs.

In a reported outbreak of 27 cases of Legionnaire's disease among tourists visiting the U.S. Virgin Islands, the infections were thought to have originated from inhalation of *L. pneumophila* detected in the drinking water system of a local hotel (Schlech et al., 1985). Case control and microbiological studies were undertaken to identify the mode of transmission. The exact mode of transmission during this outbreak could not be determined, but the potable water was implicated as the most probable cause in the absence of other sources. The hotel obtained its potable water from a RHRW system, and the identical serogroup of the *L. pneumophila* isolated from the infected patients was found in the stored RHRW and as well as in hot and cold water taps. No further cases of Legionellosis were identified after the hotel water system was chlorinated. The last of the reported incidences of RHRW-acquired infections was reported a case control study in Tasmania, Australia, where single variable associations were found between drinking untreated rainwater and cases of infection with *Salmonella mississippi* (Ashbolt and Kirk 2006). The highest risk was found to be associated with exposure to untreated RHRW away from the home of the participants. These higher risk estimates probably reflected a lower level of immunity in populations not frequently exposed to this pathogen. Direct contact with native animals known to be a source of salmonellosis was determined not to be the cause of infections. The strongest predictor of infection was found to be the indirect contamination of RHRW systems.

It is probable that incidences of gastrointestinal associated with RHRW may be underreported. It is highly likely that only a portion of people with severe gastroenteritis would seek medical attention, and most fecal specimens that were collected from patients would not be tested in a hospital. In Australia, it has been estimated that only between 8 and 11% of *Campylobacter*- and *Salmonella*-related food-borne gastroenteritis cases are reported (Hall et al., 2006). In the United States, it has been estimated that only 10 to 33% of water-related gastroenteritis are reported (Frost et al., 1996). These statistics suggest that gastroenteritis from sources such as RHRW would have at least similarly low reporting levels, if not even lower. Based on the common community belief that RHRW is of good quality, it should be considered probable that cases of gastroenteritis would be blamed on other sources such as food before being blamed on RHRW.

Another limitation is that cases of gastroenteritis due to drinking untreated rainwater could also actually be masked by the background levels of gastroenteritis from other sources such as consumption of food and community-based infections. The most credible epidemiological study to date reported that the consumption of RHRW did not increase the risk of gastroenteritis as opposed to mains water (Heyworth et al., 2006). However, such results should be interpreted with care due to the lack of sensitivity of the epidemiological tool to detect gastroenteritis (Craun et al., 2004; Hrudey and Hrudey, 2004). It has been estimated that to detect illness at an annual rate of 100 cases per 10,000 people per year would require samples of 416,000 participants (Eisenberg et al., 2006). Considering the high costs and time required, therefore, epidemiological studies from sources such as RHRW may not be practical for the sensitive detection of gastroenteritis in the community.

Management of the Risk of Infections Associated with Potable and Nonpotable Uses of Roof-Harvested Rainwater

A recent review paper identified important parameters for optimum performance of RHRW systems (Lye, 2009). The fecal contamination of RHRW appears to be limited to improperly designed systems as well as systems that are not well maintained and do not undergo any disinfection procedures. It has been suggested that all RHRW systems should be appropriately maintained, including ensuring the cleanliness of the systems before rainfall events, especially roofs and gutters, which should be cleaned frequently, while the receiving tanks should be cleaned at least two times per year to improve the quality of water (Dillaha and Zolan, 1985). For example, the addition of first flush devices to the systems may reduce the contamination levels in the systems. Another recent study in Sydney, Australia, concluded that RHRW could provide drinking water quality that complied with the drinking water guidelines after bypassing the first 2 mm of rainfall using first flush devices (Kus et al., 2010).

In addition to the use of appropriate maintenance processes for rainwater tanks, initial risk assessments can be used to determine the relative health risks associated with the use of RHRW for different end uses. A few studies have attempted to identify the inherent risk of infection associated with the drinking and nonpotable uses of RHRW using Quantitative Microbial Risk Assessment (QMRA). A QMRA is a four-step probabilistic tool for estimating the human health risk associated with defined scenarios from exposure to specified pathogens (NRC 1983). The four steps are (i) hazard identification, (ii) exposure assessment, (iii) dose–response assessment, and (iv) risk characterization. One such study was undertaken by Fewtrell and Kay (2007), who investigated the risk of infection of *Campylobacter* from toilet flushing with RHRW in homes in the United Kingdom. A QMRA estimate was performed to quantify the risks of *Campylobacter* infection via ingestion of aerosols. The outcomes of this QMRA estimate concluded that any risk from flushing the toilet with harvested rainwater would be well within the acceptable range.

Another recent study used QMRA analysis to quantify the risk of infection associated with the exposure to zoonotic pathogens from drinking and nonpotable uses of RHRW in Queensland, Australia (Ahmed et al., 2009). This study concluded that the risk of infection from *G. lamblia* and *Salmonella* spp. associated with the use of rainwater for biweekly garden hosing was below the threshold value of one extra infection per 10,000 persons per year. However, the estimated risk of infection from drinking the rainwater daily was 44 to 250 (for *G. lamblia*) and 85 to 520 (for *Salmonella* spp.) infections per 10,000 persons per year, which is above the acceptable guideline levels outlined in the Potable Reuse section of the Australian Guidelines for Water Reuse (NRMMC–EPHC–NHMRC, 2008). Despite this, the overall health risk appeared to be higher than predicted from reported incidences of gastroenteritis in the local community where the study was undertaken. The authors noted that further work is needed to improve the assumptions needed to be made in the analysis, such as the proportion of gene copies that represent both viable and infective organisms, since quantitative PCR does not provide information regarding viability or infectivity and the occurrence of pathogens. These studies showed that health risk analyses have their place in aiding the use of RHRW but are currently restricted by the lack of comprehensive work on the prevalence of pathogens in RHRW. Improved levels of available data would enable accurate calculations of the level of risk and allow an assessment of the required levels of reductions in pathogens numbers for different end uses (drinking vs. nonpotable uses). This can then enable more appropriate treatment measures such as filtration and ultraviolet disinfection (Daschner et al., 1996; Jordan et al., 2008) can be undertaken to reduce the risk of infection from RHRW.

Conclusions and Future Directions

The review of the published literature reported here indicates that the microbial quality of RHRW water may be more highly variable than is commonly perceived. The published data also suggests that overall, the microbial quality of RHRW should be considered potentially poor until a more rigorous microbial assessment can be undertaken. On the basis of the reported data, it would be anticipated that the quality of RHRW is strongly influenced by the season, the number of preceding dry days, animal activities in close proximity to the roof and rainwater tanks, geographical location, and other factors (Lye, 2009; Kus et al., 2010). In addition, little information is currently available on the number of microbial pathogens that can be present in RHRW. The majority of the studies reported in the literature assessed the quality of the rainwater on the basis of the presence or absence of specific microbial pathogens, with little information available regarding the actual numbers of these pathogens in RHRW. In addition, no information is available concerning the ongoing prevalence of different pathogens in RHRW over time. It is recommended, therefore, that further research be undertaken on the occurrence and numbers of potential pathogens in RHRW in a range of locations over time using appropriately designed longitudinal sampling schemes.

In addition, any microbial assessment should involve the analysis of RHRW for actual pathogenic species, not just the common fecal indicator bacteria. The available data in the literature have predominantly indicated that the commonly used indicators such as fecal coliforms and *E. coli* may not be suitable to indicate the risk of illness from untreated rainwater due to their observed poor correlation with pathogens (Ahmed et al., 2010). In addition, several zoonotic bacterial and protozoan pathogens capable of causing infections in humans have been detected in individual rainwater systems, probably from wild birds and animals that have access to roofs (Ahmed et al., 2010; Simmons et al., 2001), and more testing of RHRW is needed to quantify the potential impact pathogens originating from animals on health risks from the different uses of this water.

Several case control studies established links between gastroenteritis and consumption of untreated RHRW. However, these reported outbreaks tended to involve small numbers of individuals, and the reported illnesses were often related to communal RHRW systems (Brodribb et al., 1995; Franklin et al., 2008; Murrell and Stewart, 1983). On the other hand, other studies could not identify RHRW as a source of infection and therefore could only hypothesize that RHRW was the possible source of infection via circumstantial evidence (Koplan et al., 1978; Merritt et al., 1999; Simmons and Smith, 1997). It should be noted that most of these case control studies used culture-based methods to establish a link between RHRW and fecal specimens from patients. Additional studies that focus on the collection and matching of pathogenic strains from fecal specimens from self-reported incidences of gastroenteritis, and from potential sources such as tap water and tank water using sensitive molecular typing methods, would provide valuable information to determine if there is a direct link between gastroenteritis and RHRW. This could be more practical than a comparable epidemiological study due to the complexity and costs of epidemiological studies and the fact that the most incidences of gastroenteritis remain unreported. The use of a QMRA health risk analysis using data on the reported incidences of microbial pathogens in RHRW and a series of potential exposure pathways would be another valuable tool to assess overall health risks associated with RHRW and the need for treatment before certain uses (i.e., drinking).

Finally, it is evident that new or improved guidelines and policies for RHRW systems are needed to assist maximizing the uptake and use of RHRW for a range of end uses while ensuring that any associated health risks are minimized through appropriate management procedures. Proper design and maintenance must be achievable to ensure the long-term success of RHRW integration in urban water systems. This should include ongoing monitoring of RHRW systems, health risks assessments, such as those using QMRA model, and appropriate management requirements to mitigate these risks. This will only be achieved through the collection of more data on the incidence and ongoing prevalence of microbial pathogens in RHRW systems.

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