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RAINWATER HARVESTING: A COMPREHENSIVE REVIEW OF LITERATURE

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List of Acronyms and Abbreviations

Ag	Silver
Al	Aluminum
AODC	Acridine orange direct count
As	Arsenic
B	Boron
Ba	Barium
BD	Below detection
Bi	Bismuth
BOD	Biological oxygen demand
Br	Bromide
Ca	Calcium
Cd	Cadmium
CI	Confidence interval
Cl	Chloride
Co	Cobalt
COD	Chemical oxygen demand
Cr	Chromium
Cu	Copper
CU	Color units
DALY	Disability adjusted life year
d	Day
DOC	Dissolved organic carbon
DW	Drinking water
DWG	Drinking water guidelines
DWS	Drinking water standards
EC	E-coli
EU	European Union
F	Flouride
FC	Fecal coliform
Fe	Iron
HCO_3	Bicarbonate
Hg	Mercury
HPC	Heterotrophic Plate Count
HU	Hazen Units
K	Potassium
L	Liter
m	Meter
Mg	Magnesium
mg/L	Milligrams per liter
mm	Millimeter
mmol/L	Millimols per liter
Mn	Manganese
Mo	Molybdenum
Na	Sodium
ND	Non-detectable
ng/L	Nanograms per liter
NH_3	Ammonia
NH_4	Ammonium
Ni	Nickel
nmol/L	Nanomols per liter
NO_2	Nitrite
NO_3	Nitrate
NTU	Nephelometric Turbidi
O	Oxygen
O & G	Oil and grease
PAH	Polycyclic aromatic hy
PCR	Polymerase chain reac
Pb	Lead
PO_4	Phosphate
PVC	Polyvinyl chloride
QMRA	Quantitative microbial
Rb	Rubidium
RCC	Reinforced cement co
RWH	Rainwater harvesting
Se	Selenium
Si	Silica
SO_4	Sulphate
Sr	Strontium
SS	Suspended solids
TC	Total carbon
TCo	Total coliform
TDS	Total dissolved solids
Ti	Titanium
TIC	Total inorganic carbon
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TS	Total solids
TSS	Total suspended solids
TTC	Thermo-tolerant colifo
TVC	Total viable count
U	Uranium
USEPA	U.S. Environmental Pr
V	Vanadium
WHO	World Health Organiza
Zn	Zinc
µeq/L	Microequivalents per l
µg/L	Micrograms per liter
µmol/L	Micromols per liter
µS/cm	Microsiemens per cen

Introduction to Rainwater Harvesting

Rainwater harvesting is the method by which rainwater that falls upon a roof surface is collected and routed to a storage facility for later use. As shown in Figure 1, rainwater harvesting (RWH) systems are a compilation of many components and processes, including (but not limited to) a catchment surface, conveyance system, pre-storage filtration, storage container, pump, post-storage filtration/treatment and post-storage distribution system. For the majority of systems, precipitation falls onto the roof, is collected via gutters, and conveyed to the storage container by a pipe network. Pre-storage filtration is often utilized to prevent sediment, leaves and debris from entering the storage container. A piping network then conveys the water to the storage container. A first flush diverter may be incorporated into the conveyance piping to divert the dirtiest of the runoff water (usually the first 1-3mm) away from the storage container, thereby preserving the quality of water collected for later use (Kus et al. 2010b). From the storage container, the water either drains via gravity or is pumped to the point(s) of use. Post-storage treatment is sometimes included in the RWH system, depending upon the quality of harvested water and the quality needed for designated uses.

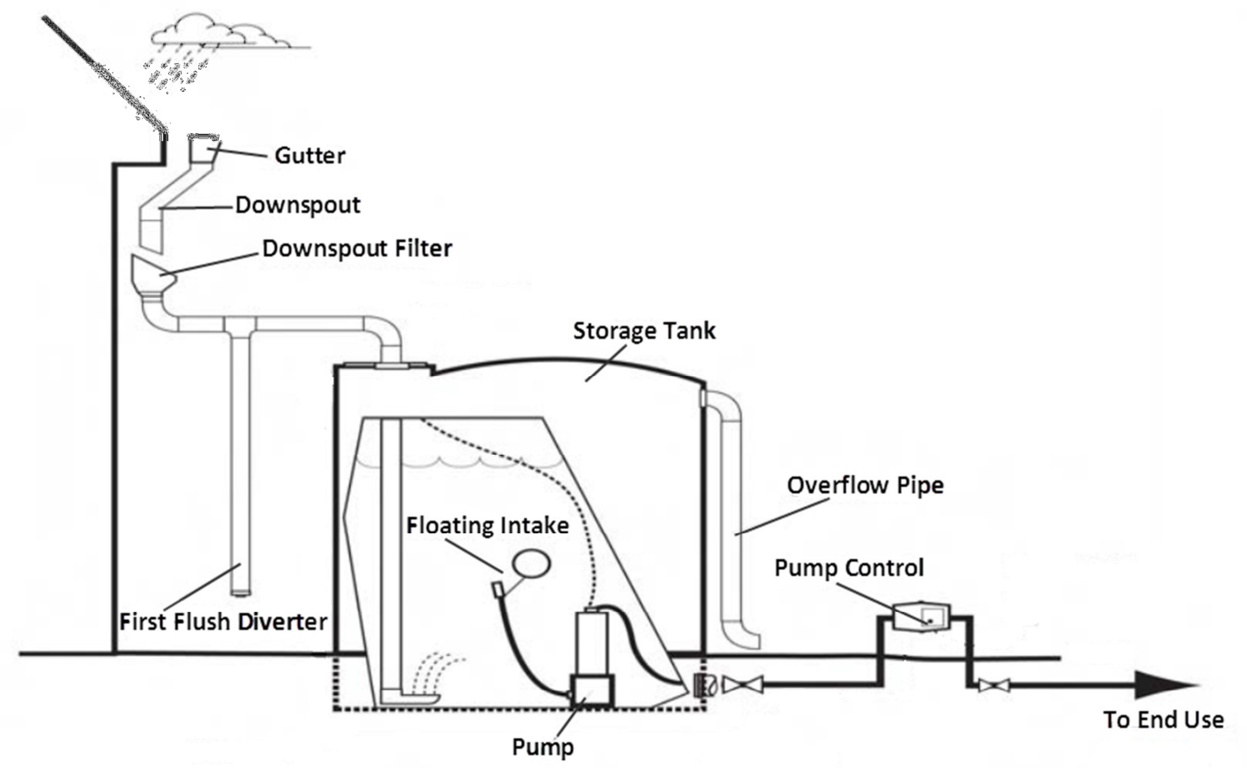


Figure 1. Example of an above-ground rainwater harvesting system (modified from Georgia 2009, with permission).

Rainwater harvesting (RWH) is far from a novel practice, as its use has been documented in ancient Greek and Roman civilizations (Phoca and Valavanis 1999; Crasta et al. 1982). Traditionally implemented in regions with limited access to water resources, RWH was commonplace in India, Jordan and other parts of Asia, Italy, South America and portions of Africa from the Middle Ages through the late 1900s (Radhakrishna 2003; Abdulla and Al-Shareef 2009; Gianighian 1996; Lee et al. 2000). The 20th and 21st centuries have brought population growth, climate change and increasing water supply shortages to many areas, including Australia, Germany, China and the United States (Coombes and Barry 2007; Hermann and Hasse 1997; Zhang et al. 2009a; Mendez et al. 2011); thus, RWH systems have grown in popularity and quantity in recent years as an alternative water supply in these regions.

This document presents a comprehensive review of research that has been conducted on rainwater harvesting throughout the world. In some cases collecting runoff from other surfaces, such as parking lots, sidewalks and landscaped areas, is referred to as rainwater harvesting; however, in this paper only systems collecting roof runoff are discussed.

Water Quality Aspects of Rainwater Harvesting

The need for conserving public potable water supplies continues to increase throughout the world and RWH is a valuable tool that may be used to fulfill this need; however, the lack of knowledge regarding the quality of harvested rainwater has prevented widespread use of this practice (Lye 2009). This section presents a review on the origin, transport and fate of potential RWH contaminants, including sediment, nutrients, heavy metals and other chemicals, and the implications these pollutants and processes have on the use of RWH as a supplemental water source.

Previous studies on harvested rainwater quality have produced contradictory conclusions, with some claiming harvested rainwater was severely polluted while others concluded that it was unpolluted (Abdulla & Al-Shareef 2009; Förster 1996; Sazakli et al. 2007; Zhang et al. 2010a). As more research has become available, it has become apparent that the quality of harvested rainwater is determined by the environment in which a given system is located and the materials used to construct the system (Abbasi and Abbasi 2011; Lee et al. 2010). As a result, it is imperative that designers and users of RWH systems understand the potential contaminants associated with their use and how these contaminants interact with each other and their environment, as these interactions will often dictate the necessary design, treatment and maintenance protocols to ensure harvested rainwater does not present a safety hazard to those using it (Magyar et al. 2007).

Sources of Nutrients and Heavy Metals in Rainwater Harvesting Systems

Although many ancient forms of RWH employed watershed-scale basins and dams to collect runoff, present-day RWH is often employed where a roof serves as the source of runoff (Hamdan 2009). This is most likely due to the fact that rooftops are comparatively cleaner than parking lots, sidewalks and other impervious surfaces; however, it is well documented that even runoff from roof surfaces can contain substantial amounts of heavy metals and nutrients (Yaziz et al. 1989; Melidis et al. 2007; Chang and Crowley 1993). There are several sources that can contribute these pollutants to rooftop runoff: the precipitation (i.e. wet deposition), atmospheric deposition that has accumulated on the roof surface (i.e. dry deposition) and materials used in the construction of the roof (Abbasi and Abbasi 2011).

Precipitation (Wet Deposition). The quality of rainfall falling onto a given surface is the key factor determining the quality of runoff leaving the surface (Hamdan 2009). Numerous studies have been conducted on the quality of rainwater prior to its contact with a surface and results vary substantially (Tables 1a and 1b). This is to be expected, as the chemical composition of rainwater is influenced by a multitude of factors, such as geographic location and influences, prevailing meteorological conditions and anthropogenic activities (agriculture, industry, motor vehicle emissions, etc.) and thus varies greatly by location, season, and even storm type (Adeniyi and Olabanji 2005; Chang et al. 2004; Lee et al. 2010; Avila and Alarcón 1999). For all results reported in Tables 1a and 1b, the original values have been converted to the same units. In cases of nitrogen species, all original molecular concentrations were converted to concentrations as nitrogen.

As rain droplets descend through the atmosphere, they dissolve gases, absorb aerosols and collect other suspended particulates such as dust and ash (Zobrist et al. 2000; Hamdan 2009; Huston et al. 2009; Adeniyi and Olabanji 2005; Abbasi and Abbasi 2011). The composition of precipitation is influenced by the proximity and strength of emission sources, chemical reactions occurring in the atmosphere and scavenging mechanisms of moving air masses (Avila and Alarcón 1999). Perhaps the most well-known phenomenon that can be attributed to the scavenging of atmospheric particles by rainwater is that of acid rain. When rainwater absorbs sulfur and nitrogen oxides, the pH decreases and the rain becomes acidic (Lee et al. 2010; Hamdan 2009). The presence of sulfur and nitrogen oxides can be attributed to fossil fuel combustion (specific sources include motor vehicle emissions, combustion in building heating systems and industrial processes); consequently, acid rain is prominent in regions characterized by high vehicle traffic volumes, high density residential development and industry (Olem and Berthouex 1989; Melidis et al. 2007; Lee et al. 2010; Hamdan 2009).

The relationship between human development and acidic rainfall has been verified by countless studies, a few of which are referenced in Table 1a. Yaziz et al. (1989) conducted a study in an area of Malaysia that was in close proximity to heavily trafficked highways and was geographically confined such that the dispersion of atmospheric pollutants via wind was limited. Consequently, the pH of rainwater samples collected during the study were predominantly below the World Health Organization's (WHO) drinking water requirements of 6.5-8.5 (Table 2), and averaged approximately 5.9. Lee et al. (2000) reported seasonal fluctuations in rainwater concentrations of SO_4^{2-} and NO_3^- in northern Taiwan that corresponded to increases in the use of heating systems (and, thus, fossil fuel combustion) during winter months. This study area was also characterized by heavy traffic volumes, densely populated residential areas and somewhat enclosed geographically (thereby limiting the dispersion of atmospheric pollution), thus resulting in an average measured pH of 5.25 (Lee et al. 2000).

Acid rain is not the only environmental concern resulting from atmospheric pollution. As shown in Tables 1a and 1b, numerous other pollutants have been measured in rainwater due to their presence in the atmosphere. Yaziz et al. (1989) reported an average lead (Pb) concentration four times greater than the WHO drinking water guideline of 50µg/l, purportedly due to motor vehicle exhaust emissions from a nearby highway. Yufen et al. (2008) measured total nitrogen (TN) concentrations of rainwater samples in highly-urban Beijing, China, 85% of which exceeded the country's surface water standard of 2mg/L. In East Texas, U.S., rainwater concentrations of copper (Cu) and zinc (Zn) exceeded U.S. 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. Results from a study by Thomas and Green (1993) showed higher suspended solids concentrations in areas with industrial emissions and higher nitrate concentrations when fertilizers were used nearby.

While atmospheric pollution is often associated with decreases in rainwater pH, some geographic influences and types of pollution can lead to an increase in pH. Melidis et al. (2007) reported an average pH of 7.44 (Table 1a) in rainwater samples collected in Xanthi, Greece, and attributed the alkaline nature of the water to the presence of calcium (Ca) and magnesium (Mg), which originate from limestone dust generated from nearby mountains via physical weathering processes. The relative lack of emissions containing sulfur and nitrogen compounds and prevailing winds that disperse atmospheric pollution also contribute to the high pH (Melidis et al. 2007).

Table 1a. Physico-chemical characteristics of rainwater. Values in mg/L unless otherwise stated.

Reference	**Location**	**pH**	**Conductivity (µS/cm)**	**Turbidity (NTU)**	**TSS**	**TDS**	**Total Nitrogen**	**NH_4^+-N**	**NO_2^--N**	**NO_3^--N**	**Total Phosphorus**	**PO_4**	**SO_4^{2-}**
Adeniyi & Olabanji (2005)	Ile-Ife, Nigeria	6.68	10.4	6.3	20.1	19.3		0.05		0.86			0.5
Avila & Alarcón (1999)[c]	Catalonia, Spain	6.4	18					0.41		1.28			2.21
Chang and Crowley (2004)	Nacogdoches, TX							0.584*				0.04*	
Chang et al. (2004)	Nacogdoches, TX	5.55	27.6										
Hamdan (2009)	Germany	5.1	49.8							1.061			9.6
He et al. (2011)	Singapore						0.643	0.19		0.273	0.026	0.009	
Lee et al. (2010)	Gangneung, South Korea	5.25	25										
Mantovan et al. (1995)	Italy	5.73	36.78					1.61		1.04		0.008	7.12
McColl and Bush (1978)	Berkeley, CA	5	13.2										
Melidis et al. (2007)	Xanthi, Greece							0.41		1.87			0.02
Olem & Berthouex (1989)[a]	Kentucky/Tennessee	4.53	17.2							1.19		0.010	1.97
Peters and Bonelli (1982)	Essex, NY		12.3										
Quek & Förster (1993)[b]	Bayreuth, Germany	3.88			17.0								
Sazakli et al. (2007)	Kefalonia Island, Greece	8.31*	103*					0.01*	0.013*	.269*		0.09*	8.0*
Smath and Potter (1987)	Greenville, ME	4.6	22.4										
Thomas & Green (1993)	Armidale, Australia (Rural)	6.9	25	0.2	2.0					0.23			
Thomas & Green (1993)	Armidale, Australia (Urban)	6.8	30	0.2	3.0					0.21			
Thomas & Green (1993)	Armidale, Australia (Industrial)	6.7	20	0.8	6.0					0.05			
Yaziz et al. (1989)	Selangor, Malaysia	5.9	13.7	3	17.0	7.0							
Yufen et al. (2008)	Beijing, China				6.49		3.99				0.06		

*median value

[a] reported as wet deposition

[b] values are the average of event 1 and event 2

[c] volume-weighted mean

Table 1b. Heavy metal and ionic concentrations in rainwater. Values in mg/L unless otherwise stated.

Reference	**Location**	**Al^{3+}**	**Ca^{2+}**	**Cd**	**Cl^{-}**	**Cu^{2+}**	**Cr**	**Fe**	**HCO_3^{-}**	**K^{+}**	**Mg^{2+}**	**Mn^{2+}**	**Na^{+}**	**Ni**	**Pb^{2+}**	**Zn^{2+}**
Adeniyi & Olabanji (2005)	Ile-Ife, Nigeria		0.77		1.7				5.5	0.06	0.14		0.21			
Al-Khashman (2009)	West Jordan	0.32		0.052		0.073	0.0031	0.43						0.0035	0.066	0.21
Al-Momani et al. (2000)	Irbid, Jordan		2.63							0.4	0.5		1.9			
Al-Momani et al. (2008)	Irbid, Jordan	0.01		0.00005		0.0007	0.0001	0.004				0.00007		0.0003	0.00198	0.0014
Avila & Alarcón (1999)[c]	Catalonia, Spain		1.15		1.01					0.2	0.1		0.5			
Baez et al. (2007)	Mexico	0.02		0.00037			0.00026					0.00834		0.00298	0.00158	
Beysens et al. (2006)	Bordeaux, France		1.52			0.0088				0.33			4.18			0.14
Cao et al. (2009)	Guangzhou, China		2.08							1.3	0.2		1.3			
Chang and Crowley (2004)	Nacogdoches, TX								9*						0.031*	2.199*
Chang et al. (2004)	Nacogdoches, TX	0.35				0.043					0.823	0			0.034	0.139
Demirak et al. (2006)	Mugla, Turkey		0.174							0.0035			0.017			
Gatz et al. (1984)	Glen Ellyn, IL	0.68				0.08									0.04	0.057
Hamdan (2009)	Germany		1.1	0.0004	2.9		0.0009				0.2				0.0053	0.0257
Hontoria et al. (2003)	Madrid, Spain		11							1.37	1.0		2.2			
Lazrus et al. (1970)	USA					0.021						0.012			0.034	0.107
Lee et al. (2010)	Gangneung, South Korea	0.1		0		0.035	0.002					0.04			0.02	0.5
Mantovan et al. (1995)	Italy		1.86		1.45				1.8	0.44	0.44		0.86			
McColl and Bush (1978)	Berkeley, CA					0.005					0.07	0.003				0.016
Melidis et al. (2007)	Xanthi, Greece		20							1.1	1.4					
Olem and Berthouex(1989)[a]	Kentucky/Tennessee		0.4		0.14					0.05	0.05		0.14			
Peters and Bonelli (1982)	Essex, NY										<0.1	0.002			0.003	0.052
Quek & Förster (1993)[b]	Bayreuth, Germany		3	0.00075		0.01									0.03	0.09
Salve et al. (2008)	Nagpur, India		0.6							0.1	0.04		0.3			
Sazakli et al. (2007)	Kefalonia Island, Greece		15.2*	0.00005*	7*	<0.0025*	<0.0013*	0.011*		2.4*	0.6*	0.001*	6*	<0.01*	<0.002*	0.01
Smath and Potter (1987)	Greenville, ME					0.005					0.022				0.004	0.014
Thomas & Green (1993)	Armidale, Australia (Rural)														0	0
Thomas & Green (1993)	Armidale, Australia (Urban)														0	0
Thomas & Green (1993)	Armidale, Australia (Industrial)														0	0.5
Yaziz et al. (1989)	Selangor, Malaysia														0.2	0.034

*median value

[a] reported as wet deposition

[b] values are the average of event 1 and event 2

[c] volume-weighted mean

Table 2. Summary of drinking water standards (DWS) and guidelines (DWG) from various agencies.

	WHO DWG (WHO, 2008)	USEPA Primary DWS (USEPA, 2009)	USEPA Secondary DWS (USEPA, 2009)	Australian DWG (Australian, 2011)	EU Directive DW Guidelines (EU, 1998)
Al	0.2 mg/L		0.5 - 0.2 mg/L	0.2 mg/L	0.2 mg/L
As	0.05 mg/L	0.01 mg/L		0.01 mg/L	0.01 mg/L
B	1.0 mg/L			4 mg/L	1.0 mg/L
Ba	1.0 mg/L	2 mg/L		2 mg/L	
Ca	75 mg/L				
Cd	0.005 mg/L	0.005 mg/L		0.002 mg/L	0.005 mg/L
Cl	200 mg/L		250 mg/L	250 mg/L	250 mg/L
COD_{CR}	15 mg/L				
Color	15 mg Pt-Co/L		15 color units	15 HU	
Conductivity					2500 µS/cm
Cr	0.05 mg/L	0.1 mg/L		0.05 mg/L	0.05 mg/L
Cu	0.05 mg/L	1.3 mg/L	1.0 mg/L	2 mg/L	2.0 mg/L
F	1.5 mg/L	4.0 mg/L	2.0 mg/L	1.5 mg/L	1.5 mg/L
Fe	0.3 mg/L		0.3 mg/L	0.3 mg/L	
Hardness	500 mg $CaCO_3$/L			200 mg/L	
Hg	0.001 mg/L	0.002 mg/L		0.001 mg/L	0.001 mg/L
K	20 mg/L				
Mg	30 mg/L				
Mn	0.3 mg/L		0.05 mg/L	0.5 mg/L	0.05 mg/L
Na	100 mg/L			180 mg/L	200 mg/L
Ni	0.05 mg/L			0.02 mg/L	0.02 mg/L
$NO_{3-}N$		10 mg/L		11.3 mg/L	11.3 mg/L
Pb	0.05 mg/L	0.015 mg/L		0.01 mg/L	0.01 mg/L
pH	6.5-8.5	6.5-8.5	6.5 - 8.5	6.5 - 8.5	6.5 - 9.5
Se	0.01 mg/L	0.05 mg/L		0.01 mg/L	0.01 mg/L
SO_4	400 mg/L		250 mg/L	250 mg/L	250 mg/L
TDS	500 mg/L		500 mg/L	600 mg/L	
Total Nitrogen	10 mg/L	10 mg/L			
Total Phosphorus	n/a	n/a			
Turbidity	5 NTU			5 NTU	
Zn			5 mg/L	3 mg/L	

There are many regions of the world where atmospheric pollution and acid rain are prevalent; however, some regions still enjoy relatively clean atmospheric conditions. This is evident in the study conducted by Sazakli et al. (2007) (Table 1a), which reported a median rainwater pH of 8.31. Sazakli et al. (2007) attributed this elevated pH to the relatively unpolluted state of the region (very little traffic, industrial or agricultural emissions) and the influence of a marine environment.

Atmospheric (Dry) Deposition. Dry deposition, a process by which particulates in the atmosphere that are generated via automobile emissions, industrial processes and fertilizer applications settle out and accumulate on surfaces, can be a contributor of nutrients, sediment and heavy metals in rooftop runoff (Yaziz et al. 1989; Lee et al. 2010; Despins et al. 2009; Thomas and Greene 1993; Huston et al. 2009; Quek and Förster 1993). Constituents that have been linked to atmospheric deposition include TSS, Pb (due to heavy traffic or industrial emissions), chloride (Cl) (due to application of de-icing salts in the winter), Cu, nitrate (due to agricultural fertilizer applications), nitrite, Zn, Al, Fe and Ca (Förster 1999; Förster 1996; Thomas and Green 1993; Lee et al. 2010; Quek and Förster 1993; Morrow et al. 2010; Mendez et al. 2011). Examples of rates at which certain constituents can be deposited on roof surfaces via dry deposition can be found in Table 3.

As rain falls onto a roof surface, it will wash off the particulates that have accumulated on the surface since the prior precipitation event, thus adding these constituents to the roof runoff. A longer antecedent dry period results in a greater amount of accumulated deposition and, thus, a higher concentration of pollutants in runoff during the next rainfall (Förster 1999; Thomas and Greene 1993; Quek and Förster 1993, Chang and Crowley 1993). Yufen et al. (2008) reported an increase in TN and total phosphorus (TP) concentrations as the number of preceding days without precipitation increased. Similarly, Thomas and Green (1993) noted a significant positive relationship between TSS, turbidity, conductivity and Pb concentrations in roof runoff and the length of the dry period between rainfall events. 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 of a precipitation event (Yufen et al. 2008; Förster 1996; Kus et al. 2010b; Quek and Förster 1993). This results in high initial concentrations of pollutants during the first 1-2mm of runoff, followed by a rapid decrease in concentrations as rainfall continues (Förster 1999; Förster 1996).

Although there is no question that atmospheric deposition can contribute pollutants to roof runoff, the relative extent to which runoff contamination can be attributed to dry deposition remains debatable. Morrow et al. (2010), Avila and Alarcón (1999) and Huston et al. (2009) conclude that atmospheric deposition is a minor contributor to the total contaminant load in roof-harvested rainwater, while Yaziz et al. (1989) and Thomas and Greene (1993) claim that dry deposition greatly influences the quality of runoff leaving a roof catchment. These differing opinions could be due to monitoring/assessment methods or environmental and climatic characteristics of the monitoring sites. Morrow et al. (2010) and Huston et al. (2009) compared roof runoff and rainwater concentrations to those of harvested rainwater after it had passed through the conveyance piping and storage tank of the RWH system and consequently concluded that rainwater composition had little effect on quality of harvested water. Contrarily, Yaziz et al. (2010) and Thomas and Green (1993) compared rainwater and roof runoff to WHO drinking water guidelines, which led to a contradictory conclusion that rainwater composition was a major factor with respect to harvested water quality.

Table 3. Physico-chemical characteristics of dry deposition (all values in mg m^{-2} d^{-1}).

	Rossini et al. (2005) Venice, Italy	Lim et al. (2006) Los Angeles, CA	Wu et al. (2006) Taiwan	Chang & Crowley (1993) Nacogdoches, TX
TSS				8.39
As	0.0009			
Ca^{2+}				1.5
Cd	0.0004			0.00012
Cl				0.565
Cu^{2+}	0.0118	0.021	0.0219	0.0056
Cr	0.0027	0.0046	0.0112	0.0008
Fe				0.108
Mg^{2+}				0.21
Mn^{2+}				0.0037
Na				0.37
Pb^{2+}	0.0099	0.019	0.056	0.0048
Zn^{2+}	0.0795	0.12	0.109	0.03
Total Nitrogen				1.84
$NH4^{+}$				0.71
NO_3^{-}				0.23
Total Phosphorus				0.097
SO_4^{2-}				2.26

Roofing Materials. As shown in Table 4 and summarized in Table 5, there is overwhelming evidence that roofing materials can serve as a significant source of contaminants in roof runoff (Melidis et al. 2007; Förster 1999; Adeniyi and Olabanji 2005; Hamdan 2009; Förster 1996; Despins et al. 2009; Clark et al. 2008; Chang et al. 2004; Zobrist et al. 2000; Chang and Crowley 1993; Quek and Förster 1993; Simmons et al. 2001). 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 (Förster 1999; Despins et al. 2009; Zobrist et al. 2000).

Depending on the type of material, the pH of rainwater can either increase or decrease when it contacts the roof surface. As pH is a key factor in the chemical phases (e.g. dissolved vs. adsorbed) of heavy metals, this has substantial implications for water quality (Hamdan 2009). Roofs comprised of metal (e.g., Iron-zinc, aluminum, galvanized iron, zinc) or wood shingles have been shown to decrease the pH of rainwater (Adeniyi and Olabanji 2005; Thomas and Greene 1993; Mendez et al. 2011; Chang et al. 2004). An increase in the acidity of water running over the roof surface increases the reactivity between the water and the roofing materials and particulates accumulated on the roof surface from atmospheric deposition, potentially causing leaching of chemicals and metals (Chang et al. 2004).Roofs comprised of alkaline materials, such as concrete, gravel, asphalt shingles, clay, or pantile, instigate a significant increase in the pH of rainwater (Olem and Berthouex 1989; Hamdan 2009; Adeniyi and Olabanji 2005; Thomas and Green 1993; Förster 1996; Förster 1999; Mendez et al. 2011; Yaziz et al. 1989; Chang and Crowley 1993; Quek and Förster 1993). This increase in pH shifts the predominant phase for metals from dissolved to particulate, thereby facilitating precipitation and adsorption (Förster 1999; Hamdan 1999; Quek and Förster 1993). The pH can also affect the reactivity of metals. Zobrist et al. (2000) showed that a decrease in pH slightly increased the fraction of labile species (i.e. reactive species) for Zn, Cu, Pb and Cd.

Table 4a. Water quality data from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Sediment	Nitrogen Species	Phosphorus Species
Adeniyi & Olabanji 2005	Nigeria	Thatch (T), Concrete (C), Aluminum (Al), Iron-Zinc (Fe-Zn), Adex-asbestos (A)	TSS Thatch: 34.20 mg/L Concrete: 42.57 mg/L Aluminum: 33.32 mg/L Iron-Zinc: 44.09 mg/L Adex: 43.43 mg/L TDS Thatch: 38.97 mg/L Concrete: 44.49 mg/L Aluminum: 19.66 mg/L Iron-Zinc: 24.42 mg/L Adex: 36.59 mg/L TS Thatch: 73.17 mg/L Concrete: 87.05 mg/L Aluminum: 50.99 mg/L Iron-Zinc: 68.51 mg/L Adex: 60.02 mg/L MEAN VALUES	Nitrate (NO_3^--N): Thatch: 0.93 mg/L Concrete: 0.75 mg/L Aluminum: 1.40 mg/L Iron-Zinc: 0.34 mg/L Adex: 0.51 mg/L Ammonium (NH_4-N^+): Thatch: 0.04 mg/L Concrete: 0.04 mg/L Aluminum: 0.04 mg/L Iron-Zinc: 0.05 mg/L Adex: 0.05 mg/L MEAN VALUES Note: Data source methodology unclear. Values were assumed to be reported as ionic concentrations and were converted to -N values.	
Chang & Crowley 1993	Nacogdoches, TX, USA	Rock and tar (RT), terra cotta (TC), wood shingle (WS), composition shingle (CS)		NH_4-N (mg/l): RT: 0.197 TC: 0.597 WS: 2.268 CS: 1.225 MEAN VALUES	PO_4 (mg/l): RT: 0.09 TC: 0.1 WS: 0.15 CS: 0.11 MEAN VALUES

Table 4a, cont. Water quality data from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Sediment	Nitrogen Species	Phosphorus Species
Clark et al. 2008	Alabama, USA	Individual Building Materials, as listed		NO$_3$-N NH$_3$-N Asphalt/tar shingles: 1.52 0.83 Roofing felt: 4.2 108 Ondura red vinyl roofing: 2.44 1.44 Fiberglass roofing: 0 0 White plastic roofing: 0.99 0 Cedar roofing shingles: 0 0 Galvanized metal roofing (1): 58.4 * 12.1 Galvanized metal roofing (2): n/a 1.14 Waterproofed wood: 9.12 0 Pressure-treated wood: 6.47 0.38 Fake slate roofing shingle: 2.71 0 Leak stopper rubberized roof patch: 9.43 0 Kool seal acrylic patching cement: 0 0 Gardner Wet-R-Dri roofing: 0 0 Silver dollar aluminum roof coating: n/a n/a All values in mg/kg MEAN VALUES	PO$_4$ (mg/kg) Asphalt/tar shingles: 29.4 Roofing felt: 44.6 Ondura red vinyl roofing: 0 Fiberglass roofing: 0.86 White plastic roofing: 0 Cedar roofing shingles: 1.23 Galvanized metal roofing (1): 53.8 Galvanized metal roofing (2): 30.8 Waterproofed wood: 0 Pressure-treated wood: 62.2 Fake slate roofing shingle: 0.07 Leak stopper rubberized roof patch: 0.05 Kool seal acrylic patching cement: 21.6 Gardner Wet-R-Dri roofing: 203 Silver doller aluminum roof coating: 0 MEAN VALUES
Farreny et al. 2011a	Spain	1 of each: Clay tile, metal sheet, polycarbonate plastic and flat gravel	Min: 0 Max: 38.5 Mean±SE: 5.98±0.95 Median: 3.63 All values in mg/L	NH$_4$ (mg N/L): Min- 0.04 Max- 2.42 Mean±SE- 0.50±0.07 Median- 0.42 N0$_3$ (mg N/L): Min- 0.002 Max- 2.11 Mean±SE- 0.40±0.06 Median- 0.26 NO$_2$ (mg N/L): Min- 0 Max- 2.68 Mean±SE- 0.10±0.04 Median- 0	Phosphates (PO$_4$), mg/L): Min- 0 Max- 6.60 Mean±SE- 0.32±0.14 Median- 0

*Exceeds USEPA primary drinking water standards (Table 2).

Table 4a, cont. Water quality data from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Sediment	Nitrogen Species	Phosphorus Species
Lee et al. 2012	South Korea	Wooden shingle (WS), Concrete tile (CT), Clay tile (CL), Galvanized steel (GS)	Average TSS (mg/L) in first flush tanks: CT = 309.0 GS = 285.8 WS = 213.9 CL = 219.3 Average TSS (mg/L) after first flush: CT = 45.0 GS = 15.1 WS = 35.65 CL = 41.6	Average nitrate-N (mg/L) in first flush tanks: CT = 0.58 GS = 0.6 WS = 0.7 CL = 0.43 Average nitrate-N (mg/L) after first flush: CT = 0.06 GS = 0.01 WS = 0.1 CL = 0.64	
Melidis et al. 2007	Greece	Varied (concrete, mosaic, clay tiles, iron-sheet and Maxitherm)		Roof Drainage Concentrations: NH_4:-N: 0.37 (0.10 - 1.03) mg/L NO_3-N: 0.33 (0.09 - 0.61) mg/L MEAN VALUES	
Mendez et al. 2011	Texas, USA	Asphalt fiberglass shingle (shingle), Galvalume® (55% aluminum-zinc allow coated steel, "metal")	Metal Pilot: 20-87 Metal Full: 10-50 Shingle Pilot: 12-54 Shingle Full: 20-150 All values in mg/L VALUE RANGES	Nitrate (mg N/L): Metal Pilot- 0-2.0 Metal Full - 0.4-4.1 Shingle Pilot- 0-1.8 Single Full- 0.3-4.7 Nitrite (mg N/L): Metal Pilot- 0.01-0.03 Metal Full - 0.01-0.05 Shingle Pilot- 0.01-0.04 Shingle Full- 0.01-0.06 VALUE RANGES	

Table 4a, cont. Water quality data from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Sediment	Nitrogen Species	Phosphorus Species
Moon et al. 2012	Korea	Vinyl Chloride	Turbidity (NTU): Max = 303.5 Min = 0.2 Mean = 4.8 Median = 1.2	NO_2-N (mg/L): Max = 0.75 Min = ND Mean = 0.01 Median = 0.01 NO_3-N(mg/L): Max = 16.4 Min = ND Mean = 0.84 Median = 0.34 NH_4-N (mg/L): Max = 29.2 Min = 0.01 Mean = 1.04 Median = 0.81	PO_4 (mg/L): Max = 0.34 Min = ND Mean = 0.01 Median = ND
Morrow et al. 2010	Australia	Average of 3 Colorbond™ roofs (of various ages) and 1 Zincalume™ roof			elemental P: 145 µg/L MEAN VALUES

Table 4a, cont. Water quality data from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Sediment	Nitrogen Species	Phosphorus Species
Van Metre & Mahler 2003	Austin, Texas, USA	Metal roof nearest highway (MNM), metal roof furthest from highway (MFM), Asphalt shingle roof nearest highway (ANM), Asphalt shingle roof furthest from highwater (AFM)	Suspended Sediment (mg/L): MNM = 278 MFM = 122 ANM = 297 AFM = 128.3 AVERAGE OF 3 SAMPLES		
Yaziz et al. 1989	Selangor, Malaysia	Galvanized iron (GI) & tile	GI Tile TS (mg/L): 92.6 156.8 TSS (mg/L): 72 124 TDS (mg/L): 20.2 33.8 MEAN VALUES		
Yufen et al. 2008	Beijing, China	Asphalt	Mean: 121.31 mg/L Range: 0.01-1073 mg/L	Total nitrogen: Mean: 10.55 mg/L Range: 0.02-50.56 mg/L	Total phosphorus: Mean: 0.28 mg/L Range: 0.03-1.47 mg/L
Zobrist et al. 2000	Switzerland	Clay tile, Polyester (Poly), Gravel	Tile Poly Gravel SS: 64 18 3.0 in mg/L MEAN VALUES	Tile Poly Gravel NH_4: 0.52 1.4 0.22 in mg N/L MEAN VALUES	

Table 4b. Water quality data from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Heavy Metals	Other Parameters
Adeniyi & Olabanji 2005	Nigeria	Thatch (T), Concrete (C), Aluminum (Al), Iron-Zinc (Fe-Zn), Adex-asbestos (A)	Mg^{2+}: Thatch: 1.61 mg/L Concrete: 0.52 mg/L Aluminum: 0.27 mg/L Iron-Zinc: 0.81 mg/L Adex: 0.31 mg/L MEAN VALUES	T C Al Fe-Zn A Turbidity (NTU): 24.7 10.1 11.3 6.7 6.4 pH: 7.00 7.45 6.68 6.77 7.09 Conductivity (µs/cm): 122.6 84.13 29.54 19.46 64.68 Ca (mg/L): 6.12 9.48 1.29 2.03 5.84 Na (mg/L): 0.31 0.38 0.52 0.99 0.31 K (mg/L): 1.09 0.14 0.09 0.31 0.12 Cl (mg/L): 0.76 2.63 1.51 4.48 1.88 SO_4 (mg/L): 1.49 0.05 2.69 0.88 0.41 SiO_2 (mg/L): 7.3 10.4 10.2 10.2 10.9 MEAN VALUES
Chang & Crowley 1993	Nacogdoches, TX, USA	Rock and tar (RT), terra cotta (TC), wood shingle (WS), composition shingle (CS)	RT TC WS CS Zinc (mg/L): 4.88 1.08 5.64 2.33 Lead (mg/L): 0.05* 0.028* 0.045* 0.056* MEAN VALUES	

Table 4b,cont. Water quality data from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Heavy Metals	Other Parameters
Chang et al. 2004	Texas, USA	Wood shingle (WS), composition shingle (CS), aluminum (Al), galvanized iron (GI)	WS CS Al GI Al (mg/L): Mean- 0.382 0.495 0.381 0.435 Med- 0.224 0.181 0.169 0.194 Max- 2.343 6.736 4.077 6.884 Min- 0.008 0.008 0.008 0.008 Mg (mg/L): Mean- 0.982 0.713 0.372 0.362 Med- 0.646 0.368 0.292 0.246 Max- 6.68 5.063 1.478 3.659 Min- 0.082 0.023 0.004 0.001 Mn (mg/L): Mean- 0.044 0.028 0.015 0.017 Med- 0.022 0.018 0.020 0.020 Max- 0.404 0.369 0.117 0.252 Min- 0.001 0.001 0.001 0.001 Cu (mg/L): Mean- 0.029 0.025 0.026 0.028 Med- 0.022 0.018 0.020 0.020 Max- 5.410* 0.126 0.248 0.224 Min- 0.001 0.001 0.001 0.001 Pb (mg/L): Mean- 0.045* 0.038* 0.037* 0.049* Med- 0.025* 0.025* 0.025* 0.025* Max- 0.70* 0.203* 0.134* 0.255* Min- 0.025* 0.025* 0.025* 0.025* Zn (mg/L): Mean- 16.317 1.372 3.230 11.788 Med- 9.717 0.859 2.248 8.219 Max- 109.7 13.59 16.6 212.33 Min- 0.039 0.043 0.514 0.124	WS CS Al GI Conductivity (µS/cm): Mean- 38.78 30.19 14.53 20.34 Med- 28 22 10 17 Max- 232 179 57 172 Min- 7 6 2.2 4 pH: Mean- 5.07 6.69 6.20 6.59 Med- 5.03 6.73 6.22 6.63 Max- 6.89 8.25 7.26 7.41 Min- 3.33 4.08 4.78 3.62

*Exceeds USEPA primary drinking water standards (Table 2).

Table 4b, cont. Water quality data from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Heavy Metals	Other Parameters
Clark et al. 2008	Alabama, USA	Individual Building Materials, as listed	Cu Pb Zn Fe Asphalt/tar shingles: 0.66 0.34 1.22 46.7 Roofing felt: 0.026 0.11 0 1.87 Ondura red vinyl roofing: 0 0 0 0 Fiberglass roofing: 0.017 0.005 0.53 0 White plastic roofing: 0.076 0 1.42 2 Cedar roofing shingles: 0.033 0.11 0.64 1.64 Galvanized metal roofing (1): 0.44 0.16 16500 9400 Galvanized metal roofing (2): 0 1.61 11900 3300 Waterproofed wood: 161 0.29 3.72 3.22 Pressure-treated wood: 191 0 1.35 2.69 Fake slate roofing shingle: 0.2 0.42 1.81 20.1 Leak stopper rubberized roof ptch: 0.13 3.78 2.61 2.25 Kool seal acrylic patching cement: 0.15 0.65 2.94 229 Gardner Wet-R-Dri roofing: 0 0.094 0 1.39 Silver doller Al roof coating: 1.14 0.3 0 151 All values in mg/kg MEAN VALUES	
Davis et al. 2001	Maryland, USA	Varied (first flush samples only)	Roof Runoff Sampling (mg/L) (median, mean) Residential: Pb = 0.002*, 0.0015* Cu = 0.007*, 0.0075* Cd= 0.0001*, 0.00012* Zn= 0.11, 0.1 Commercial: Pb= 0.012*, 0.062* Cu= 0.029*, 0.2* Cd= 0.0007*, 0.0013* Zn= 0.76, 1.1 Institutional: Pb= 0.064*, 0.064* Cu= 2.1*, 5* Cd= 0.0004*, 0.0006* Zn= 0.46, 1.1	

*Exceeds USEPA primary drinking water standards (Table 2).

Table 4b, cont. Water quality data from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Heavy Metals	Other Parameters
Farreny et al. 2011a	Spain	1 of each: Clay tile, metal sheet, polycarbonate plastic and flat gravel		Min Max Mean±SE Median Conductivity (µS/cm): 15.4 456 85.0±10.0 59.3 pH: 6.54 8.85 7.59±0.07 7.61 TOC (mg/L): 0.65 53.6 11.6±1.7 6.4 TIC (mg/L): 1.36 19.0 7.37±0.66 5.78 SO_4 (mg/L): 0 11.5 3.54±0.39 2.59 Cl (mg/L): 0.15 119 8.86±2.38 3.38 Total carbonates: (mmol/L) 0.12 1.62 0.63±0.06 0.49
Lee et al. 2012	South Korea	Wooden shingle (WS), Concrete tile (CT), Clay tile (CL), Galvanized steel (GS)	Aluminum (mg/L) First Flush After First Flush CT 0.535 0.099 GS 0.622 0.033 WS 0.227 0.043 CL 0.243 0.036 Copper (mg/L) First Flush After First Flush CT 0.058 0.015 GS 0.059 0.016 WS 0.034 0.009 CL 0.037 0.012 Iron (mg/L) First Flush After First Flush CT 0.160 0.048 GS 0.302 0.027 WS 0.154 0.023 CL 0.155 0.024 Lead (mg/L) First Flush After First Flush CT 0.014 0.005 GS 0.012 0.003 WS 0.010 0.003 CL 0.011 0.003	Sulfate (mg/L) First Flush After First Flush CT 3.64 0.38 GS 2.87 0.11 WS 5.57 0.65 CL 3.1 2.87 Total Organic Carbon (mg/L) (First Flush Only) CT = 32.9 GS = 31.8 WS = 49.7 CL = 35.6

Table 4b, cont. Water quality data from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Heavy Metals	Other Parameters
Melidis et al. 2007	Greece	Varied (concrete, mosaic, clay tiles, iron-sheet and Maxitherm)	• Cu, Cr and Ni undetectable in roof drainage Roof Drainage Samples (mg/L): Fe: (0.019-0.195) Mn: (0.005-0.068) Zn: (0.01-0.54) Mg: 1.21 (0.19-2.97)	Roof Drainage Concentrations (mg/L): K: 5.9E-3 (4.7E-4 - 1.7E-2) Ca: 2.4E-2 (1.1E-2 - 3.3E-2) SO_4: 5.8E-2 (6.4E-3) pH: 7.6-8.4 MEAN (RANGE) VALUES
Mendez et al. 2011	Texas, USA	Asphalt fiberglass shingle (shingle), Galvalume® (55% aluminum-zinc allow coated steel, "metal")	Pilot-Scale Full-Scale Metal Roofs: Lead (mg/L)- 0.0003-0.0023 0.0021-0.0058 Zinc (mg/L)- 0.08-0.36 0.018-0.023 Shingle Roofs: Lead (mg/L)- 0.0001-0.0012 0.0007-0.009 Zinc (mg/L)- 0.008-0.09 0.001-0.015 VALUES RANGES	Pilot-Scale Full-Scale Metal Roofs: pH- 6.0-6.8 5.4-6.3 Conductivity- 9-56 18-60 Turbidity (NTU)- 7-30 5-35 DOC (mg/L)- 2-11 4-13 Shingle Roofs: pH- 6.7-6.9 5.8-6.5 Conductivity- 18-57 20-102 Turbidity (NTU)- 8-24 6-23 DOC (mg/L)- 10-15 5-31 VALUES RANGES
Moon et al. 2012	Korea	Vinyl Chloride	Parameter Max Min Mean Median Mg (mg/L) 9.35 ND 0.30 0.10 Fe (mg/L) 1.39 0.00 0.059 0.015 As (mg/L) 0.03 0.00 0.01 0.010 Mn (mg/L) 0.53 0.0006 0.022 0.009 Sr (mg/L) 0.17 0.003 0.011 0.0079	Parameter Max Min Mean Median pH 7.4 3.1 5.2 5.1 Conductivity (µS/cm) 680 3 36 13 F (mg/L) 0.67 ND 0.03 0.02 Cl (mg/L) 164 0.09 3.22 0.82 Br (mg/L) 0.2 ND 0.02 ND SO_4 (mg/L) 114 0.15 3.49 1.77 HCO_3 (mg/L) 47.50 0.00 3.71 2.20 Na (mg/L) 32.32 ND 1.37 0.26 K (mg/L) 8.73 0.01 0.46 0.24 Ca (mg/L) 11.27 ND 0.51 0.19 Si (mg/L) 0.247 0.006 0.021 0.021

Table 4b, cont. Water quality data from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Heavy Metals	Other Parameters
Morrow et al. 2010	Australia	Average of 3 Colorbond™ roofs (of various ages) and 1 Zincalume™ roof	Mg (mg/L): 0.21 Zn (mg/L): 0.10 Mn (mg/L): 0.01 Fe (mg/L): 0.003 Cu (mg/L): 0.002 V (mg/L): 0.002 Ba (mg/L): 0.001 Cr (mg/L): 0.0005 Rb (mg/L): 0.0002 As (mg/L): 0.0006 Co (mg/L): 0.0005 Cd (mg/L): 0.0001 Sr (mg/L): 4.62E-4 Cs (mg/L): 7.50E-7 Ti (mg/L): 2.50E-7 Pb (mg/L): 7.30E-5 Mo (mg/L): 2.10E-05 Ag, Sn, Bi, U, Ni below detection limit from roof MEAN VALUES	Se (mg/L): 0.00029 Na (mg/L): 1.35 K (mg/L): 0.145 MEAN VALUES
Polkowska et al. 2002	Poland	Ceramic tile & Tar paper		• Sum of concentrations of all cations ranged from 0.11 to 1.66meq/L - Na, K, Ca found in all samples, Na and Ca concentrations highest • Sum of anions concentrations ranged from 0.1 to 1.03 meq/L; Anions Cl, NO_3 and SO_4 found in all samples; - Sum of anions generally less than sum of cation – indicates that not all anions occurring at significant concentrations were accounted for • All samples had high salt content and low acidity (i.e. Ca+Mg+Na+K+NH4>50µeq/L and H+<(Ca+Mg+Na+K+NH4)
Schriewer et al. 2008	Germany	14 year old zinc	Max Min Med Mean Zn (mg/L): 30 0.3 5.6 6.8 Pb (mg/L): 0.031 BDL -- -- Cd (mg/L): 0.0008 BDL -- --	Max Min Med Mean TOC (mg/L): 51.0 1.0 2.8 4.3 pH: 8.4 5.8 6.7 6.7 Conduc.(µS/cm): 242 10 41 50

Table 4b, cont. Water quality data from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Heavy Metals	Other Parameters
Van Metre & Mahler 2003	Austin, Texas, USA	Metal roof nearest highway (MNM), metal roof furthest from highway (MFM), Asphalt shingle roof nearest highway (ANM), Asphalt shingle roof furthest from highwater (AFM)	Parameter MNM MFM ANM AFM As (mg/kg) 7.73 9.63 7.6 8.2 Cd (mg/kg) 7.03 5.9 4.07 2.67 Cr (mg/kg) 68 60.3 63.7 56.7 Cu (mg/kg) 101.67 73.7 90 64 Hg (mg/kg) 0.07 0.11 0.20 0.21 Ni (mg/kg) 40.7 41.3 29.7 43 Pb (mg/kg) 123.3 150 350 297 Zn (mg/kg) 4300 4700 1567 847	Parameter MNM MFM ANM AFM Organic Carbon % 11.67 10.53 12.2 10.87 Total PAH (µg/kg) 21000 41000 19000 27700
Yaziz et al. 1989	Selangor, Malaysia	Galvanized iron (GI) & tile	GI Tile Zinc (mg/L): 423.4 93.6 Lead (mg/L): 198.8 197.4 MEAN VALUES	GI Tile pH: 6.54 6.88 Conductivity (µS/cm): 72.92 108.84 Turbidity (NTU): 15.4 40.2 MEAN VALUES
Yufen et al. 2008	Beijing, China	Asphalt		COD (mg/L): Mean: 177.82 Range: 6.46-815.66 BOD_5 (mg/L): Mean: 20.63 Range: 0.05-105.33
Zobrist et al. 2000	Switzerland	Clay tile, Polyester (Poly), Gravel	Tile Polyester Gravel Total Cr (mg/L): 0.002 0.001 0.001 Total Fe (mg/L): 0.042 0.360 0.090 Total Pb (mg/L): 0.041 0.024 0.003 Total Zn (mg/L): 0.048 0.115 0.009 Total Cu (mg/L): 0.304 0.842 0.018 Total Cd (mg/L): 0.0004 0.0003 0.0001 MEAN VALUES	Tile Polyester Gravel DOC (mg C/L): 4.3 14 6.0 MEAN VALUES

Table 5. Summary of key findings from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Sampling	Key Findings
Adeniyi & Olabanji 2005	Nigeria	Thatch (T), Concrete (C), Aluminum (Al), Iron-Zinc (Fe-Zn), Adex-asbestos (A)	11 sites, sampled May 2001 thru October 2001	• For Adex-concrete roofs, relatively high concentrations of Ca and bicarbonate; relatively low concentrations of other major cations and anions • For asbestos, aluminum and iron-zinc roofs, concentrations of Ca, Mg and nitrate increased as roof age increased • Turbidity, Cl and sulphate concentrations also increased with age for asbestos roofs • Roof runoff 'enrichment' due to nutrients from roofing materials most likely caused by leaching of materials • Adex-concrete roofs are more likely to be colonized by plants, which lead to flaking and cracking of roof materials; also contribute more nutrients • Contact with roof materials caused two- to three-fold enrichment of most water quality parameters • The extent of runoff enrichment depends on the type and age of roof - Enrichment highest for Adex-asbestos roofs, lowest for Al roofs - Enrichment increases as roof age increases
Chang & Crowley 1993	Nacogdoches, TX, USA	Rock ballast and tar (RT), terra cotta (TC), wood shingle (WS), asphalt composition shingle (CS)	47 storms over 6 months	• Zn and NH_4 concentrations exceeded Texas surface water quality standards for 86% and 54% of samples, respectively, for wood shingle roof; 67% and 4%, respectively, for terra cotta • High Zn concentrations could be due to: galvanized gutters, nails coated with galvanized paints and solder • Storm duration, amount and intensity negatively correlated to elemental concentrations due to dilution effect (especially for Zn, NH_4 and bicarbonate) • Terra cotta roof yielded least amount of precipitated elements; wood shingle yielded the most • Average and median Zn concentrations for all roof types exceeded USEPA and Texas surface water quality standards • 19 of 24 variables yielded concentrations higher than those in rainfall (Ca, Mg, K, Zn, Cu, Mn, Fe, Si, Ni, Pb, NO_3, NO_2, HCO_3, NH_4, SO_3, conductivity, color, oil) • Terra cotta roof produced lowest water quality concentrations; wood shingle produced the highest
Chang et al. 2004	Texas, USA	Wood shingle (WS), composition shingle (CS), aluminum (Al), galvanized iron (GI)	32 roofs (4 roof types, 2 aspects, 4 replicates); 31 storms; October 1997 thru December 1998	• Zn concentrations increased significantly as rainwater contacted the four types of roof materials - Potential sources of Zn: galvanized gutters and downspouts, nails, solder, fungi resistant materials, coating, and decomposition of organic matter • The four roofing materials did not contribute appreciable quantities of Cu to roof runoff • No significant differences in mean Al runoff concentrations • Mean Mn concentrations from wood and composition shingle roofs significantly greater than painted Al or galvanized roofs • Mean runoff concentrations of Pb from galvanized iron roofs significantly greater than other 3 roofing materials • Variations reflect differences in roofing materials, industrial treatments, care and maintenance, age, climatic conditions, orientation and slope of roofs and air quality of the region • Only pH, conductivity and Zn significantly affected by roof material type • Mean and median Zn concentrations highest for wood shingles, followed by galvanized iron, painted aluminum and composition shingle • Zn concentrations from new wood shingle roofs significantly higher than from aged • Runoff quality from wood shingles worst of the 4 types studied; care and maintenance extermely important with respect to runoff quality

*Studies that did not present raw data are not included in Table 4, but are summarized herein.

Table 5, cont. Summary of key findings from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Sampling	Key Findings
Clark et al. 2008	Alabama, USA	Individual Building Materials, as listed	pilot scale roofs, 2 years of monitoring	• Traditional galvanized metal roofing contributed the greatest concentrations of cations, metals (especially Zn) and nutrients • Pressure treated and waterproofed wood contributed substantial Cu loads • There is the potential for galvanized metal and wood products to release nutrients due to natural degradation • Pollutant release may continue for extended period of time after roof construction; low-level, long-term release of many pollutants noted
Coombes et al. 2007*	Australia	not specified	40 rain events in July & August 1998	• For first flush (the first 2mm) samples, pH values and ammonia concentrations exceeded Australian guidelines in 24% and 68% samples, respectively. Iron and lead concentration guidelines were exceeded in one sample, each. • Roof samples collected after the first flush exceeded guidelines for ammonia (29% of samples), pH (17% of samples) and lead (two samples). • Significant water quality improvement occured within the storage tank; Samples collected from the storage tank did not exceed metal and chemical standards. • Water collected from the hot water tap did not exceed metal and chemical guidelines either.
Davis et al. 2001	Maryland, USA	Varied (first flush samples only)	38 samples	• Roof samples • High Zn concentrations for all types (residential, commercial, industrial) • All other metals relatively low for residential roofs • All metal levels from commercial and industrial buildings significantly higher than residential by approximately 1 order of magnitude for Pb and Zn, and by >2 orders of magnitude for Cu • All metal levels from commercial and institutional buildings were significantly larger than those from residences • For Pb and Cu: fiberglass and asphalt roof catchments demonstrated better runoff quality than slate tile, rubber and galvanized metal • Highest Zn concentration – galvanized metal roof
Despins et al. 2009*	Canada	Asphalt shingles, steel shingles	7 sites, October 2006 thru October 2007, 30 sampling occasions (360 samples total)	• pH, turbidity, TOC, TN and color found to vary significantly with catchment materials - poorer quality = asphalt shingles (compared to steel roofs); higher turbidity, TOC and color - may be attributable to textured surface and corresponding adsorption of atmospheric particulates between rain events • Zn concentrations from steel roofs much higher than from asphalt shingle roofs (but still below Health Canada's 5 mg/l aesthetic level) • Temperature, rainfall and antecedent dry period found to have little effect on majority of WQ parameters • Physicochemical properties of rainwater most influenced by the catchment surface, storage materials and site environment • Absence of metal contamination other than Zn; asphalt shingle and steel acceptable for rainwater harvesting with respect to metals

*Studies that did not present raw data are not included in Table 4, but are summarized herein.

Table 5, cont. Summary of key findings from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Sampling	Key Findings
Farreny et al. 2011a	Spain	Clay tile, metal sheet, polycarbonate plastic and flat gravel	4 roofs, 22-25 storms for quantity assessment, 12-15 storms for quality assessment; June 2008 thru September 2010	• Reported acceptable water quality for all parameters and all roof types • Negative correlation between rainfall depth and: conductivity, TIC, TOC, total carbonates, Cl, NO_3 & SO_4 due to dilution • Significant negative correlation between NH_4 and pH and TIC due to alkaline nature of mediums, which fosters ammonia volatization, and aerobic conditions that encourage the oxidation process (which produced CO_2) and nitrification, both of which decrease NH_4 concentrations • Significant differences found between the WQ in flat gravel roof and the 3 pitched roofs for conductivity, TIC, TOC, TC, total carbonates and NH_4 (higher levels of all parameters except NH_4 - which was lower - from gravel roof) - Due to weathering of roof materials (gravels) and accumulated deposits of particulates and assoc. flora; lower NH_4 maybe due to higher alkalinity and greater oxidation processes (other materials may produce different results) • Significant difference in TOC, TC and NH_4 between clay tiles and metal and plastic roofs; due to high porosity of clay tiles (greater physical, chemical and biological degradation) • Runoff from metal and plastic roofs is of same or better quality than other roofs for all parameters except NH_4 • Flat gravel roof presents best quality in terms of NH_4 but worst in terms of conductivity, TOC and carbonates • Sloping roofs present better water quality than flat roofs • Runoff from metal and plastic roofs of better quality than from flat gravel or clay tiles
Förster 1996*	Germany	Fibrous cement, pantile, zinc sheet, concrete tiles, tar felt	1 roof, 5 materials; May 1990 thru June 1994	• Transport of particles and pollutants adsorbed to them is dependent upon hydraulic conditions (shear stress), governed by rain intensity and surface roughness • First flush effect observable under most circumstances • Extreme heavy metal contamination of runoff when in contact with metal roof surfaces • Zn and Cu concentrations in roof runoff so high that can be classified as an environmental hazard even after strong dilution • An initial high concentration of conductivity indicates the quick dissolution of deposited aerosol particles and components of the roofing materials that had weathered since the last precipitation event • When roof runoff contacts metals surfaces, released contaminants will dominate the runoff pollution when compared to atmospheric deposition • A new copper sheet roof displayed signs of weathering and increased particulate and dissolved Cu concentrations in runoff • Copper is a minor constituent in zinc gutters, resulting in another source of Cu • A zinc-sheet roof released Zn concentrations 3 orders of magnitude higher than rainfall proper, pantile and concrete tile roof runoff • Traditional pantile roofs are good alternatives to metal roofs

*Studies that did not present raw data are not included in Table 4, but are summarized herein.

Table 5, cont. Summary of key findings from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Sampling	Key Findings
Förster 1999*	Germany	Concrete tile, clay pantiles, fibrous cement, tar felt & zinc sheet	26 events, 6 locations	• Metals roofs are associated with leaching of trace elements in dissolved form that can adhere to particulate matter • Pollution effect of roofing materials is much greater than atmospheric deposition • Zn concentrations from zinc-sheet roof 2-3 orders of magnitude above fibrous cement roof throughout rain event • Values of Pb in roof runoff exceed rain due to dissolution of lead components on roof • High Cu pollution from roof with copper sheets used as fittings around windows and chimney • Tar felt roofs may be a source of Cd; not confirmed in this study • Runoff from asphalt shingle roofs of poorer quality than runoff from steel roofs; thought to be due to the textured surface of shingles (which allow better capture and retention of particulate matter) than the smooth surface of steel • Recommend: Avoid unprotected surface of non-precious metals in the system
Khan et al. 2006	Florida, USA	n/a		• Arsenic can leach from wood treated with chromated copper arsenate (CCA)
Lee et al 2012	South Korea	Wooden shingle (WS), Concrete tile (CT), Clay tile (CL), Galvanized steel (GS)	10 events in 2009, 30 events in 2010	• pH values for WS, CT and CL were higher than GS. CT had the highest pH due to alkaline components. • Average TSS concentrations in the first flush were significantly higher for the CT and GS roofs than the CL and WS roofs. After first flush, concentrations for WS were significantly lower than the other 3 roof types. • TSS found from CT and CL roofs were composed predominantly of inorganic materials (dust, roofing debris). TSS from WS roof also contained organic materials (lichens, moss, plants). • The WS roof produced the highest concentration of TOC due to weathering of roof material. • First flush from the WS roof produced significantly higher nitrate and sulfate concentrations than first flush from other roof types. This is due to the higher porosity of wood, the establishment of lichens and mosses and the corresponding microbiological processes for which nitrate and sulfate are waste products. However, none of the nitrate and sulfate concentrations produced during first flush exceeded USEPA drinking water guidelines or European directive guidelines. • The GS roof produced significantly higher aluminum concentrations in the first flush than other roof types. • Average copper concentrations in first flush were notably (but not significantly) higher from CT and GS roofs than the other two types, perhaps due to the increased porosity and particle-trapping potential of WS and CL roofs. However, none of the roofs produced concentrations higher than the USEPA standards. • Iron concentrations in first flush significantly higher for GS roof than the other 3 roof types, most likely due to atmospheric deposition and the roofing material, and exceeded USEPA standard. • Average lead and zinc concentrations in first flush were significantly higher for CT and GS roofs, with the average lead concentration for the CT roof exceeding USEPA standard. Probable sources for both constituents were atmospheric deposition and the roofing material. • The type of roofing material has some influence on the quality of harvested rainwater. GS roofs provide the best quality of runoff of the four types studied herein, after first flush. • Rainwater collected from all 4 roof types were of acceptable quality for non-potable uses after first flush.
Melidis et al. 2007	Greece	Varied (concrete, mosaic, clay tile, iron, Maxitherm)	10 sites, 13 storms, 130 samples	• Mg and Fe generally low, but high at some sites, nearing (Fe) or exceeding (Mg and Zn) drinking water standards • High Zn concentration due to drainage pipe erosion • Older building seems to cause higher concentration of Fe and Zn in roof drainage • Cu, Cr and Ni negligible

*Studies that did not present raw data are not included in Table 4, but are summarized herein.

Table 5, cont. Summary of key findings from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Sampling	Key Findings
Mendez et al. 2011	Texas, USA	Asphalt fiberglass shingle (shingle), Galvalume® (55% aluminum-zinc allow coated steel, "metal"), concrete tile, cool roof and green roof	3 pilot-scale roofs, 4 storm events; 3 residential roofs, 3 storm events	• Rainwater from any of the tested roofing materials (asphalt fiberglass shingle, Galvalume metal, concrete tile, cool roof and green roof) would require treatment if the consumer wanted to meet USEPA primary and secondary drinking water standards or non-potable reuse guidelines • Metal roofs did not produce superior quality than other roofing materials • DOC concentrations in rainwater harvested from shingle and green roofs were very high, which could lead to high concentration of disinfection byproducts - Suggests that other roofing material would be preferable when using chlorine disinfection • First flush diverter improved the quality of water; concentrations of most parameters decreased • TSS and turbidity of metal and cool roofs significantly higher than shingle or tile due to smoothness of surface • Nitrate concentrations in first flush of shingle, metal and tile roofs significantly higher than rainwater • Cd, Cr and Se for all roofs below drinking water standards • Metal concentrations were significantly higher in the first flush than after the first flush • Tile roof produced significantly higher arsenic and Pb concentrations than rainwater, even after the first flush • Metal and tile roofs produced significantly higher Zn than rainwater after the first flush • Shingle roof produced significantly higher Cu than rainwater after the first flush • The presence of aluminum in alloy-coated steel roofs increases the corrosion resistance compared to uncoated galvanized roofs • Concentration of most water quality parameters decreased when first flush of at least 38L for every 93m^2 of collection area was diverted
Moon et al. 2012	Korea	Vinyl Chloride	1 site, June-October 2008; 30 storm events	• Substantial amounts of NO_3 and NH_4 in roof runoff most likely due to agricultural and livestock sources • Substantial amounts of SO_4 were due to anthropogenic and industrial air pollution (predominantly from the burning of fossil fuels) • Most parameters decreased in the first 20 minutes of rainfall then stabilized, which is indicative of the first flush concept • NH_4 and Fe concentrations only met Korean drinking water standards after 20 minutes, while pH and turbidity values exceeded standards even after 20 minutes
Morrow et al. 2010	Australia	Average of 3 Colorbond™ roofs (of various ages) and 1 Zincalume™ roof	5 sites, 60 samples, July 2006 - January 2008	• The leaching of Fe from paint on catchment surface is potential Fe source in runoff • Rainwater entering the system via roof surfaces contained low elemental loads; source of large elemental loads at some sites not due to catchment materials • Levels of elements in roof runoff samples were below 2004 Australian Drinking Water Guidelines
Olem & Berthouex 1989	USA & Netherlands	Asphalt shingle	25 sites, 3 month sampling period; 1986	• Roof water was approximately 1.5 pH units higher than rainfall after contact with roof and gutter materials - Stones in asphalt shingles may contribute substantially to neutralization of runoff • No significant statistical relation between metal concentrations and roofing materials found, but these cannot be rejected as causative factors

*Studies that did not present raw data are not included in Table 4, but are summarized herein.

Table 5, cont. Summary of key findings from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Sampling	Key Findings
Quek & Förster 1993	Germany	Tar felt, pantile, asbestos cement, zinc sheet, gravel	5 roofs, 2 storm events; April & May 1988	• Samples were only collected during first 3mm of runoff • Increase in concentration of zinc from zinc sheet roof due to dissolution • Dissolution of $CaCO_3$ on asbestos cement and gravel roofs cause pH to increase • Maximum TSS concentration produced by zinc sheet roof due to smooth surface and greater inclination • Flat gravel roof acted as a sink for particles and heavy metals due to hydraulic properties that facilitate sedimentation and immobilization • Asbestos cement roof showed high degree of weathering, which caused TSS concentrations to increase (concentrations were greater than for tar or pantile roofs) • Pb concentrations doubled during high intensity rain event on sloped roofs • Zinc sheet roof runoff was most heavily polluted with heavy metals - Zn concentrations originate from roofing materials; other metals originate from dry deposition or minor constituents in roofing materials • Tar felt roof released least polluted runoff of all inclined roofs due to high pH of roofing material (shifts most heavy metals to adsorbed phase) and rough surfaces (retain particles on roof except during high intensity rains) • Pantile roof exhibited Cu contamination due to copper sheets fitted onto roof sides • Flat gravel released least polluted runoff - due to high pH, runoff retention and filtering effects of gravel
Schriewer et al. 2008	Germany	14 year old zinc	1 site, 38 storm events; May 2004 thru May 2005	• Significant amount of zinc in runoff could be observed, mostly in dissolved form • Negative correlation between rain intensity and zinc concentrations; lower rain intensities = increases in amount of Zn in runoff; high intensities dilute concentrations - Exclusion of runoff due to extreme flows is recommended • 93% of events exhibited first flush characteristics
Simmons et al. 2001	Auckland, New Zealand	Varied	125 houses, sampled once	• High lead levels likely result of corrosion of galvanized iron, lead and lead-based paint on catchment surface
Thomas & Greene 1993	Australia	Galvanized iron, concrete tile	2 roofs, 8 samples each	• High Zn concentrations likely due to leaching of Zn from galvanized iron roof • Galvanized iron roofs produce best runoff quality when compared to concrete tile
Van Metre & Mahler 2003	Austin, Texas, USA	Metal (nearest road), Metal (furthest from road), Asphalt shingle (nearest road), Asphalt shingle (furthest from road)	2 roof types, 2 locations, 3 sampling events	• There were no observed differences between the concentrations of TSS or PAHs from each type of roof • Concentrations of all major elements, except Ca and Mg, were higher in runoff from metal roofs than asphalt shingle roofs, most likely due to increase particle trapping and dilution of particles by Ca and Mg on asphalt roofs • Lead and mercury concentrations were significantly higher in runoff from asphalt shingle roofs • The metal roof was a source of particle-bound Cd and Zn • Concentrations of some parameters (Cd, Cr, Cu) were higher at roof sites closer to a major highway, while other parameters (As, Ni, PAHs) had higher concentrations at sites further from the highway. The latter phenomenon could be due to the deposition of larger amounts of uncontaminated sediment closer to the highway, which results in a dilution factor • Each roof was a source of a contaminant of concern: Zn from metal roofs, Pb from asphalt shingle roofs and PAHs from both. Therefore, the roof runoff should be treated to remove particles prior to it being used

*Studies that did not present raw data are not included in Table 4, but are summarized herein.

Table 5, cont. Summary of key findings from numerous studies on the effect of roofing materials on rooftop runoff quality.

References	Study Location	Roof Type	Sampling	Key Findings
Yaziz et al. 1989	Selangor, Malaysia	Galvanized iron (GI) & concrete tile	2 roof types, 24 samples each; Sept. 1987 thru Jan. 1988	• Relatively better water quality for galvanized iron roofs (compared to concrete tile) due to smoother surface (with respect to TSS, turbidity, conductivity) - Coarses surfaces allow better deposition and entrapment of atmospheric pollutants • Some dissolution of Zn likely for galvanized iron roof due to acid rain, but Zn concentrations within WHO guidelines for drinking water (5 mg/l)
Zobrist et al. 2000	Switzerland	Clay tile, Polyester, Gravel	3 roof types, 14 storm events; 2 year study period, 1994/1995	• Pb and Fe present predominantly in particulate form for tile and polyester roofs • Cu, Zn, Cd, Mn and Cr occurred predominantly in dissolved form for tile and polyester roofs; particulate/dissolved partitioning did not change significantly with runoff depth for tile roof, but this ratio decreased with runoff depth for the tile roof • In gravel roof, all heavy metals predominantly in dissolved fractions • Most total Zn existed in labile (i.e. reactive) form • Cu, Pb and Cd occurred predominantly in the moderately reactive form, representing the continuum of reactivity between labile and inert (labile and inert forms very small) • When pH in runoff decreased from about 7 to 5, labile species of Zn, Cu, Pb and Cd slightly increased • In general, constituents in dissolved form showed a lower initial concentration and a faster decrease than those in particulate form (indicates that particles were being washed off roof and drain surfaces) • Data indicate that roof and drains acted as source for Cu • Tile roof acted as slight source for alkalinity, TSS, total Mn, total Pb and total Fe • Polyester roof contributed TOC, DOC and total Mn via erosion; otherwise just conveyed compounds present in rainwater • Weathering of gravel on gravel roof produced significant amounts of Ca and alkalinity (considered a beneficial water quality change); gravel roof retained most heavy metals and phosphorus and supported nitrification (indicated by transformation from NH_4 to NO_3)

*Studies that did not present raw data are not included in Table 4, but are summarized herein.

The type of roofing surface can have substantial impacts on roof runoff. 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 water quality (Bradford & Denich 2007; Despins et al. 2009; Förster 1999). Materials that contain constituents prone to leaching, such as zinc or copper, should be avoided (Bradford & Denich 2007).

In addition to the roofing materials proper, gutters have been identified as major contributors of heavy metals to roof runoff, especially Zn and Al (Lee et al. 2010; Förster 1996; Förster 1999; Ward et al. 2010a). 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 rainwater from gutters and downspouts (Ward et al. 2010a).

Distribution piping. In addition to wet and dry deposition and roofing materials, several studies have identified distribution piping as another significant contributor of contaminants within RWH systems (Morrow et al. 2010; Olem and Berthouex 1989; Simmons et al. 2001; Martin et al. 2010). Point-of-use data from Morrow et al (2010) and Despins et al. (2009) may be found in Table 6.

Morrow et al. (2010) collected samples from indoor hot and cold taps that were fed by a rainwater harvesting system in Australia. Samples were also collected from the storage tank of the RWH system via a PVC pipe. Zn, Cu, Pb, As, Sr, and Mo were significantly higher in samples taken from the PVC pipe outlet when compared to roof runoff. Cu concentrations were higher in samples taken from both indoor taps when compared to roof runoff, with concentrations from the hot tap being significantly higher. Pb was slightly higher in the hot tap when compared to the cold tap. Based on these findings, the authors concluded the following:

1. Piping, taps and hot water systems can potentially contribute elemental loads.
2. Water sampled after passing through copper piping and a hot water system (i.e. at indoor taps) had significantly increased concentrations of Cu compared with roof runoff.
3. The effects of heat with copper pipes cause metal loadings in the collected water to increase.
4. Plumbing fixtures are a direct source of metal loads to water during passage.
5. Nickel plating used in some taps and plumbing fittings may be a source of Ni in water.

6. PVC pipes may be a source of lead , as stormwater-grade PVC pipes are extruded in lead (This was also noted by Huston et al. (2009)). PVC pipes may also contribute significant amounts of contaminant loads.

Olem and Berthouex (1989) conducted a similar study in which water was sampled at multiple points throughout 50 RWH systems (25 systems were located in Tennessee and Kentucky, the other 25 were located in The Netherlands). Two samples were taken from the kitchen tap in homes that were supplied water via a RWH system: a standing water sample (no flushing of the tap) and a running water sample (tap was flushed for approximately 1 minute prior to collecting sample). Olem and Berthouex (1989) drew the following conclusions:

1. Faucets, supply lines, fittings, valves, pumps and pressure tanks may contribute substantial amounts of trace metals to tap water.
2. Tap samples with elevated Cu concentrations often came from homes with copper piping.
3. Standing tap water was significantly higher in Pb than cistern water, but running water contained concentrations similar to cistern water.
4. Zinc concentrations were significantly higher in standing tap water than in cistern or in running tap samples.
5. Elevated metal concentration in standing tap water indicates that water can corrode piping, solder and plumbing fixtures.

Simmons et al. (2001) and Martin et al. (2010) also observed higher concentrations of Cu in water that had passed through copper piping, and Simmons et al. (2001) noted higher concentrations of Pb in standing water samples versus running water samples. Aging galvanized iron piping could also contribute to elevated Fe concentrations in tap water (Martin et al. 2010). Ward et al. (2010a) 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.

Table 6. Water quality data for rainwater harvesting system point-of-use samples.

References	Study Location & Details	Treatment	Nitrogen Species	Phosphorus Species	Heavy Metals	Other Parameters
Abdel-Shafy et al. 2010	Egypt (Mediter-ranean Sea) (n = unknown)	Cylindrical sand filter, UV light tube	NH_3-N (mg/L): Range: ND Average: ND		Element Range Average Al (mg/L) ND ND As (mg/L) ND ND Cd (mg/L) ND ND Cr (mg/L) ND ND Cu (mg/L) ND ND Fe (mg/L) 0.001-0.002 0.0013 Pb (mg/L) ND ND Hg (mg/L) ND ND Ni (mg/L) ND ND Zn (mg/L) ND ND	Element Range Average Turbidity (NTU) 0.5 - 0.7 0.55 Conductivity (µS) 480 - 520 508 pH 6.5 - 6.9 6.6 Color (CU) colorless colorless Taste & Odor acceptable acceptable TDS @ 105°C (mg/L) 188 - 196 191 H_2S (mg/L) ND ND
Despins et al. 2009	Canada (n = 30)	Varied among sites (included sand filters, particle filters, carbon filters, UV lamps, hot water tank and no treatment)	TN (mg/L): 1.6 ± 0.6 1.3 ± 0.6 2.3 ± 1.5 1.5 ± 0.6 1.5 ± 0.5 1.7 ± 0.7 1.5 ± 0.3			Point of Use Samples: pH Turbidity (NTU) TOC (mg/L) Color (CU) 7.2 ± 0.4 0.3 ± 0.1 2.3 ± 2.1 7.1 ± 6.4 5.9 ± 1.1 0.8 ± 0.3 2.7 ± 2.1 15.2 ± 17.3 7.3 ± 0.3 1.5 ± 0.8 6.9 ± 4.9 27.4 ± 19.8 7.0 ± 1.2 1.2 ± 0.5 6.4 ± 5.2 24.9 ± 19.4 8.1 ± 0.7 1.4 ± 0.6 7.4 ± 5.5 23.4 ± 10.1 8.2 ± 0.8 0.9 ± 0.3 3.2 ± 1.6 13.8 ± 8.1 7.5 ± 0.4 1.3 ± 0.7 2.4 ± 1.1 14.9 ± 8.2
Morrow et al. 2010	Australia (n = 3)	none		Elemental P Cold Tap: 0.018±0.006 (mg/L) Hot Tap: 0.023±0.006 (mg/L) PVC Pipe: 0.026±0.008 (mg/L)	Element Cold tap Hot tap PVC Pipe Mg 0.632±0.033 0.64±0.07 0.795±0.08 Zn 0.233±0.020 0.299±0.083 0.564±0.056 Fe 0.062±0.029 0.045±0.023 0.049±0.02 Mn 0.931±0.004 0.005±0.001 0.014±0.008 Cu 0.161±0.067 0.330±0.05 0.027±0.009 Pb 0.218±0.127 0.005±0.003 0.04±0.013 Ni 8E-4±7E-05 2.6E-3±7E-4 3.4E-3±1E-3 Ag 5E-5±3E-6 1E-5±6E-5 1E-4±7.4E-5 As 4.2E-4±9E-5 5E-4±4E-5 8.6E-4±2.3E-4 Cr 2.7E-5±4.9E-6 1.3E-5±8.5E-6 4.5E-5±2.3E-5 Cd 1.8E-5±8.3E-6 4.6E-5±5.4E-6 2.3E-5±1.6E-5 ALL VALUES in mg/L	Element Cold tap Hot tap PVC Pipe Na 5.0±0.38 4.68±0.4 5.67±0.80 K 1.16±0.38 1.2±0.42 1.76±0.3 Rb 9.6E-4±1.5E-7 1.0E-3±3.6E-4 1.6E-3±2.0E-4 Se 1.0E-4±3.3E-5 1.2E-4±7.5E-5 1.4E-4±1.4E-4 Co 2.1E-4±1.2E-6 3.8E-5±1.3E-5 9.2E-5±4.1E-5 V 1.3E-4±3.1E-5 1.9E-4±2.0E-5 1.33E-4±6.6E-5 Ba 1.39E-4±7.1E-4 1.6E-3±8.75E-4 2.9E-3±7.4E-4 Bi 5.3E-6±5.3E-6 BDL 5.7E-6±2.9E-6 Sr 6.9E-3±2.6E-3 8.7E-3±3.31E-3 1.44E-2±2.2E-3 Tn 5.3E-3±5.3E-3 BDL 6.33E-3±2.1E-3 Cs 3.3E-7±3.3E-7 9.67E-6±9.67E-6 2.7E-6±2.7E-6 Ti 3.3E-7±3.3E-7 1.33E-6±1.33E-6 6.7E-7±6.7E-7 U 1.53E-5±1.1E-5 2.1E-5±1.34E-5 1.8E-5±6.1E-6 Mo 1.67E-6±1.67E-6 6.3E-6±1.45E-6 1.4E-5±4.9E-6 ALL VALUES IN mg/L

Fate and Transport of Nutrients and Metals in a RWH System

After leaving the roof surface, water enters the storage tank of the RWH system. Water quality data for water within the storage tank may be found in Table 7. Key findings from numerous studies on the quality of harvested rainwater may be found in Table 8. It should be noted that methods and monitoring procedures varied widely among the available studies; therefore, comparison among studies should be performed with caution. 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 (Hermann & Schmida 1999; Despins et al. 2009; 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 potable water guidelines and standards (Kus et al. 2010a; Olem and Berthouex 1989; Morrow et al. 2010; Lee et al. 2010; Ward et al. 2010a; Daoud et al. 2011; Sazalaki et al. 2007).

The storage tank material can substantially influence water quality. Storing rainwater in concrete or plaster tanks can increase the pH of the water, thus facilitating precipitation and removal of heavy metals (Despins et al. 2009; Olem and Berthouex 1989; Daoud et al. 2011; Simmons et al. 2001). Water stored in tanks comprised of other materials, namely plastic, tended to exhibit lower pH values, which may hinder heavy metal removal and cause leaching of metals from sediments collected within the tank (Despins et al. 2009). It was not clear whether the tank material caused a decline in pH, or was simply lower than the pH of water stored in concrete tanks (and perhaps merely reflected the pH of rainwater). Metal tanks can potentially leach metals into collected water, while plastic tanks may leach organic compounds if they are not manufactured to specific standards (Despins et al. 2009; Martin et al. 2010).

Despite the numerous opportunities for water quality improvement during storage, some studies have reported poor water quality in RWH storage tanks. Long retention times of stored water can be detrimental to water quality (Sung et al. 2010; Abbasi and Abbasi 2011; Ward et al. 2010a). Despins et al. (2009) noted that turbidity and TN concentrations of tank water tended to increase during dry periods, indicating that some water quality parameters are more sensitive than others to rainfall/drought conditions. Alam et al. (2012) and Islam et al. (2010a), however, showed that physical

Table 7. Water quality data collected from storage tanks of rainwater harvesting systems.

References	**Study Location**	**Sediment**	**Nitrogen Species**	**Phosphorus Species**	**Heavy Metals**	**Other Parameters**
Abdulla & Al-Shareef 2009	Jordan (60 systems, 1 sample each)	TDS (mg/L): Min = 76.38 Max = 681.1 Average = 270.2				Parameter Min Max Average Temperature (°C) 16.3 0.197 18.6 pH 7.1 8.6 7.4 O_2 saturation (%) 50.0 77.0 61.5 Conductivity (µS/cm) 114.0 1,017.0 402.6 Total hardness (mg/L) 50.0 270.0 140.3 Total chlorine (mg/L) 0.0 0.22 0.055
Albrechtesen 2002	Denmark (7 systems, 2-4 samples each)					Parameter Range Average Temperature (°C) 5.3 - 13.9 10.7 pH 7.5 - 7.8 Organic matter (mg/L) 1 -4.6 2.4 measured as NVOC
Daoud et al. 2011	Palestine (the majority of rainfall occurs during winter months) (21 systems, 2 samples each)		Nitrate Ranges: Winter = 0.002 - 1.31 mg/L Summer = N/A Average = N/A Nitrate-N Mean ± St. Dev.: Winter = 0.69 ± 0.37 mg/L Summer = N/A Average = N/A		Copper (µg/L): Average= 0.62-30.84; 8.27±1.99 Summer= 0.62-54.35; 7.77±2.48 Winter= 2.62-30.84; 8.76±1.39 Lead (µg/L): Average= 0.37-30.67; 2.64±1.14 Summer= 0.37-3.54; 1.20±0.15 Winter= 0.84-30.67; 4.08±1.60 VALUE RANGES; MEAN ± ST. DEV.	Temperature (°C): Average= 12.0-28.8; 20.2±0.99 Summer= 20.0-28.8; 24.0±0.60 Winter= 12.0-19.0; 16.5±0.50 pH: Average= 4.8-9.9; 7.84±0.25 Summer= 7.4-9.9; 8.5±0.02 Winter= 4.8-8.6; 7.2±0.25 Conductivity (µS/cm): Average= 121.5-834; 332.5±36.4 Summer= 180.5-834; 284.6±30.3 Winter= 121.5-628; 378.5±39.8 Salinity (‰): Average= 0.10-0.40; 0.16±0.02 Summer= 0.10-0.40; 0.15±0.01 Winter= 0.10-0.30; 0.17±0.02 TDS (mg/L): Average= 57.6-394; 157.5±17.3 Summer= 0.13-1.84; 1.11±0.28 Winter= 57.6-303; 177.6±18.9 Turbidity (NTU): Average= 0.13-5.31; 0.85±0.22 Summer= 0.13-1.84; 1.11±0.28 Winter= 0.23-5.31; 0.59±0.10 VALUE RANGES; MEAN ± ST. DEV.
Despins et al. 2009	Canada (5 systems, 30 samples each)		TN in cistern samples (mg/L): 1.8 ± 0.7 1.5 ± 0.4 2.0 ± 0.6 1.5 ± 0.5 1.8 ± 0.9 MEAN ± ST. DEV.		• Ca and Strontium present above detection limits at all sites tested • Al, Ar, Co, Cd, Hg, Mg, Mn, Si, Na, Tn, Zn detected at low concentration at some sites, but below maximum acceptable concentration (MAC) for drinking water • Zn concentrations higher from steel roofs than asphalt roofs, but still below Canada's aesthetic objectives	Cistern Samples: pH Turbidity (NTU) TOC (mg/L) Color (CU) 7.1 ± 0.6 1.1 ± 1.6 3.1 ± 1.9 11.1 ± 7.8 5.8 ± 0.9 1.0 ± 0.5 1.8 ± 1.0 11.6 ± 10.6 7.2 ± 0.4 1.5 ± 0.7 6.3 ± 4.5 25.5 ± 17.0 7.5 ± 0.7 2.6 ± 3.1 8.5 ± 8.3 32.8 ± 28.7 8.2 ± 0.9 0.9 ± 0.5 2.9 ± 1.7 13.1 ± 8.0 MEAN ± ST. DEV.

Table 7, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Sediment	Nitrogen Species	Phosphorus Species	Heavy Metals	Other Parameters
Domènech & Saurí 2011	Spain (3 systems, 1 sample each)	Turbidity (NFU): System A = 0.93 System B = 0.79 System C = 0.10 Suspended Solids (mg/L): System A = 39,040 System B = 28,990 System C = 25,660 TYPE OF VALUE (MEAN/MEDIAN) NOT SPECIFIED		Total Phosphorus (mg/L): System A = 1.40 System B = 0.10 System C = <0.01 TYPE OF VALUE (MEAN/MEDIAN) NOT SPECIFIED	System A System B System C Cr (μg/L) <0.01 <0.01 <0.01 Cu (mg/L) <0.01 <0.01 <0.01 Ni (μg/L) <0.01 <0.01 <0.01 Fe (mg/L) <0.01 <0.01 <0.01 Al (mg/L) <0.01 <0.01 0.26 Zn (mg/L) 3.42 <0.01 <0.01	System A System B System C pH 7.51 7.16 8.46 Conductivity (μS/cm) 65.6 47.4 41.4 Total Hardness (mg/L) 30.50 22.65 20.05 BOD$_5$ (mg/L) 1.60 0.90 6.60 COD (mg/L) 0.48 0.32 0.38 Soluble Salts (mg/L) 30.70 22.1 7.40 Diss. Oxygen (mg/L) 7.00 5.10 0.68 Chloride (mg/L) 2.04 1.02 <0.01 Boron (mg/L) <0.01 <0.01 <0.01 Sulphates (mg/L) 5.12 4.18 2.80 Carbonates (mg/L) 3.20 3.84 <0.01
Handia et al. 2003	Zambia (2 systems, 1 sample each)	TDS (mg/L): Tank A = 7.3 Tank B = 7.0 Turbidity (NTU): Tank A = 0.42 Tank B = 0.56 TYPE OF VALUE (MEAN/MEDIAN) NOT SPECIFIED	Nitrates (NO$_3$-N mg/L): Tank A = 5.11 Tank B = 4.15 TYPE OF VALUE (MEAN/MEDIAN) NOT SPECIFIED		Parameter Tank A Tank B Lead (mg/L) <0.01 <0.01 Zinc (mg/L) 0.62 0.67 TYPE OF VALUE (MEAN/MEDIAN) NOT SPECIFIED	Parameter Tank A Tank B pH 7.3 7.0 Sulphates (mg/L) 1.66 1.69 Chlorides (mg/L) 6.0 5.0 TYPE OF VALUE (MEAN/MEDIAN) NOT SPECIFIED
Kim & Han 2011	Korea (1 system, 10 samples at inlet, 10 samples at outlet)	Turbidity (NTU): Inlet: 5.4±0.02 Outlet: 4.2±0.01 Suspended Solids (mg/L): Inlet: 2.0±0.01 Outlet: 1.0±0.00 Volatile SS (mg/L): Inlet: 1.5±0.00 Outlet: 0.9±0.00	Total Nitrogen (mg/L): Inlet: 4.9±0.4 Outlet: 4.4±0.2	Total Phosphorus (mg/L): Inlet: 0.08±0.04 Outlet: 0.05±0.01		Parameter Inlet Outlet Conductivity (μS/cm) 63.7±0.15 55.6±0.35 pH 6.7±0.06 6.5±0.03 Dissolved oxygen (mg/L) 5.8±0.05 6.5±0.06 Temperature (°C) 18.5±0.25 17.9±0.31 Total organic carbon (mg/L) 0.78±0.03 0.26±0.15 COD (mg/L) 1.9±1.12 0.9±0.01
Kus et al. 2010a	Australia (11 systems, 3 samples each)	TDS (mg/L): 46.23 (7.48-107.44) TSS (mg/L): 2.33 (0.50-17.00) MEAN (RANGE)	Nitrate (mg/L N): 0.44 (0.05-0.91) Nitrite (mg/L N): 0 (0-0.02) Ammonia (mg/L N): 0.064 (0.003-0.25) MEAN (RANGE)	Orthophosphate (mg /l P): 0.0 (0-0.36) MEAN (RANGE)	Na (mg/L): 3.47 (0.61-15.09) K (mg/L): 0.80 (0.01-2.85) Ca (mg/L): 6.41 (0.14-15.88) Mg (mg/L): 0.67 (0.04-4.84) Cl (mg/L): 8.08 (1.91-22.96) Al (mg/L): 0.04 (0-0.16) Cu (mg/L): 0.16 (0-2.37) Fe (mg/L): 0.31 (0-4.70) Mn (mg/L): 0.01 (0-0.06) Pb (mg/L): 0.01 (0-0.067) Zn (mg/L): 0.23 (0.01-1.41) MEAN (RANGE)	pH: 6.97 (5.41-8.62) Conductivity (dS/m): 0.07 (0.01-0.16) Turbidity (NTU): 1.92 (0.20-12) Hardness (mg/L CaCO$_3$): 18.77 (0.58-46.78) Sulfates (mg/L SO$_4$): 2.75 (0.81-9.81) MEAN (RANGE)
Lee et al. 2010	South Korea (3 systems, 90 samples each)	TDS (mg/L): 88 (40-230) MEDIAN (RANGE)	Nitrate (mg/L): 1.5 (0.65 - 2.21) NH$_4^+$ (mg/L): 0.07 (0.01-0.09) MEDIAN (RANGE)	Phosphate (mg/L): 0.02 (0-0.04) MEDIAN (RANGE)	Mg (mg/L): 1.2 (0.5-2.7) Mn (μg/L): 115 (70-170) Pb (μg/L): 27 (10-40) Cu (μg/L): 85 (70-120) Cr (μg/L): 4.5 (0-10) Cd (μg/L): 1.5 (0-4) As (μg/L): 3 (0-6) Zn (μg/L): 160(120-280) Al (μg/L): 225 (100-400) MEDIAN (RANGE)	pH: 7.3 (6.7-7.8) Conductivity (μS/cm): 170 (50-340) Cl (mg/L): 7.5 (5-18) Ca (mg/L): 6.4 (3.24-15.4) Na (mg/L): 3.2 (2.2-6.1) K (mg/L): 3.1 (1.3-5.9) Sulfates (mg/L): 4.1 (2-7.2) MEDIAN (RANGE)

Table 7, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Sediment	Nitrogen Species	Phosphorus Species	Heavy Metals	Other Parameters
Magyar et al. 2007	Australia (9 systems, 4 samples each)				Residential tank water sample ranges (mg/L): Al: DL-0.6 Cd: DL-0.004 Fe: ~0.05-0.8 Zn: ~0.25-3.1 Pb: DL-0.35 Total Pb: ~0.003-~0.5 Residential tank sediment sample ranges (mg/kg): Al: 15,000-40,000 Cd: DL-20 Cr: DL-~200 Cu: DL- ~1500 Fe: 20,000-~70,000 Mg: 200-~1,100 Ni: ~50-~175 Zn: DL-40,000 Pb: ~300-~3500	Residential tank water sample ranges pH: 4.3-4.9
Martin et al. 2010	Australia (2 systems, 31 samples in summer, 31 samples in winter)				Site 1 Site 1 Site 2 Site 2 Element Winter Summer Winter Summer Ag 0.032 0.009 0.047 0.014 Cd 0.18 0.17 0.05 0.10 Sn 0.34 0.08 0.64 0.22 Pb 2.78 10.5 3.59 5.77 Mg 1,600 2,620 556 437 Cr 0.09 0.21 0.03 0.05 Mn 20.0 82.3 6.95 12.1 Fe 81.1 398 1.98 4.27 Co 0.08 0.25 0.10 0.16 Ni 0.29 0.16 1.47 2.72 Cu 104 178 0.40 0.70 Zn 518 725 77.2 150 MEAN VALUES; All values in µg/l	Site 1 Site 1 Site 2 Site 2 Element Winter Summer Winter Summer Na 6,910 16,300 3,840 3,730 Rb 1.58 8.15 0.33 0.46 Sr 17.80 24.6 1.22 2.90 Cs 0.005 0.037 0.003 0.009 Ba 5.69 10.5 3.55 5.12 Ti 0.017 0.004 0.019 0.004 Bi 0.02 0.09 0.01 0.09 U 0.003 0.003 0.002 0.002 P 14.4 139 19.1 44.2 V 0.26 1.12 0.54 0.32 Cr 0.09 0.21 0.03 0.05 Mo 0.09 0.12 0.11 0.04 K 1,280 5,350 350 363 As 0.25 0.55 0.08 0.09
Morrow et al. 2010	Australia (4 systems, 1 sample each)			elemental P: 178 µg/L MEAN VALUES	Tank Tap Mg (µg/L): 387 Zn (µg/L): 73 Mn (µg/L): 16 Fe (µg/L): 0.12 Cu (µg/L): 5.11 V (µg/L): 1.56 Ba (µg/L): 1.23 Cr (µg/L): 0.27 Rb (µg/L): 0.12 As (µg/L): 0.05 Co (µg/L): 0.05 Cd (µg/L): 0.01 Sr (ng/L): 638 Cs (ng/L): BDL Ti (ng/L): BDL Pb (ng/L): 228 Mo (ng/L): BDL Na (µg/L): 3148 K (µg/L): 178 Ag, Sn, Bi, U, Ni BDL in tank MEAN VALUES	Se (µg/L): 0.19 MEAN VALUES

Table 7, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Sediment	Nitrogen Species	Phosphorus Species	Heavy Metals	Other Parameters
O'Hogain et al. 2012	Ireland (1 system, 14 samples for Regime 1, 3 samples for Regime 2)	Regime 1 Regime 2 Turbidity (NTU): Turbidity (NTU): Mean = 0.63 Mean = 1.82 Min = <0.01 Min = 0.37 Max = 2.10 Max = 4.30 Median = 0.40 Median = 1.31 TDS (mg/L): TDS (mg/L): Mean = 59.15 Mean = 54.50 Min = 15.00 Min = 24.00 Max = 174.00 Max = 84.00 Median = 49.00 Median = 55.00 TSS (mg/L): TSS (mg/L): Mean = 5.23 Mean = 3.25 Min = 2.00 Min = 1.00 Max = 22.00 Max = 5.00 Median = 3.00 Median = 3.50	Regime 1 Regime 2 NO_3-N (mg/L): NO_3-N (mg/L): Mean = 1.23 Mean = 4.68 Min = <0.01 Min = 1.77 Max = 2.84 Max = 8.99 Median = 1.20 Median = 3.98 NO_2-N (mg/L): NO_2-N (mg/L): Mean = 0.04 Mean = 0.01 Min = <0.01 Min = <0.01 Max = 0.20 Max = 0.03 Median = 0.03 Median = 0.02 NH_3-N (mg/L): NH_3.N (mg/L): Mean = 1.11 Mean = 9.15 Min = 0.09 Min = 0.52 Max = 5.90 Max = 34.24 Median = 0.46 Median = 0.91		Regime 1 Regime 2 Lead (µg/L): Lead (µg/L): Mean = 3.28 Mean = 5.32 Min = <0.01 Min = 2.63 Max = 15.46 Max = 8.16 Median = 2.21 Median = 5.24 Iron (µg/L): Iron (µg/L): Mean = 61.50 Mean = 59.75 Min = <0.01 Min = 20.80 Max = 271.12 Max = 105.00 Median = 57.25 Median = 56.59 Cadmium (µg/L): Cadmium (µg/L): Mean = <0.01 Mean = 0.30 Min =<0.01 Min = 0.20 Max = <0.01 Max = 0.40 Median = <0.01 Median = 0.30	Regime 1 Regime 2 pH: pH: Mean = 7.07 Mean = 6.33 Min = 6.67 Min = 5.69 Max = 7.83 Max = 7.00 Median = 6.98 Median = 6.32 Chloride (mg/L): Chloride (mg/L): Mean = 3.83 Mean = 6.94 Min = <0.01 Min = <0.01 Max = 27.83 Max = 18.75 Median = 1.49 Median = 4.51 Sodium (mg/L): Sodium (mg/L): Mean = 2.62 Mean = 5.46 Min = <0.01 Min = 0.09 Max = 16.40 Max = 13.69 Median = 1.50 Median = 4.03 Calcium (mg/L): Calcium (mg/L): Mean = 5.43 Mean = 10.40 Min = <0.01 Min = 3.90 Max = 46.80 Max = 22.90 Median = 1.40 Median = 7.40 Sulphate (mg/L): Sulphate (mg/L): Mean = 3.35 Mean = 3.40 Min = <0.01 Min = 1.00 Max = 37.40 Max = 7.30 Median = 0.30 Median = 2.65
Olem & Berthouex 1989	USA & Netherlands (25 systems in KT, 25 systems in Netherlands, 1 sample each)				KT Cisterns, [Netherland] Cisterns (µeq/L): Cd: 0.15 [0.10] Cu: <10 [<10] Pb: 1.1 [1.1] Zn: 60 [90] MEDIAN VALUES	KT Cisterns, (Netherland Cisterns) (µeq/L) H: 0.10 [0.02] Ca: 775 [447] Mg: 43.6 [28.8] Na: 43.1 [165] K: 19.5 [12.8] Cl: 22.6 [164] PO_4: 1.3 [1.3] SO_4: 135 [31.2] NO_3: 58 [14.5] Cation/anion ratio: 1.05 [1.02] Conductivity, µS/cm: 101 [74.6] Total dissolved solids, mg/L: 60 [40] Alkalinity, µequiv/L: 620 [430] Acidity, µequiv/L: 450 [280] Field pH: 7 [7.61] Lab pH: 7.76 [7.58] MEDIAN VALUES

Table 7, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Sediment	Nitrogen Species	Phosphorus Species	Heavy Metals	Other Parameters
Sazakli et al. 2007	Greece (13 systems, 12 samples each)		Nitrates (as N): Median- 7.04 mg/L Range- 5.28-13.02 mg/L Nitrites (as N): Median- 0.013 mg/L Range- 0.003-0.043 mg/L Ammonium (as N): Median- 0.01 mg/L Range- 0.01-0.05 mg/L	Phosphates: Median- 0.09 mg/L Range- 0.01-0.62 mg/L	Median Range Ca (mg/L): 15.2 10.6-19.2 Mg (mg/L): 0.6 0.4-2.4 Na (mg/L): 6 2-11 K (mg/L): 2.4 0.7-3.6 Fl (mg/L): <0.01 <0.01-<0.01 Fe (µg/L): 11 6-40 Mn (µg/L): 1.0 <0.5-73.0 Cd (µg/L): 0.05 <0.10-0.19 Pb (µg/L): <2.0 <2.0-6.9 Cu (µg/L): <2.5 <2.5-13.0 Cr (µg/L): <1.3 <1.3-4.8 Ni (µg/L): <10.0 <10.0-12.2 Zn (µg/L): 10.0 <10.0-77.0	Median Range pH: 8.31 7.63-8.80 Conductivity (µS/cm): 103 56-220 Sulfates (mg/L): 8 1-13 Chloride (mg/L): 7 3-16 Hardness (mg/L CaCO3): 40 24-74 Alkalinity (mg/L CaCO3): 42.5 6-48
Spinks et al. 2006	Australia (49 systems, 1 sample each)	Turbidity (NTU): <0.5 - 5 TDS (mg/L): 24 - 130			As (mg/L): <0.001 - 0.007 Cd (mg/L): <0.0002 - 0.0067 Cr (mg/L): <0.001 - 0.008 Cu (mg/L): 0.005 - 0.58 Fe (mg/L): <0.05 - 0.78 Pb (mg/L): <0.001 - 0.006 Zn (mg/L): 0.003 - 17	pH: 5.2 - 10.2 Colour (Pt/Co units): <2 - 25 HU
Sung et al. 2010	Taiwan (29 systems, 1 sample each)	- most under 5 mg/L - two exceptions: 10mg/L & 25mg/L				TOC: <6 mg/L except (1) 14 mg/L Conductivity: up to 2,000 µS/cm
Vialle et al. 2012	France (1 system, 55 samples)	Turbidity (NTU): Min = 0.50 Max = 6.1 Mean = 2.4 Median = 2.0	NO_3-N (mg/L): Min = 0.12 Max = 1.76 Mean = 0.63 Median = 0.54 NH_4-N (mg/L): Min = <0.08 Max = 1.32 Mean = 4.51 Median = 0.25 Total Nitrogen (mg/L): Min = <1 Max = 8.0 Mean = 1.7 Median = <1	PO_4 (mg/L): Min = <0.10 Max = 0.54 Mean = 0.17 Median = 0.19 Total Phosphorus (mg/L): Min = <0.1 Max = 0.2 Mean = <0.1 Median = <0.1	Mg (mg/L): Min = <0.10 Max = 0.71 Mean = 0.27 Median = 0.24	Parameter Min Max Mean Median pH 5.6 10.4 6.5 6.2 Conductivity (µS/cm) 13.5 235.0 56.2 38.2 Color (mg Pt/L) <5 39 18 19 Hardness (mmol/L) <0.01 0.58 0.16 0.11 Cl (mg/L) 0.55 4.0 1.9 1.7 SO_4 (mg/L) 0.50 6.6 1.9 1.8 Ca (mg/L) 1.0 19 4.4 2.9 Na (mg/L) 0.30 2.9 1.1 0.93 K (mg/L) 0.15 4.9 1.2 0.78 TOC (mg/L) 0.50 5.1 2.3 2.2 COD (mg/L) <30 34 <30 <30 BOD_5 (mg/L) <3 17 <3 <3
Ward et al. 2010a	UK (1 system, some parameters sampled weekly for 8 months, some parameters sampled every 3 months for 8 months)		TN: 0.31 - 4.01 mg/L NH_4-N: <0.01 - 0.49 mg/L NO_3-N: 0.30 - 4.01 mg/L NO_2-N: < 0.01 - 0.07 mg/L VALUE RANGES	Phosphorus as P: 15-50 µg/L VALUE RANGES	Ca: 5.7-10 mg/L Mg: 0.36-0.58 mg/L Cu: 218-290 mg/L Zn: 193-480 µg/L Na: 2.8-4.3 mg/L K: 1-2.4 mg/L Al: 80.2-108 µg/L Fe: 9-27.4 µg/L Mn: <2-3.18 µg/L Cu: 218-290 µg/L Pb: 25.5-64.4 µg/L Cd: <0.4 µg/L Cr: <0.5 µg/L Ni: <1.5-1.68 µg/L VALUE RANGES	pH: 7.6-10.4 O & G: BDL PAHs: BDL Conductivity: 43-261 µS Turbidiy: 0.3-2.8 NTU TDS: 30-182 mg/L BOD: <3 mg/L COD: 10-12 mg/L SO_4: <2.5-5.3 mg/L Cl: 3-28 mg/L SiO_2: 0.35-4 mg/L VALUE RANGES

Table 7, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Sediment	Nitrogen Species	Phosphorus Species	Heavy Metals	Other Parameters
Zhu et al. 2004	China	Turbidity (NTU): 2.0 - 3.5 TDS (mg/L): 185.0 - 750.0 (n = unknown)	Total Nitrogen (mg/L): 1.188±0.734 (n = 3)	Total Phosphorus (mg/L): 0.247±0.037 (n = 4)	Mg (mg/L): 0.93 - 1.143 Fe (mg/L): 0.01 - 0.083 Mn (mg/L): 0.048 - 0.112 Cu (mg/L): 0.0011 - 0.016 Al (mg/L): 0.093 - 0.336 Ni (mg/L): UD Pb (mg/L): 0.003 - 0.041 As (mg/L): UD Cr (mg/L): UD Hg (mg/L): UD Cd (mg/L): UD (n = unknown)	Average pH: 7.39 Color (mg Pt-Co/L): 0.4 - 1.2 Hardness (mg $CaCO_3$/L): 60.96 - 149.02 COD_{CR} (mg/L): 8.74 - 23.83 Cl (mg/L): 6.13 - 79.2 SO_4 (mg/L): 2.40 - 15.62 F (mg/L): 0.071 - 0.163 Na (mg/L): 3.02 - 11.2 K (mg/L): 3.36 - 8.658 Ca (mg/L): 11.2 - 31.15 B (mg/L): 0.011 - 0.056 Ba (mg/L): 0 - 0.0112 Se (mg/L): 0.004 - 0.009 (n = unknown)

Table 8. Summary of key findings from numerous studies on the quality of water stored in rainwater harvesting (RWH) systems.

References	Study Location	Sampling	Key Findings
Abbasi & Abbasi 2011	India	n/a	• The quality of harvested rainwater declines as the storage period increases. • The inlet of the storage tank should be designed such that sediments on the bottom of the tank are not disturbed when water flows into the tank. • It is best to extract water from the top of the tank via a floating inlet as opposed to the bottom of the tank, as this is where the water is dirtiest. • The overflow of the tank should be designed to exclude or discard the dirtiest water. Possible methods of doing this is designing such that overflow is taken from the bottom of the tank where the dirtiest water is, or design the inlet such that overflow bypasses the inlet and never enters the tank.
Abdulla & Al-Shareef 2009	Jordan	60 systems sampled once	• The quality of rainwater within a RWH system is dependent upon how long it is stored and the patterns of use. • Performing regular maintenance, as well as efficient management and operation of the system, improves water quality. • Roof washing and first flush diversion is encouraged to maintain good water quality. • The intensity of rainfall and the number of antecedent dry days significantly affect water quality. • 60 cisterns were tested and samples met WHO guidelines for physical and chemical parameters, indicating harvested rainwater, even including first flush, usually provides safe drinking water.
Daoud et al. 2011	Palestine	21 systems sampled twice; August 2006 and March 2007	• An increase in pH occurred due to the alkaline nature of the roofing and storage tank materials. • The overal quality of stored rainwater meet WHO drinking water guidelines, except for pH, turbidity and lead.

Table 8, cont. Summary of key findings from numerous studies on the quality of water stored in rainwater harvesting (RWH) systems.

References	Study Location	Sampling	Key Findings
Despins et al. 2009	Canada	7 systems, 30 samples each	• Storing water in a cistern improves its quality primarily through sedimenation. • Storing water in a concrete tank tends to increase the pH, minimizing the potential for leaching metals. • There is some potential for leaching chemicals from the tank material into the stored water (ex. zinc from metal tanks, organic compounds from plastic tanks). • Water quality parameters are very sensitive to the design aspects of rainwater harvesting systems as well as environmental conditions. • pH is easily affected by the type of tank material. The pH of water stored in plastic tanks was slightly acidic, while that of water stored in concrete tanks was more basic. • Color, turbidity and total nitrogen concentrations increased during dry periods. • Poorer water quality was observed during the summer and fall seasons, especially TOC. This may be due to cold climate conditions (i.e. low atmospheric deposition, decrease in plant/animal activity or presence of snow that minimized transfer of pollutants to roof surface). • The selection of appropriate catchment and storage material and the proper application of pre- and post-storage treatment can ensure a consistently high quality of harvested rainwater.
Domènech & Saurí 2011	Spain	3 systems, 1 sample each	• Acceptable chemical concentrations in all tanks sampled, except one system contained boron above the European maximum allowable concentration. • The cleanliness of the catchment surface, gutters and storage tanks was a direct indicator of water quality within the system.
Huston et al. 2009	Australia	15 sites, sampled once	• Tank water quality did not always meet Australian Drinking Water Guidelines, especially when there were local sources of airborne pollutants or roofing materials that contributed to the pollutant loading.

Table 8, cont. Summary of key findings from numerous studies on the quality of water stored in rainwater harvesting (RWH) systems.

References	Study Location	Sampling	Key Findings
Islam et al. 2010a	Bangladesh	1 system, 8 sampling events over 4 month period	• Ferrocement tanks may increase the alkalinity of stored water. • Paint coatings on roofs may oxidize during weathering processes and be washed into the storage tank. If these paints contain lead or copper, this can result in heavy metal contamination of the stored water. • If harvested rainwater has a low pH, it may increase the dissolution rate of metal components (tanks, pipes, fittings). • New tanks often have problems with odor and taste due to the leaching of coatings. Flushing the tank prior to use can help eliminate these. • As many public water supplies are supplemented with fluoride to prevent tooth decay, those using only rainwater as a drinking source should take an extra flouride supplement. • According to this study, in Dhake regions of Bangladesh, rainwater can be stored up to 3 months and still be acceptable for drinking without treatment.
Kim & Han 2011	Korea	1 site, 10 samples; Nov. 2007 - Sept. 2008	• Concentrations of physical and chemical parameters often lower at the tank outlet than at the inlet (storage tank comprised of concrete). • Biofilms that developed at the tank/water interface may remove nutrients from stored water.
Kus et al. 2010a	Australia	11 systems, 3 samples each	• The quality of stored rainwater generally met Australian drinking water standards, except for iron and lead concentrations. Average concentrations from most tanks exceeded the guidelines for both these metals. • Other heavy metals were negligible. • Turbidity in the tanks increased when roofs were noticeably dirty or after heavy rainfall occurred. • If the first flush is allowed into the tank it can have a significant impact on the quality of the stored water.

Table 8, cont. Summary of key findings from numerous studies on the quality of water stored in rainwater harvesting (RWH) systems.

References	Study Location	Sampling	Key Findings
Lee et al. 2010	South Korea	10 events in 2009, 30 events in 2010	• The concentrations of all metals in harvested rainwater increased as the water passed through the catchment system. • Common anions, major cations and metal ions, except for Al, sampled in the cistern were below drinking water guidelines. • Hygiene and maintenance practices, such as first flush diversion, can improve the quality of harvested rainwater.
Magyar et al. 2007	Australia	6 pilot tanks, monitored quarterly for one year; 9 household tanks, sampled once	• Rainwater harvesting systems connected to roof with lead flashing had elevated lead concentrations in the stored water, sometimes up to 50 times greater than the Australian Drinking Water Guideline. • Lack of maintenance can increase the concentrations of heavy metals in stored water and in sediments accumulated on the bottom of the tank.
Martin et al. 2010	Australia	2 sites, daily samples for 31 consecutive days; January 2008 and July 2007	• Warmer temperatures may accelerate the rate of metal leaching from galvanized iron tanks.
Meera & Ahammed 2006	India	n/a	• Diverting the first flush away from the rainwater harvesting system can improve the quality of harvested water. • Water quality can be reduced considerably if poor collection and maintenance procedures are practiced.
Morrow et al. 2010	Australia	5 sites, 60 samples, July 2006 - January 2008	• All parameters sampled from the cistern water were below Australia Drinking Water Guidelines for the entire sampling period. • Iron concentrations in 3 of the monitored systems were lower in the stored water than in the roof runoff, most likely due to flocculation, settling or microbial processes occurring within the tank. • The elemental composition of harvested rainwater varies throughout the rainwater harvesting system and depends upon individual site characteristics.

Table 8, cont. Summary of key findings from numerous studies on the quality of water stored in rainwater harvesting (RWH) systems.

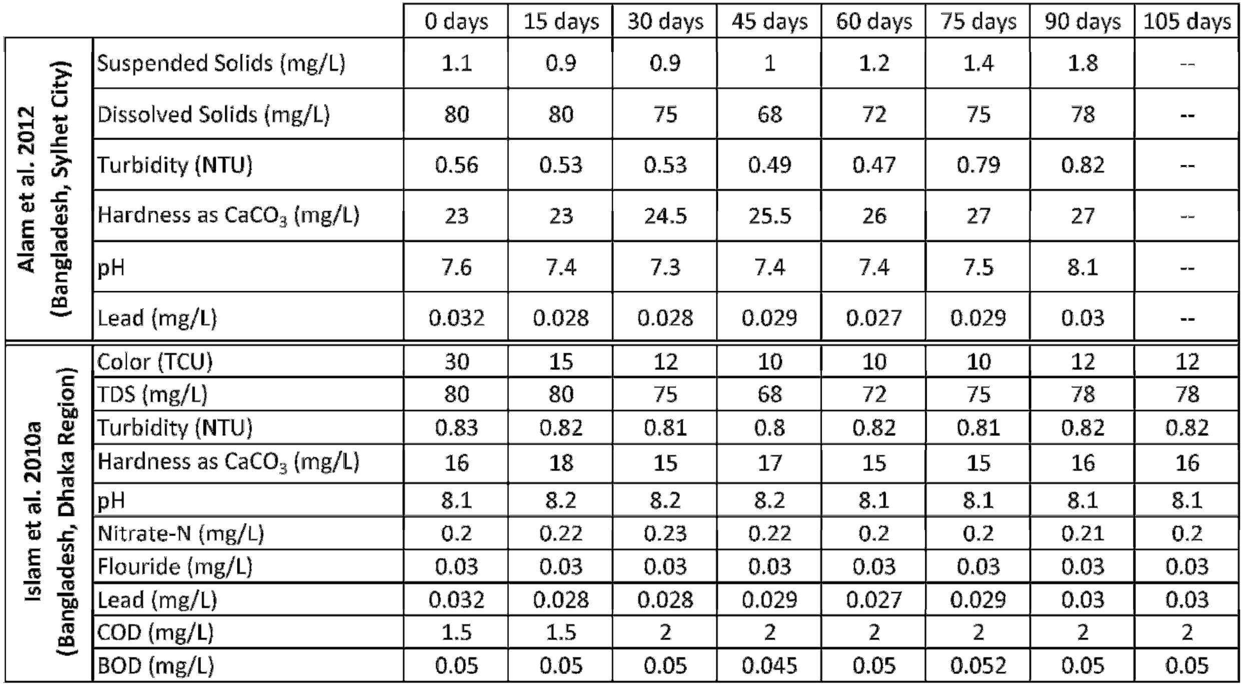
References	Study Location	Sampling	Key Findings
O'Hogain et al. 2012	Ireland	monthly samples; regime 1: Jan 2006 - Jan 2007; regime 2: Jan 2008 - April 2008	• Pre-treatment filters substantially improved water quality • Regime 1 - no pre-storage treatment, first flush diversion or disinfection. Regime 2 - pre-storage filters added. • Regime 1 parameter concentrations (see Table 7) were compliant with Ireland drinking water guidelines except for lead, iron and ammonia. Iron and lead likely leached from roof surface. The presence of ammonia most likely due to nearby agriculture and the resulting atmospheric deposition. • Regime 2 - all concentrations complied with Ireland drinking water standards except ammonia.
Olem & Berthouex 1989	USA & Netherlands	25 sites, 3 month sampling period; 1986	• Storing water in a masonry cistern increased pH due to the material's neutralizing capacity. • Concentrations of Cd, Pb and Zn decreased between the roof and the cistern. • Metal concentrations are decreased within a cistern due to sedimentation, precipitation and sorption. As pH levels increase, the solubility of metals decreases and removal via precipitation increases.
Sazakli et al. 2007	Greece	23 sites, 3 year study period, each sampled 4 times per year	• The physical and chemical characteristics of stored water met the requirements for safe drinking water. • Catchment areas and storage tanks must be cleaned regularly to maintain good water quality, and first flush should be diverted.
Simmons et al. 2001	New Zealand	125 sites, sampled once	• In Auckland, harvested rainwater was of rather poor physicochemical quality. • Water stored in ferrocement tanks significantly more likely to have a higher pH.
Spinks et al. 2006	Australia	49 systems, sampled once	• Physicochemical results were compliant with Australia Drinking Water Guidelines for all parameters except pH. None of the systems sampled disinfected the water prior to consumption; only 9 employed first flush diversion. • Elevated concentrations of cadmium in some systems most likely due to the age and type of roofing material (galvanized iron). • High zinc concentrations may also be due to age and type of roof and/or due to the corrosion of tank material, pipes and fittings. There was a significant correlation between elevated zinc levels and the use of a galvanized iron tank; however, concrete tanks were significantly correlated with zinc concentrations lower than the drinking water guidelines.

Table 8, cont. Summary of key findings from numerous studies on the quality of water stored in rainwater harvesting (RWH) systems.

References	Study Location	Sampling	Key Findings
Sung et al. 2010	Taiwan	30 sites, sampled once	• Storing water for long periods of time can decrease water quality. • Larger suspended sediment particles settled rapidly within the storage tank, therby improving water quality. • TOC concentrations were very high, perhaps due to atmospheric deposition or long retention time.
Vialle et al. 2012	France	1 system, weekly samples; 1 year sampling period	• Ionic concentrations were low, indicating the rainwater had low level of mineralization. • Harvested rainwater had relatively good physicochemical quality, but the quality varied greatly and did not meet drinking water guidelines. • Concentrations of parameters in tap samples were similar to those from tank samples where mains water was used to top-up the system.
Ward et al. 2010a	UK	1 site, weekly sampling and three-monthly sampling	• The design and construction of the roof catchment and components of the rainwater harvesting system significantly influence the quality of harvested rainwater. • Good design and construction is essential to maintain good quality and prevent the development of contaminated sediments. • Aluminum gutters can contribute aluminum to roof runoff, corrosion of brass fittings can introduce zinc and copper can leach from pipes when water has low calcium concentrations.

and chemical parameters of harvested rainwater in Bangladesh changed very little over a period of 3 months (Table 9). Both studies simulated usage by extracting approximately 25 L daily and concluded that the stored water met Bangladesh drinking water standards at the end of the 3 month period.

Table 9. Physicochemical parameters of stored rainwater, as measured every 15 days.



		0 days	15 days	30 days	45 days	60 days	75 days	90 days	105 days
Alam et al. 2012 (Bangladesh, Sylhet City)	Suspended Solids (mg/L)	1.1	0.9	0.9	1	1.2	1.4	1.8	--
	Dissolved Solids (mg/L)	80	80	75	68	72	75	78	--
	Turbidity (NTU)	0.56	0.53	0.53	0.49	0.47	0.79	0.82	--
	Hardness as $CaCO_3$ (mg/L)	23	23	24.5	25.5	26	27	27	--
	pH	7.6	7.4	7.3	7.4	7.4	7.5	8.1	--
	Lead (mg/L)	0.032	0.028	0.028	0.029	0.027	0.029	0.03	--
Islam et al. 2010a (Bangladesh, Dhaka Region)	Color (TCU)	30	15	12	10	10	10	12	12
	TDS (mg/L)	80	80	75	68	72	75	78	78
	Turbidity (NTU)	0.83	0.82	0.81	0.8	0.82	0.81	0.82	0.82
	Hardness as $CaCO_3$ (mg/L)	16	18	15	17	15	15	16	16
	pH	8.1	8.2	8.2	8.2	8.1	8.1	8.1	8.1
	Nitrate-N (mg/L)	0.2	0.22	0.23	0.22	0.2	0.2	0.21	0.2
	Flouride (mg/L)	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	Lead (mg/L)	0.032	0.028	0.028	0.029	0.027	0.029	0.03	0.03
	COD (mg/L)	1.5	1.5	2	2	2	2	2	2
	BOD (mg/L)	0.05	0.05	0.05	0.045	0.05	0.052	0.05	0.05

The processes occurring within rainwater storage tanks (decreases in heavy metal concentrations and facilitation of flocculation, precipitation and settling) lend to the hypothesis that accumulated sediments within tanks are particularly comprised of heavy metals; sediments tested in numerous studies (data included in Table 5) support this hypothesis (Olem and Berthouex 1989; Huston et al. 2009; Magyar et al. 2007). In all three studies, sediments accumulated in the bottom of the storage tank contained extremely high concentrations of heavy metals such as Cu, Ni, Zn and Pb. Olem and Berthouex (1989) reported Cu concentrations as high as 240µg/L and Magyar et al. (2007) reported Pb concentrations of 24.22mg/kg. The extent of heavy metal contamination in sediments tested by Magyar et al. (2007) resulted in the classification of the sediments as either "prescribed waste – contaminated soil" category B or C (based on Australian classification system), both of which require appropriate management options, including licensed transport permits and disposal sites. In some tanks Pb and Zn concentrations exceeded category C, thereby requiring sediments to be immobilized prior to disposal (Magyar et al. 2007). This implies the need for specialized disposal services and perhaps the need for more frequent sediment removal, which may avoid the buildup of such high levels of metal contamination (Magyar et al. 2007). It should be noted, however, that the presence of lead flashing, aluminum-zinc roof coatings and/or galvanized iron roof materials is most likely the cause of high metal concentrations within these systems and eliminating these components from the RWH systems may decrease metal contamination within tank sediments.

There are several design options that may be utilized to decrease the potential for contamination of harvested rainwater via tank sediments. Kus et al. (2010a) showed that dirty roofs and heavy rainfall events can cause increases in turbidity in tank water. In addition to first flush, Abdulla and Al-Shareef (2009) suggests roof washing to further improve the quality of water leaving the roof surface and entering the storage tank. Positioning the tank inlet in the center of the tank, instead of adjacent to the wall, may minimize the resuspension of tank sediments (Hermann & Schmida 1999; Magyar et al. 2007). Additionally, having a 'buffer layer' of water above the sediments and removing sediments often to reduce volume may also help prevent or decrease contamination of extracted tank water (Magyar et al. 2007). An alternative to this is to have a 'calming inlet' design in which the inlet pipe enters the storage tank, extends to the bottom of the tank where a U-shaped fitting directs water flow upwards into the tank. This design prevents water from spilling into the tank, potentially disturbing sediments that have collected on the bottom. Finally, low pH levels (lower than 4.5) of stored rainwater can result in the release of heavy metals from these sediments (Hamdan 2009). For systems located in regions prone to acid rain or receiving water from surfaces that tend to lower pH of runoff, choosing a tank made of alkaline materials (such as cement) can help raise the pH of stored water.

Pesticides and Organic Compounds

As pesticides are often applied aerially in a diffuse manner, it is not surprising that their presence is sometimes detected in roof runoff and stored rainwater. Physical transport of aerosol particles, volatilization into the atmosphere and sometimes direct deposition onto roof surfaces can lead to rather substantial concentrations of pesticides, transformation products of the parent chemical and other organic compounds in roof runoff (Bucheli et al. 1998; Zhu et al. 2004). Due to the toxic nature of many of these constituents, studies have been conducted to evaluate their occurrence in rainwater proper, roof runoff and water in the storage tank of a RWH system.

In a study performed by Bucheli et al. (1998), rainwater was sampled during 41 storm events at a site in Grüze, Switzerland, and analyzed for a series of pesticides. As shown in Table 10, multiple pesticides were detected in rainwater, with those most commonly detected being those most frequently used in surrounding areas (Bucheli et al. 1998). The majority of compounds were detected during or immediately following their primary application period in spring or early summer (Bucheli et al. 1998). More volatile compounds were generally detected during the application period, while less volatile compounds were detected sometimes weeks later.

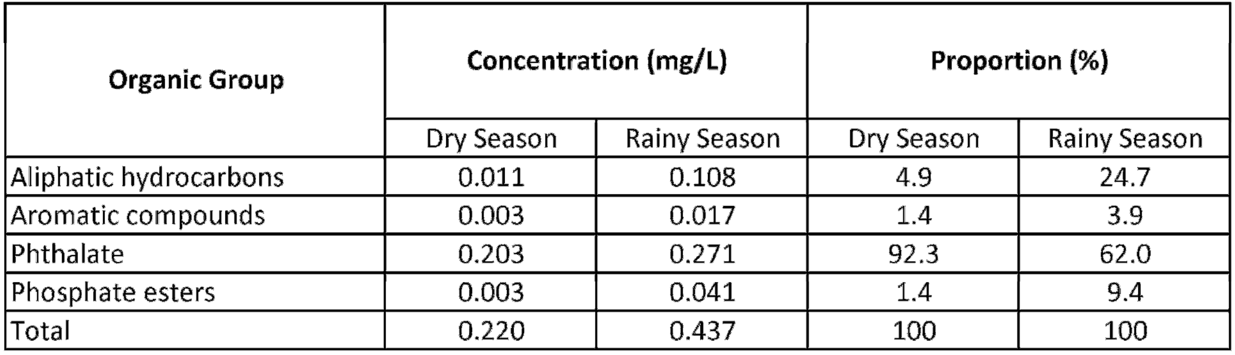
Table 10. Concentrations of pesticides found in rainwater proper in Switzerland (Bucheli et al. 1998).

Chemical	Detected in n samples out of 41	Concentration (ng/L)	
		Median	Max
Triazines			
Atrazine	28	33	903
Desethylatrazine	20	29	166
Deisopropylatrazine	13	26	137
Terbuthylazine	13	9	48
Simazine	10	10	53
Propazine	1	7	7
Acetamides			
Alachor	16	19	191
Metolachlor	16	15	124
Propachlor	12	10	48
Dimethenamid	4	24	78
Metalaxyl	2	14	17
Metazachlor	1	12	12
Phenoxy Acids			
R-mecoprop	17	10	50
S-mecoprop	11	10	19
R-dichlorprop	20	12	106
S-dichlorprop	2	9	11
2,4 D	2	16	23
MCPA	4	16	27

Zhu et al. (2004) sampled 12 RWH systems in Dingxi County, China, over a 3-year period. The systems received runoff from roof and paved yard surfaces. A total of 41 organic compounds were detected in this runoff, with concentrations of the following compounds exceeding 1 ng/L: decane (2-, 4- and 5-methyl), undecane, dodecane, eicosane, docosane, heptacosane, tritriacontane, hexatritriacontance, hexacosane, dodecanenitrile, cedrol, triethylene glycol, pentaethylene glycol, cyclohexanone, isopropyl palmitate, isopropyl stearate, 1,2-benzenedicarboxylic acid – bis (2-methylethyl) ester, ethylbenzene, 1*H*-3a 7-Methanoazulene 2,3,4,7,8,8a-hex, phosphoric acid tributyl ester, phthalate anhydride, dibutyl phthalate and bis(2-ethylhexyl) phthalate. When the detected compounds were combined into organic groups, it was apparent that phthalates were the predominant group present in harvested rainwater (Table 11). The most likely source of these compounds is fuel leakage on roads, although they are also associated with petrochemical and plastichemical industries. Aliphatic hydrocarbons were the next most prominent group in harvested rainwater and likely originate from vehicle fuel leakage or the burning of oil and coal. Potential sources for aromatic compounds and phosphate esters are crude oil, coal, coal tar pitch or creosote, and plastic film, respectively (Zhu et al. 2004).

As shown in Table 11, water quality was worse during the rainy seasons with respect to organic pollutants (Zhu et al 2004). Zhu et al. (2004) also observed that the quality of water tended to improve as storage time increased, most likely due to biodegradation and decomposition.

Table 11. Concentrations of organic groups measured in harvested rainwater (Zhu et al. 2004)



Organic Group	**Concentration (mg/L)**		**Proportion (%)**	
	Dry Season	Rainy Season	Dry Season	Rainy Season
Aliphatic hydrocarbons	0.011	0.108	4.9	24.7
Aromatic compounds	0.003	0.017	1.4	3.9
Phthalate	0.203	0.271	92.3	62.0
Phosphate esters	0.003	0.041	1.4	9.4
Total	0.220	0.437	100	100

Spinks et al. (2006) also analyzed harvested rainwater for organic compounds in Australia after a major brushfire occurred. There were no samples with concentrations of benzo(a)pyrene, benzene, toluene, ethylbenzene, xylene or PAHs above the detection limits; therefore, it was concluded that brushfires did not cause an increase in the concentration of organic compounds in harvested rainwater (Spinks et al. 2006). Mendez et al. (2011) conducted a study in Texas and found similar results to Spinks et al. 2006; No pesticides or PAHs were detected in runoff from pilot-scale roofs. Benzyl alcohol and 2,4-dinitrophenol were detected only in the first flush. Mendez et al. (2011) attributes the lack of pesticide presence to the lack of use in the surrounding areas.

Implications for Using Collected Rainwater

The enormous potential of water quality contamination throughout a rainwater harvesting system necessitates the use of treatment options to produce water of suitable quality for potable and non-potable uses. 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 & Al-Shareef 2009; Kus et al. 2010b; Lee et al. 2010; Despins et al. 2009; Abbasi and Abbasi 2011; Mendez et al. 2011; Meera and Ahammed 2006). Diverting the first flush can retard the buildup of particulates and sediments within storage tanks, prevent odor 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). While the recommendation for including first flush diversion is universal, the diversion volume recommendation varies greatly. The exact volume that can be considered of first flush quality at any given time is dependent upon several factors, including the number of preceding dry days, amount and type of debris present on roof surface, season, and quality and type of roof surface (Abbasi and Abbasi 2011).First flush precipitation depths range from 0.5 to 2mm (Abbasi and Abbasi 2011).

Debris screens and filters can be used between the roof surface and the storage tank to prevent particulate matter (and contaminants adsorbed in particulate matter) from entering the tank (Abbasi and Abbasi 2011). Most debris filters include a coarse filter to exclude leaves, pine needles and other large debris, as well as a fine screen to exclude smaller particulates (such as asphalt shingle grit) (Abbasi and Abbasi 2011). Regardless of filter style (self-cleaning, basket-shaped, etc.), the Abbasi and Abbasi (2011) recommend the following characteristics to maximize the effectiveness of debris screens when employed by a RWH system:

- Filter should be easy to clean or largely self-cleaning,
- Filter should not clog easily and clogging should be easy to detect and rectify, and
- Filter should not provide an entrance for additional contamination (e.g. corrodible materials, openings large enough to allow animals to access the system. etc.).

Post-storage treatment can consist of in-line sediment filters on pumps, slow sand filtration, clariflocculation and/or disinfection. Particle filtration (sediment filters, sand filtration, other types of filters), have been shown to remove particulates and heavy metals and improve 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 and ultraviolet light. Each of these options has pros and cons to its use; however, disinfection is predominantly used to improve microbiological quality of water, which is discussed later in the section entitled "Microbial Characteristics of Rainwater Harvesting Systems".

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 (Abdulla and Al-Shareef 2009; Lee et al. 2010; Magyar et al. 2007; Meera and Ahammed 2006). 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 possible points of entry for mosquitoes and vermin (Domènech and Saurí 2011; Kus et al. 2010a; Sazalaki et al. 2007).

Conclusions and Recommendations

The findings and data discussed herein emphasize that harvested water quality is highly dependent upon design aspects of the RWH system, design and composition of materials connected to the RWH system (e.g., roofing materials, gutters, downspouts), local sources of pollution and contaminants and geographic, meteorological and environmental conditions of a given site (Despins et al. 2009; Morrow et al. 2010; Lee et al. 2010; Ward et al. 2010a). However, appropriate selection of catchment and storage materials and the inclusion of pre- and post-storage treatment can improve the quality of harvested rainwater (Despins et al. 2009). Regardless of design and environmental conditions, good hygiene and maintenance of RWH systems, including regular cleaning of catchment areas and storage tanks, is essential in maintaining good water quality (Meera and Ahammed 2006; Lee et al. 2010; Sazalaki et al. 2007; Lee et al. 2011).

The following are characteristics should be employed whenever possible to ensure optimal quality of harvested rainwater. It is expected that water quality would be directly proportional to the number of these features employed within a system:

- A smooth roofing material with a protective coating (such as paint) to prevent water from contacting raw metal,
- No lead flashing on roof surface or gutters,
- No overhanging vegetation, antennae or other structures that animals/birds could perch upon,
- Plastic downspouts (or if made of metal a protective coating such be applied to the inside of the downspout, to prevent water from contacting raw metal),
- Debris filters employing the characteristics described in the previous section,
- A first flush diverter for each downspout,
- A concrete or plastic storage tank with a calming inlet design,
- PVC (not stormwater grade) distribution piping (as opposed to metal), with no metal fittings or solder,
- Regular use of harvested water to prevent long retention times, and
- Frequent maintenance to ensure proper function of all components.

Future Research Needs

Future research needs that may serve to improve our understanding of water quality pollution with respect to RWH systems are listed below, in no particular order:

- Further research and development is needed on: (1) first flush diversion volumes and their automated control via sensors; (2) sorbents for heavy metals; (3) durable coatings of heavy metal surfaces; (4) alternative materials (i.e. not metal or PVC) for gutters and downspouts; and (5) roof runoff quality database that is sufficient for accuratemodeling (Förster 1999).
- Any model predicting runoff properties should account for climatic influences such as temperature, rain intensity and humidity (Schriewer et al. 2008).
- Health implications should be assessed regarding the use of rooftop RWH systems in developing countries where rainwater is becoming a widespread drinking source (Meera and Ahammed 2006).
- Research and development is needed on debris filters and screens to reconcile the conflicting requirements (hydraulic efficiency and particle removal efficiency) and maximize filter performance (Abbasi and Abbasi 2011).

- More research is needed on how design features and maintenance practices of RWH systems can be modified to improve the quality of rainwater collected from rooftop catchments (Meera and Ahammed 2006).
- Further exploration is needed of tank designs to reduce sediment resuspension, promote easy removal of sediments and mitigate impacts of sediments on the quality of extracted water (Magyar et al. 2007).
- Additional investigation of plastic plumbing materials, joining materials including solder and faucets or other fixtures is needed to clarify contribution of contaminants to tap water (Olem and Berthouex 1989).
- The impact of Pb in sludge and the partitioning between tank sediments and the water quality should be furthered studied to develop recommendations for the removal of accumulated sediments and subsequent decontamination (Huston et al 2009).
- Further investigation is needed regarding the best methods of communicating maintenance procedures for RWH systems used as private drinking water supplies (Spinks et al. 2006).
- The potential for asphalt shingle roofs to serve as a source of mercury should be investigated further (Van Metre & Mahler 2003).
- More research is needed on potential health risks caused by the presence of organic compounds in harvested rainwater (Zhu et al. 2004).

Microbiological Characteristics of Rainwater Harvesting Systems

In addition to the various water quality constituents identified in the previous sections, a variety of micro-organisms have also been detected in RWH systems. These organisms range from indicator bacteria (such as enterococci, fecal coliform fecal streptococci) to pathogens (E-coli, Salmonella, Giardia, Cryptosporidium, etc.) and even viruses. While some of these organisms may be harmless, others warrant considerable concern with respect to human health. The following sections will discuss the sources of microbiological contamination, the presence and associated risks of micro-organisms in rainwater harvesting systems, methods of treatment to reduce contamination and risk and the implementation of design modifications and/or maintenance protocols to reduce the likelihood of contamination.

Sources of Contamination

To effectively manage and reduce microbial contamination and associated health risks within RWH systems, one must first identify its sources (Ahmed et al. 2012a). A primary source of bacteria and pathogens in collected rainwater has been identified as fecal contamination from wildlife such as insects, birds, small mammals (bats, possums, squirrels, rats, etc.) and small reptiles or amphibians (lizards, frogs) that is washed into the RWH system during rain events (Ahmed et al. 2012a; Ahmed et al. 2012b; Ahmed et al. 2008; Ahmed et al. 2011b; Chilvers et al. 1998; Evans et al. 2006; Karim 2010; Merritt et al. 1999; O'Hogain et al. 2012). Some studies have identified correlations between the presence of overhanging trees or fecal droppings on roof surfaces and microbial contamination of collected rainwater (Ahmed et al. 2012a; Ahmed et al. 2012b). Ahmed et al. (2012a) reported that 4 out of 5 RWH tanks containing Campylobacter had overhanging trees or visible evidence of fecal matter on the roof surface. Furthermore, 2 of the 3 RWH systems containing Giardia had rooftop evidence of fecal droppings (Ahmed et al. 2012a). Ahmed et al. (2012b) used binary logistic regression analyses to confirm a positive correlation between the number of Enterococci spp. and the combined factors of overhanging vegetation and fecal droppings on the roof surface.

Other studies, as shown in Table 12, have sampled fecal material and identified the presence of the same bacteria and pathogens that are found in harvested rainwater, including Campylobacter, Giardia, Cryptosporidium, Salmonella and E-coli (EC) (Ahmed et al. 2012a; Ahmed et al. 2011b; Chilvers et al. 1998). Chilvers et al. (1998) found Giardia to be present in the fecal matter of all mammal species tested (possum, rat, hedgehog, rabbit, ferret and mouse) and in 6 of the 9 bird species tested. Giardia

Table 12. Results of fecal sampling for microbiological parameters.

<table>
<tr><th>References</th><th>Study Location & Details</th><th>Data</th></tr>
<tr><td>Ahmed et al. 2012a</td><td>Australia; feces samples tested from Brushtail possum (n=40) and birds (n=38) (species: plover, wood duckling, noisy minet, Pacific black duckling, blue faced honey eater, magpie, crow, ibis, seagull, topknot pigeon, crested tern, juvenile black swan, Pacific baza, fantail cuckoo, rainbow lorikeet and tawny frogmouth)</td><td>
<table>
<tr><th></th><th>Possum Feces</th><th>Bird Feces</th></tr>
<tr><td>Campylobacter (# cells per g)</td><td>$2x10^{5}$ - $2x10^{7}$</td><td>$6.6x10^{4}$ - $6.6x10^{6}$</td></tr>
<tr><td>Giardia (cysts per g)</td><td>$2.1x10^{1}$ - $1.6x10^{3}$</td><td>$1.3x10^{0}$ - $1.0x10^{2}$</td></tr>
<tr><td>Cryptosporidium</td><td>not quantifiable</td><td>not quantifiable</td></tr>
<tr><td>Salmonella (bacteria per g)</td><td>not detected</td><td>$6.3x10^{2}$ - $1.8x10^{3}$</td></tr>
</table>
Possum Fecal Samples:
Campylobacter: 60% samples positive
Cryptosporidium: 13% samples positive
Giardia: 30% samples positive
Salmonella: not detected

Bird Fecal Samples:
Campylobacter: 24% samples positive
Salmonella: 11% samples positive
Cryptosporidium: 5% samples positive
Giardia: 13% samples positive</td></tr>
<tr><td>Ahmed et al. 2011b</td><td>Australia; 40 fresh fecal samples tested from Brushtail possums and various bird species; tested for 200 E.coli isolates</td><td>Possum feces:
stx$_2$: 1 (5%) sample tested positive
cdtB: 2 (10%) samples tested positive

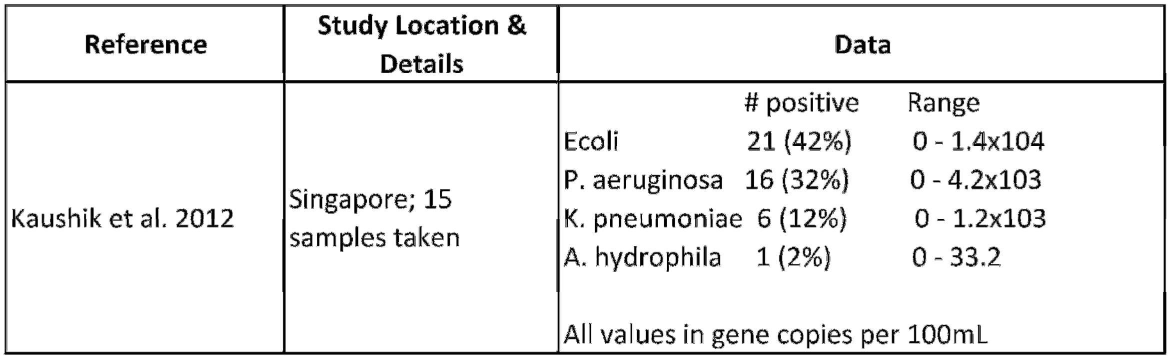
Bird feces:
stx$_2$: 3 (15%) samples tested positive
stx$_1$: 1 (5%) sample tested positive
ST1: 1 (5%) sample tested positive
cdtB: 3 (15%) samples tested positive</td></tr>
<tr><td>Chilvers et al. 1998</td><td>New Zealand; 2 farms, feces of wild animals tested May 1991 - Jan 1992</td><td>
<table>
<tr><th></th><th colspan="2">----Giardia----</th><th colspan="3">-----Cryptosporidium-----</th></tr>
<tr><th>Species</th><th>n</th><th>%+ve</th><th>n</th><th>+ve</th><th>percent (%)</th></tr>
<tr><td>Possum</td><td>76</td><td>23.6</td><td>34</td><td>5</td><td>14.8</td></tr>
<tr><td>Rat</td><td>19</td><td>42.1</td><td>5</td><td>2</td><td>40</td></tr>
<tr><td>Hedgehog</td><td>6</td><td>33.3</td><td>3</td><td>0</td><td>0</td></tr>
<tr><td>Rabbit</td><td>5</td><td>25</td><td>2</td><td>0</td><td>0</td></tr>
<tr><td>Ferret</td><td>3</td><td>33.3</td><td>2</td><td>0</td><td>0</td></tr>
<tr><td>Mouse</td><td>46</td><td>30.4</td><td>14</td><td>1</td><td>7.1</td></tr>
<tr><td>Blackbird</td><td>20</td><td>35</td><td>12</td><td>0</td><td>0</td></tr>
<tr><td>Chaffinch</td><td>10</td><td>60</td><td>7</td><td>0</td><td>0</td></tr>
<tr><td>House sparrow</td><td>104</td><td>15.4</td><td>58</td><td>5</td><td>8.6</td></tr>
<tr><td>Hedge sparrow</td><td>14</td><td>14.3</td><td>15</td><td>0</td><td>0</td></tr>
<tr><td>Starling</td><td>4</td><td>0</td><td>2</td><td>1</td><td>0</td></tr>
<tr><td>Thrush</td><td>14</td><td>50</td><td>11</td><td>3</td><td>27.3</td></tr>
<tr><td>Greenfinch</td><td>1</td><td>0</td><td>1</td><td>0</td><td>0</td></tr>
</table>
</td></tr>
</table>

concentrations in fecal samples from mammals were significantly higher than those in bird species and concentrations varied among species (concentrations in sparrows' fecal matter were lowest, while chaffinches and thrushes had significantly higher concentrations in their fecal matter). Cryptosporidium concentrations were not significantly different among species.

Other potential sources of microbial contamination include atmospheric deposition of organisms, the presence of organisms in rainwater proper and the introduction of contaminants via extraction and handling methods of harvested rainwater (Ahmed et al. 2012a; Evans et al. 2006; Evans et al. 2007; Kaushik et al. 2012; Zhu et al. 2004; Schets et al. 2010). Table 13 shows results from a study investigating the microbial composition of rainwater prior to contact with a roof surface. In this study, Kaushik et al. 2012 identified the scavenging of airborne micro-organisms and bioaerosols to be the primary contributor of EC and P. aeruginosa in rainwater. Accordingly, the presence of regional smoke haze from burning biomass as well as the path of weather-driven air masses played a significant role in the composition and concentration of microbial contamination. Zhu et al. (2004) theorized that high Fecal coliform (FC) in runoff could be due to the influence of nearby cattle and poultry manure, suggesting atmospheric deposition to be a primary contributor of micro-organisms. Evans et al. (2006) and Evans et al. (2007) also suggested atmospheric deposition to be the predominant source of microbial contamination in rooftop runoff (as opposed to fecal matter from wildlife). This conclusion was based upon data that showed wind direction and speed significantly affected the concentrations of heterotrophic plate count (HPC) and Psuedomonas spp. in roof runoff (Evans et al. 2006; Evans et al. 2007). Schets et al. (2010) reported similar findings regarding the concentration of C. perfringens and its correlation with wind speed. When collected rainwater is extracted from the storage tank by dipping containers into the water, bacteria and pathogens can be introduced from the container or hands of the person collecting water (Pinfold et al. 1993). In humid regions or during wet seasons, the risk of transmission in this manner increases greatly; E-coli contamination on fingertips of handlers has been significantly correlated with humidity (Pinfold et al. 1993).

Table 14 presents a summary of findings from four studies investigating the presence of micro-organisms in roof runoff. Lee et al. (2012) identifies a substantial difference in concentrations of Total coliform (TC), EC and enterococci in samples taken during and after the first flush. As was seen with many chemical constituents, samples taken during the first flush produced much higher concentrations than those taken after the first flush had passed (Lee et al. 2012). This suggests that the majority of microbial contamination occurs within the first few millimeters of runoff and, if diverted, could substantially reduce the amount of contamination entering the storage tank of a RWH system (Lee et al. 2012; Ahmed et al. 2012b).

Table 13. Microbial composition of rainwater.



Reference	**Study Location & Details**	**Data**		
			# positive	Range
Kaushik et al. 2012	Singapore; 15 samples taken	Ecoli	21 (42%)	0 - 1.4x104
		P. aeruginosa	16 (32%)	0 - 4.2x103
		K. pneumoniae	6 (12%)	0 - 1.2x103
		A. hydrophila	1 (2%)	0 - 33.2
		All values in gene copies per 100mL		

Table 14 also highlights differences in microbial concentration with respect to the type of roof surface. Lee et al. (2012) and Mendez et al. (2011) reported lower concentrations of TC in runoff from metal roofs versus shingle roofs. Mendez et al. (2011) found galvanized steel and clay tile produced the highest quality of runoff while concrete tile and wooden shingle produced the worst quality. These phenomena are most likely due to the presence of flora and organic matter on the roof surface, the retention of fecal matter within the crevices of the shingle roof and high temperatures and concentration of UV light on the surface of the metal roofs (Mendez et al. 2011; Lee et al. 2012; Ahmed et al. 2010a; Schets et al. 2010).

Conducting a visual assessment of a given RWH system can provide a good indication of potential sources of microbial contamination. The following is a list of risk factors that increase the risk of contamination (Karim 2010; Kaushik et al. 2012; O'Hogain et al. 2012; Spinks et al. 2006):

- Presence of fecal matter on roof surface or in gutters,
- Plant debris, organic matter or dust on the roof surface or in gutters,
- Leaking or defective tap on the storage tank(s),
- Overhanging vegetation, presence of antennae or other perches for wildlife,
- Manual abstraction of water from the tank,
- Defective access points in storage tank that allow for animals or insects to enter,
- Nearby sources of pollution (brush fires, burning organic matter, agricultural operations), and
- Chimneys or ash from fuel-burning stoves.

Table 14. Microbiological data from numerous studies on rooftop runoff.

References	Study Location	Site Description	Data
Evans et al. 2006	Australia	Figtree place development; 11 rain events sampled; Colourbond roof and gutter system	Mean microbial counts for all samples (CFU/mL): Heterotrophs: 1,362±194 Pseudomonas spp.: 593±132 Total coliforms: <4±0.76 Fecal coliforms: <2±0.42
Evans et al. 2007	Australia	Roof swab	Plate count: 102 CFU/mL Percent of plate count gram +ve: 13% Number of difference gram +ve species: 2 Percent of plate count gram -ve: 0% Number of difference gram +ve species: 0 Percent of plate count that is fungi: 87% Percent of plate count that is fecal coliforms: 0% Number of different FC species: 9
Lee et al. 2012	South Korea	Roof runoff; wooden shingle (WS), concrete tile (CT), clay tile (CL), galvanized steel (GS)	WS CT CL GS Total coliform counts (CFU/100 mL) First flush 131 197 76 70 After first flush 12 12 2 <1 E-coli (CFU/100 mL) First flush 14 18 8 4 After first flush 1 2 <1 0 Enterococci (CFU/100 mL) First flush 1 2 <1 <1 After first flush 0 0 0 0 Percent positive: Pseudomonas spp. First flush 12.5% 7.5% 2% 0% Salmonella spp. First flush 5% 5% 0% 0% Cryptosporidium First flush 0% 0% 0% 0%
Mendez et al. 2011	Texas	3 pilot-scale roofs, 4 storm events; 3 residential roofs, 3 storm events	-------------Metal---------- -----------Shingle---------- Pilot-scale Full-scale Pilot-scale Full-scale TC 117-770 64-173 177-1,367 102-353 FC <1-8 37-127 9-87 73-253 Values reported in CFU/100mL

Microbiological Quality of Rainwater Harvesting Systems

Tables 15 and 16 summarize data and conclusions from numerous studies investigating the microbiological quality of harvested rainwater in RWH systems. As shown in these tables, a large number of bacteria and pathogen species have been detected in harvested rainwater, with concentrations of these species being highly variable. Substantial variations in concentrations can be expected among studies due to differences in locations and sampling protocols; however, this variation is seen even within individual studies.

Factors such as cistern size, cistern materials, usage patterns, maintenance practices, storage volume, antecedent dry period length, stored water temperature, physico-chemical properties of runoff water, seasonal variations, weather conditions and presence/absence of inlet screens can impact the concentrations of bacteria and pathogens within a RWH system (Lye, 1987; Schets et al. 2010; Dillaha and Zolan 1985; Despins et al. 2009). Two studies reported that microbial contamination tended to improve during winter months, most likely due to reduced animal activity on the roof and decreased temperatures of stored water resulting in a decline in microbial growth (Vialle et al. 2012; Despins et al. 2009). Ahmed et al. (2010a), Schets et al. (2010) and Birks et al. (2004) reported elevated concentrations of pathogens and fecal indicator bacteria following rain events (especially those with high-intensity rainfall).

Fecal indicator organisms, such as thermo-tolerant coliforms (TTC), TC, FC, enterococci and EC are often used as surrogates for pathogen presence and to characterize microbial contamination within RWH systems (Ahmed et al. 2011a; Australian, 2000). Several studies have expressed concern with this convention due to a lack of correlation between fecal indicator and pathogen concentrations (Ahmed et al. 2009; Ahmed et al. 2008; Ahmed et al. 2010b; Ahmed et al. 2011a; Crabtree et al. 1996; Evans et al. 2006); however, it should be noted that the majority of data supporting this conclusion was published by the same author (Ahmed) in the same location (Australia). Ahmed et al. (2009) and Ahmed et al. (2011a) suggested the use of Bacteriodes spp. and Bifodobacterium spp. as indicators of fecal pollution, as opposed to EC, TC or enterococci, due to their higher sensitivity, shorter survival time outside of host and a stronger correlation with fecal pollution. Ahmed et al. (2012b) suggested the use of enterococci in lieu of E-coli as a fecal indicator due to its higher prevalence in rainwater and shorter survival time outside of host. Evans et al. (2006) and Evans et al. (2007) concluded that the majority of the bacterial load within a RWH system can originate from airborne, non-fecal sources versus fecal matter; therefore, traditional fecal indicators would not adequately predict the presence of pathogens in these systems

(Evans et al. 2006; Evans et al. 2007). While each indicator has benefits and drawbacks when used to predict fecal contamination and pathogen presence, using multiple indicators when possible can greatly increase the accuracy of these predictions (Ahmed et al. 2010b; Ahmed et al. 2012b). This protects against false-positives (presence of indicator bacteria when fecal contamination is not present) as well as false negatives (the absence of an indicator when fecal contamination is present), as demonstrated by Ahmed et al. (2010b).

Another controversial topic regarding the microbiological quality of harvested rainwater is the role biofilms on the walls of the storage tank play in microbial communities. Some studies suggest that biofilm formation within RWH systems can positively impact the quality of stored rainwater via competitive exclusion of pathogens and sequestration or degradation of contaminants and bacteria (Evans et al. 2006; Kim and Han 2011; Islam et al. 2010a). Others indicate that biofilms can be problematic due to their harboring and protection of pathogens and other bacteria, support of bacterial regrowth and the depletion of disinfection agents (Schets et al. 2010). Further research is needed on this topic to accurately characterize the effect of biofilms on the microbial quality of stored water.

Treatment Options

Despite the variation in the species and concentrations of micro-organisms found in RWH systems, most studies concluded that the level of microbial contamination in harvested rainwater warrants treatment prior to drinking (Appan, 1999; Li et al. 2010; Ahmed et al. 2011b; Ahmed et al. 2008; Ahmed et al. 2010a; Ahmed et al. 2010b; Ahmed et al. 2011a; Dillaha and Zolan 1985; Lye 1987; Mendez et al. 2011; Vialle et al. 2012; Schets et al. 2010). Drinking water guidelines from various countries and organizations are found in Table 17.

Table 15. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data			
Ahmed et al. 2012a	Australia	24 households, tanks sampled 1-4 days after rain event	E-coli	$1x10^{0}$ - $2.3x10^{2}$ CFU per 100mL		
			Enterococci	$2x10^{0}$ - $1.1x10^{2}$ CFU per 100mL		
			Campylobacter	$5x10^{0}$ - $1x10^{2}$ CFU per L		
			Salmonella	$7.3x10^{3}$ CFU per L		
			Giardia	$1.2x10^{2}$ - $5.8x10^{2}$ CFU per L		
Ahmed et al. 2008	Australia	27 homes sampled, 1-4 days after a rain event; polymerase chain reacion (PCR) used for analyses		#positive/total	%positive	Range
			E coli	17/27	63	4±3 - 800±235
			Enterococci	21/27	78	5±1 - 200±33
			C. perfringens	13/27	48	2±1 - 31±17
			Bacteriodes	24/27	89	
			A. hydrophila	4/27	15	
			C. jejuni	1/27	4	
			L. pneumophila	7/27	26	
			C. coli	11/27	41	
			Salmonella invA	3/27	11	
			G. lamblia	4/21	19	
			Salmonella spvC	0/27	0	
			All values in CFU/100 mL			

Table 15, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data
Ahmed et al. 2009	Australia	84 rainwater tanks sampled from bottom outlet, flushed 30-60 secs; polymerase chain reaction (PCR) used for analyses	E-coli: 57 of 84 tanks (65%) positive Enterococci: 72 of 84 tanks (82%) positive Binary Pathogen Results #positive/total % positive Aeromonas hydrophila lip gene 7/84 8 Campylobacter coli ceuE gene 10/27 37 Campylobacter jejuni mapA gene 1/84 1 Escherichia coli 0157 LPS gene 0/84 0 Escherichia coli VT1 gene 0/84 0 Escherichia coli VT2 gene 0/84 0 Legionella pneumophila mip gene 8/84 10 Salmonella invA gene 17/84 20 Salmonella spvC gene 0/27 0 Giardia lamblia β-giradin gene 15/84 18 Giardia parvum COWP gene 0/84 0
Ahmed et al. 2010a	Australia	Phase I: 82 tanks, 214 samples Phase II: subset of 19 tanks, samples collected every 2 weeks for 3 months right after rainfall Analyses performed using binary and quantitative PCR	Phase I: #positive/total %positive Range Salmonella invA 23/214 10.7 $6.5x10^{1} - 3.8x10^{2}$ G. lamblia β-giradin 21/214 9.8 $0.9x10^{1} - 5.7x10^{1}$ L. pneumophila mip 12/214 5.6 $6.0x10^{1} - 1.7x10^{2}$ Phase II: Salmonella invA: present in 4.4% of samples G. lamblia β-giradin: present in 5.3% samples L. pneumophila mip: present in 3.5% samples Values in # genomic copies per 1000mL of water

Table 15, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data
Ahmed et al. 2010b	Australia	73 rainwater tank samples from 55 houses	E coli: <1 - 3060±456 CFU/100mL Enterococci: <1 - 3400±700 CFU/100mL C. perfringens: <1 - 200±30 CFU/100mL ---------- % of samples ------------- CFU/100mL · E coli · Enterococci · C. perfringens <1 · 42 · 17 · 54 1 - 10 · 18 · 17 · 21 11-100 · 17 · 36 · 22 101-500 · 14 · 14 · 3 501-1000 · 4 · 7 · 0 > 1000 · 5 · 9 · 0 #positive/total Aeromonas hydrophila lip gene · 7/100 Campylobacter jejuni ceuE gene · 19/100 Campylobacter jejuni mapA gene · 1/100 Escherichia coli 0157 gene · 0/100 Escherichia coli VT1 gene · 0/100 Escherichia coli VT2 gene · 0/100 Legionella pneumophila mip gene · 8/100 Salmonella invA gene · 17/100 Salmonella spvC gene · 0/100 Giardia lamblia β-giradin gene · 15/100 Cryptosporidium oocyst wall protein gene · 0/100
Ahmed et al. 2011b	Australia	30 rainwater tanks sampled	#positive/total · %positive · Range E coli · 22/30 · 73 · 2±0 - 986±61 CFU/100 mL

Table 15, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data			
Ahmed et al. 2012b	Australia	23 RW tanks sampled, 212 Enterococcus species isolated	Number of species/number of total species isolated (%): - E. faecalis: 115-212 (24%) - E. faecium: 12-212 (6%) - E. casseliflarus: 27-212 (13%) - E. durans: 1/212 (0.5%) - E. hirae: 12/212 (6%) - E. axium: 2/212 (1%) - E. mundtii: 28/212 (13%) - others: 15/212 (7%)			
Albrechtsen 2002	Denmark	7 RWH system tanks sampled 2-4 times		n	#positive	Range
			Total #s (AODC) (10^3/mL)	5		81 - 5,800
			HPC - R2A Agar (10^3/mL)	13		0.38 - 2,300
			HPC - 37°C (10^3/mL)	14		0.013 - 11
			Yeast cells per mL	13		0.02 - 84
			Microfungi per mL	14		0.06 - 26
			E. coli per 100 mL	14		4 -990
			Pseudomonas aeruginosa per 100mL	14	1	<1 - 20
			Aeromonas sp. per mL	14	2	<10 - 30
			Legionella pneumophila	14	0	
			Legionella non-pneumophila	7	5	ND - Detected
			Campylobacter	17	2	ND - Detected
			Mycobacterium arium	14	1	ND - Detected
			Giardia	17	0	
			Cryptosporidium per L	17	6	ND - 50

Table 15, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data
Birks et al. 2004	United Kingdom	Millenium Dome in London	Median Range Total coliforms (total units) 1.8 x 10^4 0 - 2.4x10^6 E-coli (CFU/100mL 5.2 x 10 0 - 1.6x10^4 Fecal enterococci (CFU/100mL) >2.0 x 10^2 0 - 6.8 x 10^2 Plate count, 22°C (CFU/mL) 6.7 x 10^4 0 - 8.6 x 10^7 Plate count, 37°C (CFU/mL) 6.4 x 10^3 0 - 5.5 x 10^7 2 samples analyzed for pathogens in December: - E-coli (0157), Salmonella, Campylobacter, Cryptosporidium, Legionella pneumophila (serotype 1 & 2-14) and Shigella were not detected - Giardia detected in 1 of 2 samples (0.2 counts per L)

Table 15, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data						
Crabtree et al. 1996	US Virgin Islands - St. Thomas and St. Croix	4 samples from 9 private and 4 public cisterns; 45 samples over a 1 year period; taken from tap		Median	Range	Percent Positive			
			Cryptosporidium (oocysts/100L)	2.41	<1 - 70.29	48%			
			Giardia (cysts/100L)	1.09	<1 - 3.79	26%			
			Total coliforms (CFU/100mL)		<1 - 3,140	57%			
			Fecal coliforms (CFU/100mL)		<1 - 770	36%			
				Private	Public	July 1992	Jan 1993	Apr 1993	June 1993
			Oocysts/100L						
			n	58	32	22	22	22	24
			Average	2.78	1.73	1.33	4.64	1.33	2.42
			Range	<1 -70.29	<1-10.57	<1-4.19	<1-70.29	<1-6.46	<1-10.57
			Cysts/100L						
			n	58	32	22	22	22	24
			Average	1.12	1.05	1.08	1.15	1.00	1.15
			Range	<1-3.79	<1-2.11	<1-2.09	<1-3.79	<1-1.06	<1-3.16
			TC/100L						
			n	26	14	10	7	12	11
			Average	350	430	192.9	162.9	642.3	395.5
			Range	0-3140	0-2120	<1-845	<1-720	<1-3140	<1-2120
			FC/100mL						
			n	26	14	10	7	12	11
			Average	13.6	61.7	1.3	0.3	5.1	101.0
			Range	0-308	0-770	<1-6	<1-2	<1-28	<1-770
			HPC/1.0mL						
			n	26	14	10	7	12	11
			Average	4130000	238000	5700000	7200000	51000	220000
			Range	5-56000000	<10-9990000	<10-56000000	<200-49000000	5-290000	<50-990000

Table 15, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data
Despins et al. 2009	City of Guelph, Canada	7 RWH systems; 30 samples for each system from October 2006 thru October 2007; varying treatments - most prevalent was particle filtrations and UV disinfection	----------------Total Coliform-------------- --------------Fecal Coliform------------------ Site # GM Range % ≥ 1 CFU/100mL GM Range % ≥ 1 CFU/100mL 1 <1 <1 - 128 76 <1 <1 - 14 31 2 <1 <1 - 86 4 <1 <1 - 4 11 3 <1 <1 - 255 46 <1 <1 - 234 36 4 <1 <1 - 398 89 <1 <1 - 400 54 6 <1 <1 - 51 17 <1 <1 - 10 7 All values in CFU/100mL
Dillaha and Zolan 1985	Micronesia	203 rainwater harvesting systems sampled once	Total Coliforms (n=155) Median = 4.4/100mL Percent of samples with concentrations per 100mL of: 0: 30% ≤10: 61% ≤20: 72% >200: 14% Fecal Coliforms (n=176) Median = 0.4/100mL Percent of samples with concentrations per 100mL of: 0: 57% ≤10: 81% ≤20: 84% >200: 7%
Domènech and Saurí 2011	Spain	3 RWH tanks	System A System B System C E-coli 1 52 31 Legionella pneumophila 0 0 0 All values in CFU/100mL
Handia et al. 2003	Zambia	2 tanks sampled once; tank A was concrete, tank B was brick with cement mortar; no first flush, treatment or filters	Tank A Tank B Total coliform (#/100mL) 8 0 Fecal coliform (#/100mL) 7 0

Table 15, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data				
Isquith and Winters 1987	U.S. Virgin Islands	10 cisterns, sampled in-tank water column and submerged portion of cistern wall	TOTAL BACTERIA COUNT (Bacteria/100mL)				
			Site	Dec 1979	Feb 1980	July 1980	Oct 1980
			1	$2.5x10^3$	$4.1x10^4$	$6.1x10^5$	$2.0x10^2$
			2	$3.4x10^4$	$4.7x10^5$	--	--
			3	$4.0x10^4$	$1.5x10^3$	$8.2x10^5$	$>1.0x10^4$
			4	$5.7x10^6$	$4.6x10^5$	$9.2x10^7$	$>2.0x10^2$
			5	$6.0x10^5$	$1.6x10^5$	$6.4x10^6$	TNTC
			6	--	$4.7x10^4$	$5.2x10^6$	$>1.0x10^3$
			7	$8.7x10^3$	$2.0x10^4$	$5.8x10^6$	$>1.0x10^3$
			8	$7.3x10^5$	$1.5x10^5$	$2.4x10^7$	$>1.0x10^4$
			9	$7.0x10^3$	$7.8x10^4$	$7.3x10^6$	$>1.0x10^3$
			10	$5.6x10^2$	$4.0x10^4$	$4.0x10^6$	$6.0x10^3$
			TOTAL COLIFORM COUNT (Coliforms/100mL)				
			Site	Dec 1979	Feb 1980	July 1980	Oct 1980
			1	$1.6X10^2$	$4.3X10^2$	$4.6X10^3$	$5.2X10^3$
			2	$2.3X10^2$	$7.3X10^1$	--	--
			3	$2.3X10^2$	$4.3X10^2$	$1.1X10^5$	$>1.0X10^3$
			4	$2.3X10^2$	0	$2.4X10^2$	$1.5X10^2$
			5	$1.6X10^2$	$9.3X10^2$	$1.1X10^5$	$9.0X10^2$
			6	--	--	$1.1X10^5$	$>2.0X10^3$
			7	$9.1X10^1$	$2.1X10^2$	0.0	$>2.0X10^3$
			8	$7.5X10^2$	$2.1X10^2$	0.0	$1.0X10^3$
			9	$2.3X10^2$	--	0.0	$>2.0X10^3$
			10	$1.6X10^2$	0.0	$1.1X10^5$	$8.75X10^3$

Table 15, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data			
Isquith and Winters 1987	U.S. Virgin Islands	10 cisterns, sampled in-tank water column and submerged portion of cistern wall	TOTAL STREPTOCOCCI COUNT (Fecal Streptococci/100mL)			
			Site	Feb 1980	July 1980	Oct 1980
			1	0	0	$4.0x10^{2}$
			2	$7.3x10^{1}$	--	--
			3	0	0	$5.0x10^{5}$
			4	0	0	$2.8x10^{2}$
			5	$1x10^{3}$	$1x10^{3}$	$1.2x10^{2}$
			6	$1x10^{3}$	$1x10^{3}$	$2.0x10^{5}$
			7	$3.6x10^{1}$	$1x10^{3}$	$4.0x10^{2}$
			8	0	$1x10^{5}$	$5.0x10^{5}$
			9	--	$1x10^{3}$	$5.0x10^{5}$
			10	0	$1x10^{3}$	$7.5x10^{2}$
			TOTAL SALMONELLA SP. COUNT (Salmonella Sp./100mL)			
			Site	Feb 1980	July 1980	Oct 1980
			1	positive	$1.9x10^{3}$	$1.0x10^{4}$
			2	negative	--	--
			3	positive	$1.7x10^{4}$	$2.0x10^{2}$
			4	positive	$9.6x10^{3}$	$1.6x10^{5}$
			5	positive	$6.6x10^{4}$	$8.0x10^{2}$
			6	--	$6.6x10^{4}$	$8.0x10^{5}$
			7	positive	--	$4.0x10^{5}$
			8	negative	--	$8.0x10^{5}$
			9	positive	$6.0x10^{1}$	$9.3x10^{4}$
			10	negative	$4.2x10^{4}$	$3.3x10^{4}$

Table 15, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data
Karim 2010	Bangladesh	60 household and 38 community RWH systems; 308 samples collected	TC (#/100mL) TTC (#/100mL) EC (#/100mL) Plastic tank (n=27) Median 0 0 0 Range 0-63 0 0-15 Brick (n=28) Median 0 0 0 Range 0-20 0-2 0-3 Ferrocement (n=129) Median 0 0 0 Range 0-30 0-4 0-9 RCC (n=124) Median 0 0 0 Range 0-74 0-19 0-56
Lye 1987	Kentucky	30 RWH systems; sampled at water surface within storage tank and at 15cm above bottom of the tank	Average coliform concentrations: Cistern water surface: 374/100mL Cistern bottom samples: 600/100mL
Merritt et al. 1999	Australia	7 RWH tanks sampled from June 19-22 due to outbreak of illness	Tank Coliform Count E.coli Count 1 500 55 2 51 13 3 positive* positive* 4 positive* 27 All values in colonies per 100mL *Detected but count not possible due to confluent growth
Nawaz et al. 2012	South Korea	1 RWH system; values before disinfection	P. aeruginosa: 350-440 CFU/100mL E. coli: 740-920 CFU/100mL

Table 15, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data				
O'Hogain et al. 2012	Ireland	Sampling regime 1: 12 monthly samples without filters (Jan 2006-Jan 2007) Sampling regime 2: 3 monthly samples with filters added (Jan 2008-Apr 2008)	Regime 1:				
				Mean	Min	Max	Median
			Coliforms (MPN/100mL)	5171.36	13.50	48800	920.80
			E-coli (MPN/100mL)	259.62	<0.01	2419.60	48.20
			Fecal Coliforms (CFU/100mL)	83.92	<0.01	600.00	30.00
			TVC @ 22°C (CFU/mL)	5291.90	<0.01	16800.00	3684.00
			TVC @ 37°C (CFU/mL)	2898.77	2.00	31500.00	431.00
			Pseudomonas spp. (CFU/100mL)	62.25	<0.01	299.00	33.00
			Regime 2:				
				Mean	Min	Max	Median
			Coliforms (MPN/100mL)	73.93	3.10	275.50	8.55
			E-coli (MPN/100mL)	0.75	<0.01	2.00	1.00
			Fecal Coliforms (CFU/100mL)	1.50	<0.01	5.00	1.0
			TVC @ 22°C (CFU/mL)	364.25	50.00	800.00	303.50
			TVC @ 37°C (CFU/mL)	62.25	31.00	140.00	39.00
			Pseudomonas spp. (CFU/100mL)	556.75	27.00	2000.00	100.00

Table 15, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data
Pinfold 1993	Thailand	2000L rainjars were sampled; 'other' jars, where rainwater transferred from rainjars was stored closer to point of use	Ban Sahart Results: n Fecal Coliforms Fecal Streptococci Rainjars* 20 0.7 (3.7) 2.1 (4.7) Rainjars** 56 2.3 (10.3) 15.7 (46.4) Fecal coliform results from both villages: Samples with concentrations of: n FC 0 1-9 10-99 >99 Rainjars** - Ban Daengnoi 96 2.0 (18) 60% 20% 15% 5% Rainjars** - Ban Sahart 40 1.8 (8) 58% 22% 20% 0% Other jars - Ban Daengnoi 438 4.2 (42) 46% 20% 24% 10% Other jars - Ban Sahart 52 3.5 (57) 54% 15% 21% 10% Fecal coliform results from several villages (volume = 100mL) Samples with concentrations of: n FC 0 1-9 10-99 >99 Rainjars** 86 1.6 (9) 56% 27% 15% 2% Rainjars* 40 0.5 (1) 72% 27% 1% 0% All values reported in # colonies/50mL Values without parenthesis represent geometric mean Values in parenthesis represent arithmetic mean *Rainjars with mosquito nets **Rainjars without mosquito nets

Table 15, cont. Water quality data collected from storage tanks of rainwater harvesting systems.

References	Study Location	Site Description	Data				
Schets et al. 2010	Netherlands	2005 Initial/pilot study: 4 sites, 4 weekly samples; 2006 Followup study: 4 sites, 8 weekly samples	2005 Results				
			Site:	WVE	ECO	GD	RT
			Total coliform	20 (12-37)	15 (6-18)	3818 (160-10900)	480 (45-1004)
			E.coli	5 (4-10)	4 (0-7)	125 (17-330)	2 (0-6)
			Enterococci	3 (0-4)	2 (1-6)	1720 (130-1590)	10 (2-20)
			HPC @ 22°C	1022 (610-1960)	1894 (95-5455)	9100 (3100-151000	131383 (62150-183500)
			Aeromonas	1162 (320-1250)	31 (0-124)	2848 (1200-3925)	77 (0-242)
			C. perfringens	3 (0-5)	2 (1-3)	5 (2-10)	8 (0-18)
			2006 Results				
			Site:	WVE	ECO	GD	
			Total coliform	104 (24-314)	54 (0-314)	2783 (0-15500)	
			E.coli	20 (0-53)	33 (0-175)	1934 (0-10000)	
			Enterococci	22 (2-100)	167 (0-1255)	1555 (0-9546)	
			HPC @ 22°C	5946 (505-15950)	5685 (536-18636)	394673 (392-3045000)	
			Aeromonas	4193 (70-16818)	733 (7-3182)	15642 (18-85000)	
			C. perfringens	1 (0-4)	2 (0-11)	13 (3-31)	
			Values reported are mean values in number per 100mL Values in parenthesis are ranges				

Table 16. Results and conclusions from numerous studies on the microbiological quality of RWH systems.

References	Study Location	Site Description	Key Findings
Ahmed et al. 2012a	Australia	24 households, tanks sampled 1-4 days after rain event	• E.coli detected in 62% and 58% of storage tank and household tap samples, respectively • Enterococci detected in 92% and 83% of tank and tap samples, respectively. • 92% of tank samples had one fecal indicator present; 58% contained both indicators. • 92% of tap samples contained one fecal indicator; 50% contained both indicators. • A significant correlation existed between E.coli and enterococci . • There was no significant difference between indicator concentrations in tank and tap samples • Campylobacter, Salmonella and Giardia present in 21%, 4% and 13% of tank samples, respectively. • 21% and 13% of tap samples contained Campylobacter and Giardia, respectively; no Salmonella detected in tap samples.
Ahmed et al. 2008	Australia	27 homes sampled, 1-4 days after a rain event; polymerase chain reacion (PCR) used for analyses	• 41% of samples positive for E.coli, enterococci and C. perfringens; 63% positive for at least 2; 85% positive for at least 1. • Significant correlations existed between E.coli and enterococci, and between enterococci and C. perfringens. • 11% of samples positive for 3 pathogens, 33% positive for at least 2 pathogens; 67% positive for at least 1; 33% of samples free of all pathogens. • Positive correlation existed between enterococci and A. hydrophila; Presence/absence of all other pathogens did not correlate with indicator bacteria concentrations. • High prevalence of potential pathogens and indicators indicates microbial contamination and could be a risk to human health if consumed.
Ahmed et al. 2009	Australia	84 rainwater tanks sampled from bottom outlet, flushed 30-60 secs; polymerase chain reaction (PCR) used for analyses	• 64% of samples exceeded Australia and New Zealand guidelines for fresh and marine waters for primary contact (35 enterococci/100mL). • 61% of samples positive for both enterococci and E.coli; 89% positive for at least one • Campylobacter coli most prevalent (375 of samples positive). • E.coli 0157 LPS, VT1, VT2, Salmonella sprC and C. parvum cowP genes were not detected in any samples. • Presence/absence of potential pathogens did not correlate with indicator bacteria concentrations.

Table 16, cont. Results and conclusions from numerous studies on the microbiological quality of RWH systems.

References	**Study Location**	**Site Description**	**Key Findings**
Ahmed et al. 2010a	Australia	Phase I: 82 tanks, 214 samples Phase II: subset of 19 tanks, samples collected every 2 weeks for 3 months right after rainfall Analyses performed using binary and quantitative PCR	• Pathogens were present in 0-32% of samples in Phase 1. • Pathogens were present in approximately 5% on average in Phase 2. • 12.2% of samples positive for Salmonella spp. on at least one sampling occasion. • 15.9% of samples positive for G. lamblia spp. on at least one sampling occasion. • 7.3% of samples positive for L. pneumophila on at least one sampling occasion. • Pathogen concentrations were highest immediately following rain events.
Ahmed et al. 2010b	Australia	73 rainwater tank samples from 55 houses	• Enterococci detected more frequently than E.coli and C. perfringens. • 36% of samples positive for E.coli, enterococci and C. perfringens; 62% positive for at least 2; 89% positive for at least 1. • Significant correlations existed between E.coli and enterococci and between enterococci and C. perfringens. • 1% positive for 4 target genes (see Table 15); 8% positive for 3; 18% positive for 2; 40% positive for 1. • 60% of samples contained no pathogens. • Presence/absence of pathogens did not correlate with any indicator bacteria concentrations. • 58% of samples exceeded Australian DWG standards for E.coli (<1CFU/100mL). • Testing multiple indicators is important, as one given indicator may not always be present when there is fecal pollution and microorganisms. • Concentrations were highly variable. • C. perfringens concentrations may be indicative of the magnitude of fecal pollution but may not always be reliable. • Samples collected in open area with no overhanging trees contained relatively low concentrations of indicator bacteria compared to older areas with more overhanging vegetation. • In some cases pathogens were present when no fecal indicator bacteria were detected.
Ahmed et al. 2011a	N/A	N/A	• Until a thorough microbial assessment is performed, harvested rainwater should be considered of poor microbiological quality.

Table 16, cont. Results and conclusions from numerous studies on the microbiological quality of RWH systems.

References	Study Location	Site Description	Key Findings
Ahmed et al. 2011b	Australia	30 rainwater tanks sampled	• 27% of RWH tank samples contained less than 1 CFU/100mL. All of these systems contained first flush diverters or did not contain overhanging vegetation or signs of fecal matter on the roof surface. • 53% of the systems used as a drinking water source exceeded the Australia DWG • 10 viral genes were found in 77% of the RWH tanks that tested positive for E-coli: eaeA, ST1, cdtB, cvaC, ibeA, kpsMT allele III, kpsMT allele K1, PAI, papAH and traT. • Viral genes not detected in these systems included: hiyA, stx1, stx2, bmaE, focG, iutA, papG allele II, papG allele III and papET). • Of the 94 E-coli isolates carrying viral genes in this study, 58% carried 2 or more., which may pose a human health risk when the water is used for drinking purposes. • E-coli isolates in RWH tanks may carry one or more viral genes, although this does not mean a strain is pathogenic (the correct combination of viral genes must be present for this to occur).
Ahmed et al. 2012b	Australia	23 RW tanks sampled, 212 Enterococcus species isolated	• 85% of collected samples contained culturable enterococci, ranging from 2±1 to 450±43 CFU/100mL. • E. faecalis and E. mundtii were the most commonly detected species. • All 6 virulence genes detected in 87% of the 23 samples that contained culturable enterococci isolates.
Albrechtsen 2002	Denmark	7 RWH system tanks sampled 2-4 times	• Toilets fed by harvested rainwater tended to contain pathogens that were not found in toilets supplied by the potable water supply (12 of 27 samples from rainwater-fed toilets contained at least 1 pathogen). • E-coli was present in 11 of the 14 RWH tanks sampled; median concentration was 245CFU/100mL. • Aeromonas spp. and P. aeruginosa were only detected in RWH systems accepting rainwater from paved parking lots, indicating that roof runoff provided less microbially-contaminated water.
Birks et al. 2004	United Kingdom	Millenium Dome in London	• E-coli concentrations in RWH storage tanks were generally higher immediately following rain events. This would be expected if fecal matter on the roof surface was being washed into the tank with runoff. • 88% of tank samples contained enterococci concentrations greater than 200CFU/100mL. • In two samples collected in December, Giardia was found in 1 at 0.2 counts per L, which coincided with a relatively high enterococci concentration of 400CFU/100mL. The following pathogens were not detected: E-coli 0157, Salmonella, Campylobacter, Cryptosporidium, Legionella pneumophila (serotype 1 and 2-14), Shigella.

Table 16, cont. Results and conclusions from numerous studies on the microbiological quality of RWH systems.

References	Study Location	Site Description	Key Findings
Coombes et al. 1999	Australia	6 samples taken from 3 hot water systems between 6/98 and 10/99; 13 samples taken from storage tanks of 4 RWH systems; over 40 rain events sampled for roof runoff in July and August 1998	• Bacterial concentrations of roof runoff were often 2 orders of magnitude higher than storage tank concentrations. • Despite bacteria being present in tank water, samples collected from the hot water tap were compliant with DWG. • The operating mode of the 125-L hot water system did not produce temperatures high enough to reduce bacterial contamination to acceptable levels for drinking on a regular basis; however, the 250-L system ensured reliable reduction to acceptable drinking levels.
Crabtree et al. 1996	US Virgin Islands - St. Thomas and St. Croix	4 samples from 9 private and 4 public cisterns; 45 samples over a 1 year period; taken from tap	• 53% of rainwater tank samples contained Cryptosporidium and/or Giardia cysts. • Cryptosporidium cysts were detected more frequently than Giardia. • Both were detected more frequently in public RWH systems versus private. 75% of public tank samples were positive for Cryptosporidium, 31% positive for Giardia and 81% had at least one. In private systems, 33% of samples contained Cryptosporidium, 23% contained Giardia and 47% contained at least one of these two species. • No significant correlations existed between the presence of cysts and bacteria or turbidity. • Significant correlations did exist between TC and FC, TC and HPC and turbidity and HPC.
Despins et al. 2009	City of Guelph, Canada	7 RWH systems; 30 samples for each system from October 2006 thru October 2007; varying treatments - most prevalent was particle filtrations and UV disinfection	• TC concentrations exceeded 1 CFU/100mL in 30% of samples. • FC detected in 14% of samples, with 52 of 360 samples exceeding 1 CFU/100mL. • The best water quality occurred during winter, possibly due to decreased animal activity (and reduced deposition of fecal matter on roof surfaces) and a decline in microbial growth within the cistern due to colder temperatures. Statistical analyses indicate colder temperatures are most likely the predominant cause. • TC and FC detected in 22% and 2% of samples, respectively, in winter, versus 50% and 30%, respectively, in summer. • Campylobacter and Legionella not detected in any samples.
Dillaha and Zolan 1985	Micronesia	203 rainwater harvesting systems sampled once	• Concentrations varied greatly among samples and systems. • Harvested rainwater is of acceptable quality, but should be treated prior to drinking. • 57% and 30% of sampled systems were absent of FC and TC, respectively. • The concentration of FC was not correlated with catchment characteristics. • TC concentrations were significantly influenced by location, cistern type, storage volume and the presence/absence of inlet screens.

Table 16, cont. Results and conclusions from numerous studies on the microbiological quality of RWH systems.

References	Study Location	Site Description	Key Findings
Evans et al. 2007	Australia; Samples taken from cold and hot water outlets of the rainwater tank	Unknown	• Results indicate that the majority of the bacteria load was due to airborne environmental organisms as opposed to enteric, fecal-related species. • The conditions within a RWH system (low nutrient levels, cooler temperatures and microbiologically competitive environment) are more likely to sustain environmental organisms as opposed to enteric species, as enteric species thrive in warm, nutrient-rich environments. • If airborne, environmental species are the predominant contributor to bacterial loads in RWH systems, the use of fecal indicator species will reveal little about the microbial contamination of harvested rainwater. • All aspects of bacterial contamination (fecal and non-fecal species) within RWH systems should be explored to assess risk, as exposure pathways differ for each type of organism.
Isquith and Winters 1987	U.S. Virgin Islands	10 cisterns, sampled in-tank water column and submerged portion of cistern wall	• The majority of coliform species detected were Klebsiella-Aerobacter, suggesting water within the RWH system had been contaminated for a long period of time and chlorine had not been used for disinfection. • Coliform organisms located on the walls of the storage tank were the same as those in the stored rainwater. • Proteus, Shigella, Serratia and Pseudomonas species were detected in the stored water in addition to Salmonella, total Streptococci, and TC. • The environment within the cistern allowed for the reproduction of organisms. • Bacterial and pathogenic communities within the storage tank remained constant, indicating there were isolated and self-sustaining populations.
Karim 2010	Bangladesh	60 household and 38 community RWH systems; 308 samples collected	• Sanitary inspections of RWH systems revealed overall good sanitary conditions. Good correlations between sanitary inspections and microbial quality indicate good microbial quality on average. • 12% and 13% of samples collected exceeded Bangladesh water quality standards and WHO guidelines for TTC and E-coli (0/100mL). • TCs were detected in 33%, 18%, 33% and 40% of samples collected from plastic, brick, ferrocement and reinforced cement concrete storage tanks, respectively. • Microbial contamination was greater in community-based RWH systems versus private household systems, perhaps due to better maintenance.

Table 16, cont. Results and conclusions from numerous studies on the microbiological quality of RWH systems.

References	Study Location	Site Description	Key Findings
Kim and Han 2011	Korea	Samples taken of: biofilm at tank inlet, biofilm at tank outlet, harvested water at tank inlet, harvested water at tank outlet	• Bacterial composition of stored rainwater and biofilm differed. • A total of 17 species were identified during sampling, with Proteobacteria being the most common. Other species included Bacteriodes (most commonly found in systems with pristine conditions) and Firmicutes (most commonly found in polluted systems). • The following species were found only in stored rainwater: Limnohabitans sp., Aquaspirillum sp., Rubrivivax gelatinosus, Roseivirga ehrenbergii and Rhodobacter gluconicum. • The following species were found only in the biofilm: Ralstonia insidiosa, Blastochloris sulfoviridis, Bacillus sp., Sphingobium sp. and Beijerinckiaceae bacterium. • The following species were found in both the stored water and the biofilm: Novosphingobium resinovorum, Spingopyxis sp., Sphingomonas sp. and Sphingobium yanoikuyae. • Biofilm bacterial composition differed between inlet and outlet, but water composition did not. • Proteobacterial and nonpathogenic species were predominant species in samples. These species are similar to water and soil bacteria found in the natural environment. • Microbial results indicate a generally clean, oligotrophic environment within RWH systems (very little dissolved organic matter); thus, biofilm formation may be beneficial with respect to contaminant degradation capabilities. • Difference in nutrient concentrations between the inlet and outlet may be the cause of different biofilm composition, as biofilm bacteria have limited mobility. • Biofilms in storage tanks seem to promote survival and act as a natural filtering mechanism for the stored rainwater via degradation and removal of contaminants and other bacteria.
Li et al. 2010	Ireland	N/A	• Coliforms, E-coli and enterococci are commonly found in harvested rainwater. • Under certain conditions (limited light and little to no organic matter), bacteria and pathogens will gradually die off during the first few days of storage.
Lye 1987	Kentucky	30 RWH systems; sampled at water surface within storage tank and at 15cm above bottom of the tank	• Many variables can affect the microbiological quality of harvested rainwater, including cistern size, storage volume, usage patterns, maintenance practices, time since water was added, amount of chlorine added, time since chlorine was added, seasonal variations and weather conditions. • 68% of harvested water samples contained coliforms. The remaining 32% contained high HPC concentrations which interfered in the detection of coliforms. • Fecal coliforms were detected in 1 of the 30 RWH systems sampled. • All surface samples exceeded US drinking water regulations for coliforms, while 90% exceeded WHO guidelines for safe, nonchlorinated, nonpiped drinking water.
Mendez et al. 2011	Texas	3 pilot-scale roofs, 4 storm events; 3 residential roofs, 3 storm events	• All pilot-scale roof samples exceeded USEPA primary drinking water standards.

Table 16, cont. Results and conclusions from numerous studies on the microbiological quality of RWH systems.

References	Study Location	Site Description	Key Findings
O'Hogain et al. 2012	Ireland	Sampling regime 1: 12 monthly samples without filters (Jan 2006-Jan 2007) Sampling regime 2: 3 monthly samples with filters added (Jan 2008-Apr 2008)	• Coliforms were present in all samples collected during Regime I. Maximum concentration detected was 3500 MPN/100mL. • After adding downspout filters, sealing manhole covers and cleaning the storage tank, coliform and E-coli concentrations were significantly lower (average E-coli concentration decreased from 260 to 0.75 MPN/100mL). • Regime 2 samples complied with the Bangladesh drinking water guidelines for all parameters except TC and E-coli.
Pinfold 1993	Thailand	2000L rainjars were sampled; 'other' jars, where rainwater transferred from rainjars was stored closer to point of use	• Rainjars were found to be a cleaner and more convenient source than the primary water source (shallow wells); however, the WHO 1984 drinking water guideline was exceeded for many samples.
Schets et al. 2010	Netherlands	2005 Initial/pilot study: 4 sites, 4 weekly samples; 2006 Followup study: 4 sites, 8 weekly samples	• Concentrations of microbial parameters did not meet Dutch or WHO drinking water guidelines. • Concentrations of fecal indicator bacteria and pathogens within the storage tank increased following high intensity rainfall, especially after a period of drought. • HPC counts increased with increasing water temperature and length of storage time. Counts remained constant when the temperature remained approximately 15°C. • Die off of E-coli and Aeromonas was more rapid when temperatures were above 15°C. • The microbial quality of harvested rainwater is influenced by many factors, including storage temperature, cistern material and physico-chemical properties of water. • The presence/amount of fecal material on the contributing roof surface largely determines the quality of water within the storage tank. • Biofilm formation within the storage tank may harbor and protect micro-organisms and deplete disinfection agents, thus causing a decline in water quality.

Table 16, cont. Results and conclusions from numerous studies on the microbiological quality of RWH systems.

References	Study Location	Site Description	Key Findings
Vialle et al. 2012	France	Weekly samples from tank and outside tap; number of samples for different species vary	• Total flora (measure of bacterial load) ranged from 10-6.32x10^5 organisms per mL. • Coliforms were present in the majority of samples. • Enterococci concentrations were generally high, with some exceeding 10,000 CFU/100mL. • E-coli was detected in 79% of samples (n=53). • E-coli and enterococci often detected simultaneously in samples, with enterococci concentrations always being the higher of the two. • Legionella pneumophila was detected in one sample at a concentration of 700 CFU/L. • Giardia was detected in one sample with a concentration of 0.005n/100mL. • Aeromonas was detected in 43% of samples (n=28), while Pseudomonas aeruginosa was detected in 41% (n=17) of samples. • The highest level of microbial contamination occurred in the summer season.

Table 17. Summary of drinking water standards/guidelines from various organizations.

	WHO DWG (WHO, 2008)	USEPA Primary DWS (USEPA, 2009)	Australian DWG (Australia, 2011)	Australian and New Zealand Environment and Conservation Council Guideline for Fresh and Marine Waters for Primary Contact (Australian, 2000)
Cryptosporidium	--	0 CFU/100mL	--	--
E-coli	0 CFU/100mL	0 CFU/100mL	0 CFU/100mL	--
Enterococci	--	--	--	35 organisms per 100mL (maximum number in any one sample: 60-100 organisms/100mL)
Fecal Coliforms	--	0 CFU/100mL	--	150 organisms per 100mL (minimum of 5 samples taken at regular intervals not exceeding 1 month, with 4 out of 5 samples containing <600 organisms/100mL)
Giardia lamblia	--	0 CFU/100mL	--	--
Legionella	--	0 CFU/100mL	--	--
Pathogenic free-living protozoans	--	--	--	0 organisms per 100mL
Total Coliforms	--	0 CFU/100mL	--	--
TTC	0 CFU/100mL	--	--	--
Viruses (enteric)	--	0 CFU/100mL	--	--

-- no guideline listed

As shown in Table 15 and 16, very few RWH systems can meet drinking water guidelines without some form of treatment. Several studies have investigated the microbial quality of samples at the point-of-use for the RWH system (Table 18). Albrechtsen (2002) noted a slightly higher prevalence of pathogens in a toilet supplied by a RWH system when compared to the toilet supplied by the public water supply (PWS). None of the systems used for this study employed treatment mechanisms for the harvested rainwater. Lye (1987) reported a slightly lower average coliform concentration at the cold water tap compared to the storage tank concentrations, though the water did not undergo treatment in this study either.

Table 18. Microbiological data for rainwater harvesting system point-of-use samples.

References	Study Location & Details	Treatment	Data
Abdel-Shafy et al. 2010	Egypt	Cylindrical sand filter and UV light tube	Range Mean E-coli 0 0 Fecal coliform 0 0 Total coliform 0 0 Total bacteria <50 cell/mL <50 cell/mL
Ahmed et al. 2012a	Australia; Samples taken from 24 household tap	42% of households filtered water, 90% used undersink filtration (USF), 1 system had USF and UV light treatment	E-coli $1.0 \times 10^{0} - 3.0 \times 10^{2}$ per 100mL Enterococci $1.0 \times 10^{0} - 1.1 \times 10^{2}$ per 100mL Campylobacter $1.0 \times 10^{1} - 1.9 \times 10^{1}$ per L Salmonella ND Giardia $1.1 \times 10^{2} - 1.4 \times 10^{2}$ per L
Albrechtsen 2002	Denmark; Samples taken from 2 toilet bowls, one fed by RWH system, one fed by public water supply	Unknown	RWH Toilet Bowl PWS Toilet Bowl Total #s (AODC) (10^3/mL) 26 - 4,600 (n=4) 200 - 620 (n=4) HPC - R_2A Agar (10^3/mL) 63 - 1,530 (n=7) 29 - 520 (n=5) HPC - 37°C (10^3/mL) 2.6 - 62 (n=7) 13 - 130 (n=5) Yeast cells per mL <0.01 - 100 (n = 7) 1 - 150 (n=5) Microfungi per mL 0.13 - 11 (n=7) 0.3 - 140 (n=5) E. coli per 100 mL 4 - 54,000 (n=7) <1 - 200,000 (n=5) Pseudomonas aeruginosa per 100mL <1 - 870 (n=7, +=2) 0 (n=5, +=0) Aeromonas sp. per mL <10 - 4,400 (n=7, +=3) 10 - 8,800 (n=5, +=5) Legionella pneumophila n=7, +=0 n=5, +=0 Legionella non-pneumophila n=5, +=5 n=5, +=0 Campylobacter n=10, +=2 n=5, +=0 Mycobacterium arium n=7, +=0 n=1, +=0 Giardia n=10, +=0 n=5, +=0 Cryptosporidium per L n=10, +=1 n=5, +=0 n = number of samples taken + = number of positive samples

Table 18, cont. Microbiological data for rainwater harvesting system point-of-use samples.

References	Study Location & Details	Treatment	Data
Despins et al. 2009	City of Guelph, Canada	7 RWH systems; 30 samples for each system from October 2006 thru October 2007; varying treatments - most prevalent was particle filtrations and UV disinfection	---------------Total Coliform------------- -------------Fecal Coliform---------------- Site # GM Range % ≥ 1 CFU/100mL GM Range % ≥ 1 CFU/100mL 1 <1 <1 - <1 4 <1 <1 - <1 0 2 <1 <1 - <1 0 <1 <1 - <1 0 3 <1 <1 - <1 0 <1 <1 - <1 0 4 <1 <1 - 12 14 <1 <1 - <1 0 5 <1 <1 - 112 42 <1 <1 - 54 25 6 <1 <1 - 40 10 <1 <1 - 6 7 7 <1 <1 - 24 28 <1 <1 - 5 3 All values in CFU/100mL
Evans et al. 2007	Australia; Samples taken from cold and hot water outlets of the rainwater tank	Unknown	Plate Count (CFU/mL) --------- % of Total Plate Count ------------ Gram +ve Gram -ve Fungi FC Urban tank (cold) 294 39 (12) 41 (15) 20 0 (16) Urban tank (hot) 9 78 (2) 11 (3) 11 0 (3) Rural tank (cold) 825 5 (3) 95 (13) 0 0.18 (0) Rural tank (hot) 31 95 (8) 2.5 (2) 2.5 0 (3) Values in parenthesis are the number of species found in each group of organisms
Islam et al. 2010a	Bangladesh; Collected rainwater was run through sand filters of varying depths	Sand filtration	Number of Total Coliforms per 100mL: ---Depth of Sand Filter Media--- Before Filtration 30 cm 45 cm 60cm 8 5 5 4 9 7 6 4 11 8 7 5
Lye 1987	Kentucky	30 RWH systems; sampled at water surface within storage tank and at 15cm above bottom of the tank	Average coliform concentrations: Cold tap water - 205/100mL

Table 18, cont. Microbiological data for rainwater harvesting system point-of-use samples.

References	Study Location & Details	Treatment	Data				
Spinks et al. 2006	Australia	One sample collected from 49 RWH systems from household tap used for drinking water	Concentration (org/100mL):	0	1-99	100-999	1000+
			Coliforms	10.2%	49.0%	20.4%	20.4%
			E-coli	67.3%	32.7%	0%	0%
			Fecal Streptococci	26.5%	59.2%	12.2%	2.0%

There are many treatment options for RWH systems that, when used, offer adequate disinfection for harvested rainwater. These include sand filtration, membrane filters, reverse osmosis, boiling, ozone, ultra-violet (UV) light, pasteurization, chlorination and silver nitrate (Bradford and Denich 2007; Li et al. 2010; Ahmed et al. 2011b; Lye, 1992; Islam et al. 2010a; Zhu et al. 2004; Ahmed et al. 2012b; Nawaz et al. 2012). Pasteurization involves the combination of UV light and heat and is an effective method of removing E-coli and pathogens; however, its effectiveness is limited when TSS concentrations exceed 10 mg/L. Boiling can be used in the event of high concentrations or the presence of viruses, but can be very expensive and require substantial maintenance (Li et al. 2010).

Abdel-Shafy et al. (2010) and Islam et al. (2010a) showed extremely low concentrations of TC and other fecal indicators when sand filtration/UV light and sand filtration treatments were applied, respectively. Despins et al. (2009) reported a significant decrease in TC and FC concentrations via multiple treatment types, including UV light and sand filtration. The combination of a 20-µm particle filter and UV light was also effective at reducing TC and FC in stored rainwater (Despins et al. 2009). An exception to these positive results was reported by Ahmed et al. (2012a), who saw no significant difference between storage tank and household tap fecal indicator concentrations despite the use of undersink filtration (0.5µm pore-size filter). Perhaps the addition of UV light would produce acceptable water quality, such as that seen by Despins et al. (2009).

Some hot water systems may offer adequate disinfection for RWH systems. When stored rainwater was passed through a residential hot water heater set at 60°C, TC and FC decreased to 1 CFU/100mL or less for all sampling events (Despins et al. 2009). Coombes et al. (1999) showed similar results when harvested rainwater was passed through a 250-L hot water tank, as bacteria and pathogen removal was sufficient to maintain acceptable water quality for drinking. However, rainwater was not adequately disinfected when passed through a 125-L hot water system due to temperature ranges incapable of complete disinfection (Coombes et al. 1999). These results indicate the importance of selecting a system capable of producing temperatures high enough to result in elimination of all micro-organisms.

Li et al. (2010) recommends concentrations of 0.4-0.5 mg/L free chlorine for proper disinfection. Approximately 150mL of bleach (assuming 4% active ingredient) can be added per 1 m^3 of storage tank volume to achieve a 0.5 mg/L residual after 30 minutes (Islam et al. 2010a). Lye (1992) reports that chlorine levels up to 2 mg/L will effectively reduce microbial contamination, but warns that regrowth may occur within 4-5 days. This suggests chlorine should be applied on a regular basis to maintain adequate disinfection. Some parasites and protozoa have demonstrated resistance to chlorine, so filtration may need to accompany chlorination to insure removal of all micro-organisms (Li et al. 2010; Crabtree et al. 1996). Chlorination is an inexpensive and effective form of disinfection (Islam et al. 2010a); however, there are some drawbacks to its use. When chlorine reacts with organic matter present in the storage tank, undesirable byproducts form and accumulate (Li et al. 2010). This can be avoided by applying chlorine after water is extracted from the tank, thereby reducing contact with organic matter (Li et al. 2010). Alternatively, chlorine dioxide or silver nitrate may be used in lieu of chlorine when byproduct formation is a significant concern (Zhu et al. 2004; Nawaz et al. 2012). Some find the use of chlorine unacceptable due to taste and odor issues, in which case other forms of disinfection should be used (Pinfold 1993).

Associated Risks

Numerous studies have reported the occurrence of illness and gastroenteritis due to the consumption of harvested rainwater (Ashbolt and Kirk 2006; Koplan et al. 1978; Franklin et al. 2008; Simmons et al. 2008; Merritt et al. 1999; Kuroki et al. 1996; Eberhart-Phillips et al. 1997; Schlech et al. 1985; Murrell and Stewart 1983; Crabtree et al. 1996). Table 19 shows some of the diseases reportedly linked to the consumption of harvested rainwater, as summarized by Ahmed et al. (2011a) and Lye (2002).

Ashbolt and Kirk (2006) found a significant correlation between the consumption of untreated rainwater and *Salmonella Mississippi* illnesses in Tasmania. The presence of *Salmonella arechevalata* in a water supply fed by a RWH system led to 48 confirmed cases of illness at a rural camp in Trinidad (Koplan et al. 1978). An outbreak of illness due to Campylobacter at a resort in Australia was linked to fecally-contaminated RWH storage tanks, as was a Cryptosporidium-induced outbreak at a public building in Japan (Merritt et al. 1999; Kuroki et al. 1996). The presence of *Salmonella typhimurium 9* and *Legionella pneumophila* in RWH tanks resulted in illnesses at a rural camp in Australia and in 2 private households in New Zealand, respectively (Franklin et al. 2008; Simmons et al. 2008). The New Zealand outbreak was believed to be caused by the deposition of aerosolized *Legionella pneumophila* onto the collection surface by a water blaster used nearby (Simmons et al. 2008).

Dean and Hunter (2012) confirmed that the outbreaks reported by Koplan et al. (1978), Franklin et al. (2008), Simmons et al. (2008) and Kuroki et al. (1996) were strongly associated with RWH systems, as determined by descriptive epidemiology and documentation of a probable source. The event described by Merritt et al. (1999) was 'probably' associated with RWH systems due to analytical results from a case study, although it lacked epidemiological analyses and documentation of a probable source (Dean and Hunter 2012). Dean and Hunter (2012) also pointed out issues that should be considered when interpreting the results of these studies: (1) each study used self-reported diarrhea as evidence of illness, but the actual definition of diarrhea differed among the studies, and (2) the quality of the studies varied considerably and covered diverse populations. These points should be considered for all studies linking illnesses to RWH systems (or any water source), especially when trying to compare results among several studies.

There are been numerous risk assessments conducted on RWH systems, though the results and conclusions of these assessments vary greatly. Several studies have compared the health risks associated with harvested rainwater to those of alternative water sources (Kelly-Hope et al. 2007; Garrett et al. 2008; Few et al. 2009; Heyworth et al. 2006; Saadi et al. 1995; Marcynuk et al. 2009; Eberhart-Phillips et al. 1997). The majority of these studies concluded that the consumption of harvested rainwater did not produce increased health risks when compared to other sources of water (Kelly-Hope et al. 2007; Garrett et al. 2008; Few et al. 2009; Heyworth et al. 2006; Saadi et al. 1995; Marcynuk 2009); however, there were several differences among these studies. Studies performed by Few et al. (2009) and Kelly-Hope et al. (2007) were conducted in Vietnam, Heyworth et al. (2006) and Saadi et al. (1992) performed studies in Australia and Garrett et al. (2008) and Marcynuk et al. (2009) conducted their studies in Kenya and Brazil, respectively. In addition to geographical location, the comparison source for these studies varied as well. Garrett et al. (2008) and Marcynuk et al. (2009) compared risks associated with harvested rainwater and *un*improved water sources (defined by WHO as those sources at high risk of contamination, such as surface waters, shallow wells, etc.), while Heyworth et al. (2006) and Saadi et al. (1995) compared harvested rainwater risks with those associated with improved sources (those sources considered at low risk of contamination, including piped water, boreholes, treated surface water, etc.) (Dean and Hunter 2012). Few et al. (2009) compared rainwater risks with those of both improved and unimproved sources (Dean and Hunter 2012). Finally, the ages of the people included in these studies differed as well. Garrett et al. (2008) and Heyworth et al. (2006) focused their studies on children, while Few et al. (2009), Kelly-Hope et al. (2007), Marcynuk et al. (2009) and Saadi et al. (1995) included people of all ages. These substantial differences among studies make it very difficult to compare results among them and apply the results to other scenarios; thus, their conclusions should be interpreted and applied with caution.

Table 19. Human health risks and reported illnesses associated with RWH systems.

References	Study Location & Details	Data			
Ahmed et al. 2010a	Brisbane, Gold Coast and Sunshine Coast regions of Australia; 214 samples collected from 82 RWH systems	Pathogen Exposure & Risk Scenario	Volume per Day or Event	Dose Range (cells or cysts)	
		Salmonella spp.			
		Liquid ingestion via drinking	1000 mL	$6.5x10^{1}$ - $3.8x10^{2}$	
		Liquid ingestion via hosing	1 mL	$6.5x10^{-2}$ - $3.8x10^{-1}$	
		Aerosol ingestion via showering	1.9 mL	$1.2x10^{-1}$ - $7.2x10^{-1}$	
		Aerosol ingestion via hosing	1.9µL	$1.2x10^{-4}$ - $7.2x10^{-4}$	
		G. lamblia			
		Liquid ingestion via drinking	1000 mL	$5.6x10^{-1}$ - $3.6x10^{0}$	
		Liquid ingestion via hosing	1 mL	$5.6x10^{-4}$ - $3.6x10^{-3}$	
		Aerosol ingestion via showering	1.9 mL	$1.0x10^{-3}$ - $6.8x10^{-3}$	
		Aerosol ingestion via hosing	1.9µL	$1.1x10^{-6}$ - $6.8x10^{-6}$	
		L. pneumophila			
		Aerosol ingestion via showering	0.84µL	$5.2x10^{-5}$ - $1.4x10^{-4}$	
		Aerosol ingestion via hosing	0.5µL	$3.0x10^{-5}$ - $8.4x10^{-5}$	
Ahmed et al. 2009	Australia; QMRA used to quantify risk exposure to pathogens from potable & non-potable uses of roof-harvested rainwater; samples collected from bottom tank tap of 84 RWH systems		Range of genomic units/1000mL of tank water	Range of cells/ 1000mL of tank water	Range of viable & infective cells/ 1000mL of water*
		Salmonella spp.	65-380	65-380	16-95
		G. lamblia	9-57	0.6-3.6 cysts	0.1-0.9 cysts
		*Assumes 25% of cells were both viable and infective			
		Exposure & possible dose for those exposed to contaminated water:			
			Vol. per event	Range of dose**	# events per yr
		Ingestion via drinking			
		Salmonella spp.	1000 mL	16-95	365
		G. lamblia	1000 mL	0.14-0.9	365
		Ingestion via hosing			
		Salmonella	1 mL	0.02-0.1	104
		G. lamblia	1 mL	0.0001-0.0009	104
		**infective units per event			

Table 19, cont. Human health risks and reported illnesses associated with RWH systems.

References	Study Location & Details	Data		
Ahmed et al. 2009	Australia; QMRA used to quantify risk exposure to pathogens from potable & non-potable uses of roof-harvested rainwater; samples collected from bottom tank tap of 84 RWH systems	Infection risk for individuals via drinking:		
			Salmonella spp.	G. lamblia
		Infections per 10000 people from single event	18-101	28-176
		Percent population exposed to pathogens	0.68	0.83
		Infection risk per event per 10000 people	0.12-0.69	0.23-1.50
		Number of events per year	365	365
		Infection risk per year per 10000 people	44-250	85-520
		Infection risk for individuals via hosing		
			Salmonella spp.	G. lamblia
		Infections per 10000 people from single event	0.02-0.1	0.03-0.18
		Percent population exposed to pathogens	3.2	3.9
		Infection risk per event per 10000 people	0.0005-0.0033	0.001-0.007
		Number of events per year	104	104
		Infection risk per year per 10000 people	0.06-0.34	0.11-0.72

Table 19, cont. Human health risks and reported illnesses associated with RWH systems.

References	Study Location & Details	Data
Ahmed et al. 2011a	N/A	Reported diseases associated with the consumption of untreated roof-harvested rainwater: *C. botulinum* , Australia (Murrell and Stewart 1983) *Campylobacter fetus* , Australia (Brodribb et al. 1995) *Campylobacter spp* ., Australia (Merritt et al. 1999) S. Typhimurium phage 9, Australia (Franklin et al. 2009) S. Typhimurium phage 1, New Zealand (Simmons and Smith 1997) *L. pneumophila* , New Zealand (Simmons et al. 2008) *L. pneumophila* serogroup 1, U.S. Virgin Islands (Schlech et al. 1985) *S. arechevalata* , West Indies (Koplan et al. 1978)
Karim, 2010	Bangladesh; 60 household and 38 community large RWH systems sampled; 308 water samples collected from storage tanks; sanitary inspections of rooftops conducted; quantitative health risk assessment model to assess disease burden associated with drinking rainwater	Disesease Burden 95% Upper CI 95% Lower CI Median Total microbial burden 968-1222 4.10-4.20 69.14-82.83 Viral burden 898-1126 3.94-4.04 65.84-77.27 Bacterial burden 9-96 0.15-0.16 3.28-3.91 Protozoal burden 0.29-0.4 0 0.02 All values reported in µDALYs/person/year WHO guideline for all burdens: 1.0
Lye 2002	N/A	Disease cases attributed to the consumption of untreated rainwater: Reference Disease Type Pathogen Detected Koplan et al. 1978 Bacterial diarrhea Salmonella arechevalata Eberhart et al. 1997 Bacterial diarrhea Campylobacter spp. Schlech et al. 1985 Bacterial pneumonia Legionella pneumophila Murrell & Stewart 1983 Bacterial toxin Clostridium botulinum Carmona et al. 1998 Tissue helminth Echinococcus granulosis Crabtree et al. 1996 Protozoal diarrhea Giardia lamblia & Cryptosporidium parvum

Eberhart-Phillips et al. (1997) compared the risks of consuming rainwater with those of consuming improved sources in a New Zealand study. It was concluded that there were greater risks of gastrointestinal illness associated with harvested rainwater based on data collected from a small number of rainwater collectors (Eberhart-Phillips et al. 1997). However, when Dean and Hunter (2012) pooled the data from this study with those from Few et al. (2009), Heyworth et al. (2006) and Saadi et al. (1995), they concluded that there was no additional health risk or benefit between the two water sources.

Ahmed et al. (2009) and Ahmed et al. (2010a) performed quantitative microbial risk assessments (QMRAs) to estimate the exposure and risk associated with the consumption and use of harvested rainwater in Australia (Table 19). Both of these used pathogen concentrations measured in over 80 RWH systems as the basis for their analyses. Ahmed et al. (2009) found that 44-250 per 10,000 people and 0.06-0.34 per 10,000 people were at risk for infection by Salmonella due to ingestion of rainwater via ingestion and hosing (aerosol), respectively. Approximately 85-520 per 10,000 people and 0.11-0.72 per 10,000 people were at risk for infection by Giardia due to ingestion of rainwater via ingestion and hosing (aerosol), respectively. Ahmed et al. (2010a) found the numbers of infections to be expected from the consumption of rainwater were 9.8-54 per 10,000 people and 20-130 per 10,000 people for Salmonella and G. lamblia, respectively (Ahmed et al. 2010a). Due to the higher numbers found by Ahmed et al. (2009), it was concluded that the potable use of rainwater could present substantial risk of infection by Salmonella and Giardia to users. Contrarily, Ahmed et al. (2010a) concluded there is little risk associated with the use of rainwater for potable purposes.

The QMRA methodology assumes a certain percentage of the cells found in tank water are viable and infective, a value that may or may not be representative of what is actually present. Additionally, the volume of water ingested, number of exposure events per year and other variables must be estimated to produce conclusions. The method also assumes that pathogens are present at the ‘range of dose’ concentration for the entire exposure period, an assumption that may not be true in nature. Finally, the polymerase chain reaction (PCR) method of detecting the presence of pathogens in tank water is more sensitive than other analysis techniques, which may explain a higher number of pathogens reported than in other studies (Ahmed et al. 2009). Thus, Dean and Hunter (2012) assert that the application of QMRA methodology frequently overestimates risk.

Karim (2010) performed a quantitative health risk assessment (QHRA) to estimate disease burdens associated with drinking untreated rainwater. These burdens were quantified in terms of disability adjusted life years (DALYs). One DALY is defined as the “loss of one healthy life year due to death or inability to work because of illness” (Fry et al. 2010). According to WHO, 1µDALY/person/year is the maximum threshold for the disease burden associated with a given contaminant (WHO, 2004). A burden above this threshold indicates an unacceptable, significant disease burden (WHO, 2004). Karim (2010) reported significant median disease burdens for total microbial load, viruses and bacteria, with the predominant burden being from viruses and bacteria (Table 19). Protozoal burdens were below the WHO threshold and considered negligible (Karim 2010). Consequently, Karim (2010) concluded that there is low to medium risk associated with drinking untreated rainwater.

Crabtree et al. (1996) used an exponential risk assessment model to estimate the potential daily risk when 2L of rainwater are consumed each day. The concentrations used to perform this analysis were measured from 13 cisterns in the U.S. Virgin Islands (Crabtree et al. 1996). The average risk of infection was estimated to be $1.9\text{x}10^{-4}$ for Cryptosporidium and $4.3\text{x}10^{-4}$ for Giardia (Crabtree et al. 1996). Crabtree et al. (1996) compared these values to the threshold of 10^{-4}, which was established by USEPA (1989), and concluded there was substantial risk of infection associated with the consumption of harvested rainwater. As with the QMRA, it should be noted that this assessment model requires assumptions regarding the percentage of viable and infective cells.

Fry et al. (2010) applied WHO’s comparative risk assessment to estimate the potential reduction in diarrhea DALYs per month that could be achieved by supplementing or replacing existing water sources with domestic RWH. This assessment was conducted for 37 cities in West Africa using a variety of scenarios based upon daily per capita water use (Fry et al. 2010). It was found that implementing a 400L RWH system could reduce DALYs for all cities by 36,700, a total of 9%. If the RWH system was implemented in conjunction with point-of-use treatment, this number increases to 68,500 (16%) (Fry et al. (2010). Implementing a 10,000L RWH system with or without point-of-use treatment, DALYs could be reduced by 97,200and 71,100, respectfully (Fry et al. 2010). Fry et al. (2010) noted that the reductions in disease burden and diarrhea DALYs would vary significantly due to difference in rainfall and population among cities. Assumptions made in the application of this assessment include: (1) the distribution of diarrhea DALYs is consistent throughout the region studied (although this is highly unlikely due to environmental, socio-economic, pathogen and immunity characteristics of a given area), (2) diarrhea DALYs do not vary seasonally, and (3) an increase in the existing water supply due to RWH systems would be used to improve sanitation and hygiene (Fry et al. 2010).

Although conclusions regarding the relative risk of using harvested rainwater vary considerably, many of the studies reported lower incidents of gastrointestinal illnesses than expected or predicted by risk assessments. Ahmed et al. (2011b) noted that results from pathogen and protozoa sampling indicated potential exposure to pathogens but no illnesses were reported. Ahmed et al. (2009) reported substantial differences in the estimates of infection incidences from the risk assessment and the number of illnesses reported in the Notifiable Diseases Surveillance System Database. An acquired immunity in persons regularly drinking rainwater due to frequent exposure to low pathogens concentrations was the most cited reason for this phenomenon (Ahmed et al. 2011b; Ahmed et al. 2009; Ashbolt and Kirk 2006; Dean and Hunter 2012; Heyworth et al. 2006). Heyworth et al. (2006) supported this logic by showing that children primarily consuming rainwater for long periods of time were at lower risk of gastrointestinal illness than those consuming water from other sources. Ashbolt and Kirk (2006) also reported higher risk of illness among persons visiting an area or spending time away from home, indicating a lower level of immunity among those not accustomed to consuming rainwater. Other possible explanations include: (1) people may not report a gastrointestinal illness if it is mild or short-lived, (2) most RWH systems serve 1 or 2 households so outbreaks of illnesses involve few people (as opposed to large numbers of people associated with outbreaks involving public or community systems), resulting in decreased chances of epidemiological investigations and conclusions, (3) in communities experiencing a higher occurrence of gastroenteritis, gastrointestinal illnesses associated with RWH systems may become masked or considered normal and (4) the agency managing reports of illness may not record certain illnesses associated with RWH systems (ex. Queensland does not monitor the occurrence of Giardiasis) (Ahmed et al. 2011b; Ahmed et al. 2009; Ahmed et al. 2011a; Lye 1992; Dean and Hunter 2012).

Effects of Maintenance & Design

As shown in Table 20, the material comprising the storage tank of a RWH system can impact the level of microbial contamination within the system. Dillaha and Zolan (1985) reported that ferrocement storage tanks resulted in the lowest TC and FC concentrations, while metal drums resulted in the highest. Contrarily, Karim (2010) reported that RCC and ferrocement tanks are more susceptible to microbial contamination when compared to plastic and brick. Schets et al. (2010) showed that die off of Aeromonas and EC occurred more rapidly in galvanized iron storage tanks than in PVC containers, indicating superior microbial quality (though this die off was thought to be due to toxic compounds in the tank material, which could possibly jeopardize other aspects of water quality). These results indicate

Table 20. Summary of studies relating microbial quality to design and maintenance characteristics of RWH systems.

References	Study Location	Site Description	Data						
Dillaha and Zolan 1985	Micronesia	203 rainwater harvesting systems sampled once	--------------Total Coliform Bacteria---------------						
						%Sample with concentration of:			
			Characteristic	n	Median	0	≤10	≤20	>200
			Covered Cistern						
			Yes	30	4.5	30	60	60	17
			No	118	4.3	30	62	74	12
			Screened inlet						
			Yes	52	10.5	19	50	58	21
			No	75	2.7	36	71	83	5
			Cistern type						
			Reinforced concrete	81	2.1	35	70	81	10
			Ferrocement	5	3.0	20	80	80	0
			Steel tanks	34	6.5	26	53	71	15
			Metal drums	30	18.5	23	43	50	27
			Other	4	7.5	25	50	50	0
			Cistern cleanings/year						
			0	22	6.5	27	59	68	14
			1-3	59	5.0	24	59	66	22
			4-6	9	15.0	11	44	67	0
			>6	21	4.3	24	67	81	10
			Roof & gutter cleanings/yr						
			0	49	4.0	24	67	76	8
			1-3	36	7.5	28	56	64	28
			4-6	7	19.0	14	43	57	14
			>6	11	4.0	18	55	73	9
			--------------Fecal Coliform Bacteria---------------						
						%Sample with concentration of:			
			Characteristic	n	Median	0	≤10	≤20	>200
			Covered Cistern						
			Yes	37	0.4	54	84	84	5
			No	131	0.3	59	80	84	7
			Screened inlet						
			Yes	65	0.5	52	74	74	8
			No	82	0.3	60	87	93	4
			Cistern type						
			Reinforced concrete	83	0.2	70	87	88	7
			Ferrocement	14	0.3	64	86	93	7
			Steel tanks	43	1.4	40	74	79	5
			Metal drums	30	2.5	47	70	73	13
			Other	5	1.0	40	80	80	0
			Cistern cleanings/year						
			0	24	0.4	54	79	79	4
			1-3	67	0.3	58	81	84	12
			4-6	13	1.0	46	77	85	0
			>6	23	0.4	57	83	87	0
			Roof & gutter cleanings/yr						
			0	56	0.3	66	89	91	2
			1-3	42	0.5	50	71	76	14
			4-6	9	1.0	44	67	67	0
			>6	12	0.5	50	83	92	0

Table 20, cont. Summary of studies relating microbial quality to design and maintenance characteristics of RWH systems.

References	Study Location	Site Description	Data			
				Coliforms	Eugonic (SMA)	Dysgonic (R2A)
Lye 1987	Kentucky	30 RWH systems; sampled at cold tap faucet	Disinfected within last year			
			Yes	158	7.9 E7	2.3E9
			No	255	6.5 E6	7.7E8
			Cleaned within last year			
			Yes	173	6.8 E7	8.7E8
			No	222	3.1 E7	1.6E9
			Regular first flush diverter use			
			Yes	15	5.9 E6	6.4E8
			No	226	4.1 E7	1.5E9
			Filter treatment			
			Yes	131	1.0 E8	3.1E9
			No	248	1.4 E7	6.9E8
			Water supplemented with city water			
			Yes	96	2.2 E6	2.2E8
			No	257	3.1 E7	7.7E8
			Monthly	210	1.4 E8	6.6E9
			Mean values Reported in CFU/100mL			

that the effect of storage tank material on microbial quality of harvested rainwater is not adequately characterized. More research is needed on this topic to aid designers in choosing a storage tank that minimizes microbial contamination. Furthermore, if an existing RWH system is made of a material linked with higher microbial levels, users can opt to incorporate additional treatment mechanisms to reduce risk of illness.

Other aspects of system design that could influence microbial contamination within RWH systems include the presence/proximity of overhanging trees and vegetation, the presence/absence of screens on cistern openings, use of a first flush diverter, and the method of water extraction and transport (Ahmed et al. 2011b; Dillaha and Zolan 1985; Despins et al. 2009; Karim 2010; Lye 1987; Lye 1992; Pinfold 1993; Schets et al. 2010). To minimize the potential for microbial contamination, a system should be located such that overhanging vegetation is avoided or minimized, either through design modification or pruning (Ahmed et al. 2011b; Despins et al. 2009; Ahmed et al. 2012b). Other structures that would facilitate the perching of birds and other animals should also be avoided (Ahmed et al. 2011b). RWH systems with inlet screens, tank covers and other measures that prevent insects and animals from entering the storage tank have been shown to produce higher quality water than those without (Dillaha and Zolan 1985; Lye 1992; Pinfold 1993; Schets et al. 2010). The method of extraction and transport of harvested rainwater should minimize the introduction of contamination (Schets et al. 2010). Findings published by Pinfold (1993) suggest the dipping of containers into a storage tank can introduce pathogens into a RWH system and should be avoided if possible.

The inclusion of a first flush diverter is crucial in reducing concentrations of micro-organisms within a system (Despins et al. 2009; Karim 2010; Lee et al. 2012; Lye 1987; Lye 1992; Mendez et al. 2011). As shown in Table 14, Lee et al. (2012) and Mendez et al. (2011) demonstrated that TC, EC and enterococci concentrations in roof runoff decreased substantially after the first flush had passed. Lye (1987) showed TC concentrations in RWH systems were much lower when a first flush diverter was used (Table 20). As first flush diverters have been shown to substantially reduce concentrations of physico-chemical contaminants as well, it is strongly suggested that RWH system incorporate these devices whenever possible.

Finally, frequent maintenance of these systems can also reduce the potential for microbial contamination (Ahmed et al. 2011b; Karim 2010; Lye 1987; Lye 1992; Domènech and Saurí 2011; Schets et al. 2010; Ahmed et al. 2012b). Examples of these maintenance procedures include the cleaning of the roof surface and gutters, cleaning and/or disinfection storage tanks, and removal of accumulated sediment within storage tanks (Ahmed et al. 2011b; Karim 2010; Lye 1987; Lye 1992; Schets et al. 2010; Ahmed et al. 2012b). Lye (1987) measured substantially lower concentrations of coliforms in RWH systems that had been cleaned or disinfected within the last year, and Ahmed et al. (2011b) and Ahmed et al. (2012b) recommend cleaning of storage tanks at least twice a year. Despite several studies supporting the link between frequent maintenance and improve water quality, others failed to identify a significant correlation between the two (Dillaha and Zolan 1987; Spinks et al. 2006). This indicates a need for further study and investigation.

Conclusions and Recommendations

The microbiological quality of RWH systems has been extensively studied, but the findings of these many studies are often contradictory. Fortunately, there have been some aspects of this subject that most researchers agree upon:

- The presence of overhanging vegetation and structures that allow perching of wildlife is often correlated with higher concentrations of indicator bacteria and pathogens in harvested rainwater.
- All openings and possible entry points within the system should be screened or sealed to prevent the entry of insects and animals, which has been linked to elevated microbial concentrations.
- First flush diverters should be used with every RWH system to divert the first few millimeters of runoff, which has been shown to contain high concentrations of bacteria and pathogens.
- All harvested rainwater should be treated prior to human consumption to minimize the risk of illness. Treatment should include some form of filtration and disinfection.
- When assessing microbial contamination, the measurement of multiple indicator species and/or pathogens is recommended to improve the accuracy of risk assessments.

While it is fairly well established that bacteria and pathogens are commonly present in roof runoff and harvested rainwater, the human health risk associated with this contamination is a greatly debated topic. As demonstrated herein, there are many ways of assessing the risk associated with the use of harvested rainwater, but many rely on assumptions that may or may not accurately represent natural conditions (ex. the percentage of viable and infective cells). Additionally, the human health aspects of illness identification and reporting introduce challenges with respect to analyzing and addressing RWH-associated illnesses. There are many treatment options that serve to decrease the concentrations of micro-organisms in RWH systems, but the effect of these various options on human health risk have not been thoroughly explored. Similarly, the impact of specific design practices and maintenance protocols seem to reduce contamination, but their impact on human health risks remains obscure.

Future Research Needs

Future research needs that may serve to improve our understanding of microbial contamination with respect to RWH systems are listed below, in no particular order:

- More information is needed on the occurrence, survival, viability and behavior of bacterial and protozoan pathogens in storage tanks (Ahmed et al. 2011b).
- Further investigation into the assumptions regarding the percentage of gene copies that represent viable and infective organisms is needed to improve the accuracy of risk assessments (Ahmed et al. 2009).
- The accuracy of using fecal indicator bacteria as surrogates for fecal pollution and pathogen presence needs to be assessed and recommendations should be made as to the most appropriate indicators to use (Ahmed et al. 2008, Ahmed et al. 2011a).
- More accurate information is needed on the occurrence of pathogens in rainwater tanks and the dynamics of their survival or deactivation. Also, a robust method of conducting an assessment of potential human health risk from RWH systems is necessary (Ahmed et al. 2010a).
- There is a need for more studies focusing on the collection and matching of pathogenic strains from fecal specimens and from potential sources (tap water, tank water) using molecular typing methods to confirm RWH systems as the cause of gastroenteritis (Ahmed et al. 2011a, Ahmed et al. 2011b).
- More studies are needed on the survival and viability of pathogenic cysts and oocysts RWH systems (Crabtree et al. 1996).

- Little data is available on the effectiveness of treatment options for RWH systems (Dean and Hunt 2012). Further research should also be done on the effect of maintenance, system design or distribution methods on health risks associated with RWH systems (Dean and Hunter 2012).
- The effect of environmental, non-fecal organisms on the microbial quality of harvested rainwater needs to be further investigated (Evans et al. 2006).
- Research is needed on the seasonality of diarrheal diseases, the local nature of disease transmission and effects of gastro-illnesses on local populations related to the consumption of harvested rainwater (Fry et al. 2010).
- Further investigation into the associated risks of harvested rainwater use and consumption in at-risk populations (elderly, children, immuno-comprised) is needed (Heyworth et al. 2006).
- Research is needed on the role of immunity with respect to health risks associated with RWH systems to determine if new consumers are more at risk than long-term users due to a lack of immunity. (Heyworth et al. 2006; Lye 1987)
- More studies on the link between prevailing weather conditions and microbial characteristics of 'fresh' rainwater are needed to aid in the development of a microbial risk management framework for RWH. Microbial risk assessments should be conducted on 'fresh' rainwater, in addition to harvested rainwater, using a reliable molecular method. (Kaushik et al. 2012)
- A great need exists for additional evaluation of various preventative and maintenance practices (or lack thereof) and their effect on microbial quality of harvested rainwater (Lye 1992; Schets et al. 2010).
- Very little information has been gleaned on the presence of viruses in RWH systems, which should be further investigated (Lye 2002). The impact of algal growth and toxin production within the storage tanks of RWH system should also be explored (Lye 2002).
- More sensitive detection techniques are needed for Campylobacter due to the difficulties associated with isolating this pathogen in RWH systems (Merritt et al. 1999).
- The presence of virulence strains in RWH systems needs further investigation, including their potential sources, management techniques and associated health risks (Ahmed et al. 2012b).

Modeling of Rainwater Harvesting Systems

Due to the difficulties and expense associated with monitoring rainwater harvesting systems, models are often utilized to determine the feasibility of RWH at a given location, design the optimal storage tank volume, simulate the behavior of a theoretical or existing system and/or evaluate the benefits associated with a RWH system. This section discusses various modeling approaches, reviews models that have been developed for RWH including metrics that have been used to evaluate performance, summarizes modeling studies that have been conducted on RWH and presents implications for system design based on modeling results.

Modeling Approaches

There are numerous approaches to modeling RWH systems, though those most commonly used include behavioral/simulation models, statistical methods and/or probability theories. A behavioral model "simulates operation of the reservoir with respect to time by routing simulated mass flows through an algorithm that describes the operation of the reservoir" (Fewkes and Warm 2000). This type of model imitates the physical behavior of a system, making it one of the most easily understood modeling approaches (Fewkes and Butler 2000; Palla et al. 2011). Behavioral models are often used with historical precipitation data to produce continuous mass balance simulations (Palla et al. 2011; Basinger et al. 2010). Although this approach may require a large amount of data and computation, it is suggested to be one of the most accurate modeling approaches for RWH (Kim et al. 2012). For maximum accuracy, the historical rainfall record used should be at least as long as the expected lifespan of the system and the amount of missing data should be minimized (Basinger et al. 2010).

Models that simulate the hydrologic behavior of RWH systems must use a method of estimating the filling, spilling and extracting of water from the storage tank. In natural conditions, these activities can occur simultaneously; however, it is impossible to accurately reflect that in a modeling environment (Mitchell et al. 2008). Two methods of estimation are commonly used: yield before spillage (YBS) and yield after spillage (YAS). In the YBS scenario water is extracted from the tank (due to demand) after rainfall is added and before the overflow volume is determined (Islam et al. 2010b; Liaw and Tsai 2004). Using YAS, demand is extracted from the storage tank after the overflow volume is calculated (Islam et al. 2010b; Liaw Tsai 2004). When Islam et al. (2010b) compared these two method of estimation for a given RWH system, it was determined that the YAS method tends to produce lower estimates for the amount of rainwater used than the YBS method. Palla et al. (2012) also found that the YAS method produced conservative results for system performance (i.e., the system supplied more water than YAS predicted) and was less sensitive to changes in storage volumes. Mitchell (2007) recommends averaging the results of YAS and YBS simulations to improve accuracy, though most models use one or the other.

Some models rely upon an underlying probability distribution to predict dependent variables within the system, such as overflow or storage volume (Kim et al. 2012). The selected probability distribution is based upon the hydrologic relationships between meteorological distribution functions and the variables within the system (Kim et al. 2012). The application of these models can be rather limited, as the precipitation characteristics of a given location must match the statistical assumptions of the model's distribution to ensure accurate results (Basinger et al. 2010). While these models can be useful for preliminary design analyses and estimating parameter sensitivity, they lack the level of detail provided by continuous mass balance simulation models (Kim et al. 2012).

There are other modeling approaches that can be used for RWH systems, including statistical analyses, user-defined hydrologic relationships and graphical curves; however, these are considered less accurate with more application limitations than those approaches previously discussed (Basinger et al. 2010; Liaw and Tsai 2004).

As precipitation data are sometimes difficult to obtain for a given location, stochastic models have been developed to generate these data for modeling purposes. Parametric stochastic precipitation generators can only be accurately used in areas where the precipitation patterns match the statistical assumptions inherent in the model (Basinger et al. 2010). Nonparametric stochastic models do not require specific statistical characteristics in the precipitation patterns and thus can be applied in any location (Basinger et al. 2010). Another form of stochastic precipitation generation can be utilized when a short period of rainfall data exists, but does not equal or exceed the expected lifespan of the system. Cowden et al. (2008) introduced a model that uses historic rainfall data to create synthetic sequences of precipitation data that can be used as input data for another model. Benefits of this approach include ease of use, small data input requirements and fast computations (Cowden et al. 2008). As this approach was originally developed for temperate climates, it has not been extensively applied to tropic or semi-arid climates (Cowden et al. 2008).

Using Models to Design RWH Systems

There are countless models that can be used for RWH applications, some of which were specifically designed to simulate RWH systems while others have been adapted for this purpose. Table 21 summarizes a handful of these models and highlights their approaches and features. Though most models use the same general approach – behavioral simulation – the detailed processes and methods used within the model can vary substantially. The Palla et al. (2011) model accounts for mixing and detention time within the storage tank while others in Table 21 do not. Basinger et al. (2010) stochastically generates rainfall data from data inputs while other models simply use historical data input by the user. Water demands vary among the models, input and outputs differ and some incorporate a first flush allowance.

RWH models are often used during the design process to determine the optimal storage volume of a system given local rainfall conditions and water demands. Performance variables are typically used to evaluate the relative performance of systems with varying design parameters. Examples of these variables include reliability (time-based and volumetric), water savings efficiency, runoff reduction, economic efficiency, payback period, annual overflow volume, rainwater use efficiency, dry cistern frequency, detention time and failure probability (Palla et al. 2011; Basinger et al. 2010; Mitchell et al. 2008; Briggs and Reidy 2010; Ghisi 2010; Jones and Hunt 2010; Su et al. 2009; Kim and Yoo 2009; Zhang et al. 2010b; Zhang et al. 2009b; Ghisi et al. 2007; Imteaz et al. 2012; Fewkes and Warm 2000; Farreny et al. 2011b; Fewkes and Butler 2000; Guo and Beatz 2007; Gires and de Gouvello 2009; Imteaz et al. 2011a; Liaw and Tsai 2004; Lee et al. 2000; Mun and Han 2012; Palla et al. 2012). Table 22 summarizes the design and operational parameters used to describe the behavior of RWH systems. Multiple models may use the same term to describe a given variable but calculate it in different ways; thus, when comparing the performance of multiple RWH systems one must ensure the variables are defined in the same manner.

These variables can be used to evaluate how well a current design meets goals and objectives, or to determine what design modifications can be implemented to better meet objectives. As these variables can vary greatly among systems depending on climate, rainfall patterns, water usage characteristics, design features and primary goals of the user, there are no universal guidelines that suggest appropriate values or ranges. Thus, several studies have developed criteria for determining the optimal storage volume for RWH systems. Ghisi (2010) defined the optimal storage tank volume as the volume for which

Table 21. Summary of common models used for rainwater harvesting applications.

References	Model Name	Modeling Approach	Model Details
Basinger et al. 2010	SARET (Storage and Reliability Estimation Tool)	Behavioral simulation with stochastic precipitation generator based on historical data	• Generates a precipitation data set by applying statistical bootstrapping techniques with user-entered historical rainfall data. Uses a 30-day 'moving window' for more accurate results • Uses may enter a single value or a range of values for input parameters (catchment area, storage volume, first flush depth and frequency, water demands) • Water demand inputs are for daily time step, but can vary on a monthly basis. Demands can be classified as 'direct storage fed' (no backup water will be used to meet demands) or 'irrigation' (demands met with tank water if there is no precipitation within a user-specified number of days) • System performance characterized by reliability (number of days storage volume was insufficient to meet demand divided by number of days in simulation period) • Reliability reported as mean, median, minimum, maximum and standard deviation for simulation period • Most accurate when precipitation is uniform throughout the simulation period. Statistical validation should be verified when applied in areas of highly variable precipitation
Briggs and Reidy 2010	Advanced Water Budget Analysis (WBA)	Behavioral simulation with historical precipitation	• Spreedsheet-based model • Model inputs: catchment area, runoff coefficient for multiple collection areas, rainfall data, daily evapotranspiration • Demands designated 'seasonal' are only applicable May-September and cistern is set to 'full' prior to beginning of each season • Accounts for dead storage within storage tank • Water demand options: irrigation, cooling tower makeup, sewage conveyance, vehicle washing, laundry • Model outputs: water savings (percent of overall demand met and volume of domestic water saved), runoff reduction (percent of total precipitation captured and volume of runoff captured) and reliability (percent of individual daily demands fully met by the system)

Table 21, cont. Summary of common models used for rainwater harvesting applications.

References	Model Name	Modeling Approach	Model Details
Guo and Baetz 2007	n/a	Analytical probability distributions	• Uses historical precipitation, but performs statistical analyses on individual events within the data to form probabilistic model of rainfall characteristics • The rainfall probability model is used to perform stochastic analysis of hydrologic behavior of the RWH system • Hydrologic analyses performed on individual rain events that are generated using the probability model. • The amount of runoff generated from a given rain event is estimated using a cumulative distribution function based upon user-defined runoff coefficients and first flush depths • System performance is characterized by reliability (fraction of time demands are met by RWH system) • Model outputs: annual overflow volume and required storage volume for a given reliability, roof area and water demand • Will slightly overestimate required storage volume when reliability and use rate are defined, but will slightly underestimate the reliability when storage volume and use rate are defined • Can be applied to any location with rainfall data
Jones and Hunt 2010	Rainwater Harvester	Behavioral simulation with historical precipitation	• Daily or hourly time steps • Model inputs: historical rainfall data, catchment area, runoff coefficient (capture factor), water and sewer cost, nitrogen concentration of runoff, first flush depth, storage volume, system cost and additional water supply • Contains a backup supply option that is triggered by the storage volume falling below a user-defined amount and stops when volume reaches user-defined volume • Water demands can vary by month, can be entered as a consistent daily usage, toilet flushing, irrigation or custom usage • Built-in functions can calculate usage based on number of individuals and volume of flush for toilet flushing or on soil-water deficit for irrigation needs • Model outputs: total runoff volume captured, percentage of water demand met by RWH system, annual volume used from RWH system, monetary savings, volume of backup water used, cost associated with backup water supply, overflow frequency (percentage of rainfall events resulting in overflow), dry cistern frequency (percentage of days where demand cannot be met), percentage of first flush volume captured, annual mass of nitrogen removed, payback period • Designed for use in North Carolina, USA but can be applied to other locations with rainfall and evapotranspiration data

Table 21, cont. Summary of common models used for rainwater harvesting applications.

References	Model Name	Modeling Approach	Model Details
Palla et al. 2011	n/a	Behavioral simulation with historical precipitation	• Daily time steps • Daily mass balance equation: stored volume = inflow+stored volume-rainwater supply-overflow • Assumes a constant runoff coefficient for contributing drainage area • Uses YAS method of estimation • Accounts for mixing within storage tank and detention time (does not act as a plug-flow system) • System characterized by demand fraction (annual water demand divided by annual inflow) and storage fraction (system storage capacity divided by annual inflow) • System performance described by water saving efficiency (volume of rainwater suppled divided by water demand) and overflow ratio (volume of rainwater exceeding storage capacity divided by inflow during the time interval)
Roebuck and Ashley 2006	RainCycle©	Behavioral simulation with historical precipitation	• Excel/spreadsheet based • Uses YAS method • Include whole-life costing analysis • Daily time steps, up to 100 years of simulation • Includes comparison of RWH system to public water supply system • Can perform simulations on a range of values for inputs • Monte Carlo simulations available • Model outputs: long-terms savings, average annual savings, payback period and percentage of demand met by RWH system • Uses net present value technique to calculate costs

Table 21, cont. Summary of common models used for rainwater harvesting applications.

References	Model Name	Modeling Approach	Model Details
Vieritz et al. 2007	TANK	Behavioral simulation with historical precipitation	• Daily time steps • FORTRAN based with Microsoft Excel interface • User inputs daily rainfall and pan evaporation data • Australia-specific application • Applicable for any 'regularly' shaped tank • Model accounts for dead storage within tank (area not accessible to meet water demands) • Can be run with YAS or YBS estimation methods • Water demand options: toilet cold water, kitchen hot water, kitched cold water, bathroom hot water, bathroom cold water, laundry hot water, laundry cold water • Irrigation options: fixed or soil water deficit-based. Can take an annual irrigation rate and calculate daily irrigation based on season, climate and soil moisture conditions • Contains backup (top-up) water option that is triggered when storage falls below 1 day's internal water demand or another user-defined value. A volume can also be defined below which garden irrigation is disallowed. • Assumes internal demands should be met before external demands. Also assumed internal demands are the same each day of the simulation period • Can produce results for increments of user-defined catchment area and storage volume ranges, which allows identification of optimal combination
Zhang et al. 2010	AquaCycle	Behavioral simulation with historical precipitation	• Uses YBS estimation technique • Daily time steps • Water demand options: kitchen, bathroom, laundry and toilet

Table 22. Summary of design and operational parameters used to describe the behavior of RWH systems.

References	Performance Variables
Basinger et al. 2010	Reliability: $\frac{\text{number of days tank volume is sufficient to meet demand}}{\text{number of days in evaluation period}}$
Briggs and Reidy 2010	Water savings: a. percentage of overall demand met b. volume of potable water saved Runoff reduction: a. percentage of total precipitation captured by the RWH system b. volume of runoff captured and used (versus leaving the system via overflow) Reliability: percentage of individual demands fully met by the RWH system
Farreny et al. 2011b	Overall efficiency: ratio of net amount of rainwater collected and used to volume of rainwater that could have entered the system Water savings: percentage of water demand met by RWH system
Fewkes and Warm 2000; Fewkes and Butler 2000	Water saving efficiency: $\frac{\text{rainwater yield from RWH system}}{\text{total demand}}$
Gires and de Gouvello 2009	Reliability curve: percentage of water volume supplied by the RWH System vs. the percentage of days when this percentage is reached Reliability indicator 1: percentage of days that 100% of demands are met by the RWH system Reliability indicator 2: percentage of days that less than 10% of demand is met by RWH system Reliability indicator 3: percentage of water supplied by the RWH system over 95% of the days in the evaluation period
Guo and Baetz 2007	Annual total overflow volume: volume of water overflowing from system during a year
Imteaz et al. 2012; Imteaz et al. 2011a	Reliability: $\frac{\text{number of days in a year that demand was met}}{\text{number of days in a year}}$
Jones and Hunt 2010	Usage replaced: percentage of total water demand met by the RWH system Annual water savings: average of monetary savings from using rainwater to replace public water supply Overflow frequency: percentage of precipitation events that created overflow from the system Dry cistern frequency: percentage of days when demand could not be met with rainwater Payback period: number of years of system use required for monetary savings to equal the cost of the system
Lee et al. 2010	Failure probability: ratio of time that the tank is empty to the total time in the evaluation period

Table 22, cont. Summary of design and operational parameters used to describe the behavior of RWH systems.

References	Performance Variables
Liaw and Tsai 2004	Volumetric reliability: $\frac{\text{volume of rainwater supplied}}{\text{total demand during evaluation period}}$ Time-based reliability: $1 - \frac{\text{number of time steps when demand exceeds storage}}{\text{number of time steps in evaluation period}}$
Mitchell et al. 2008	Volumetric reliability: $\frac{\text{volume of rainwater supplied}}{\text{total demand during evaluation period}}$ Time based reliability: percentage of time steps in evaluation period that demand is fully met Resilience: the rate at which the storage volume recovers after a period of limited rainfall
Mun and Han 2011	Rainwater use efficiency: $\frac{\text{total rainwater volume used to meet demand}}{\text{volume of rainwater collected}}$ Water saving efficiency: proportion of total demand satisfied by the RWH system Cycle number: $\frac{\text{total volume of rainwater used}}{\text{rainwater tank volume}}$
Palla et al. 2011	Water saving efficiency: $\frac{\text{volume of rainwater supplied during evaluation period}}{\text{water demand during evaluation period}}$ Overflow ratio: $\frac{\text{rainwater volume exceeding storage capacity during evaluation period}}{\text{inflow to system during evaluation period}}$
Palla et al. 2012	Water saving efficiency: $\frac{\text{volume of rainwater supplied during evaluation period}}{\text{water demand during evaluation period}}$ Median detention time (a measure of water quality only)
Rahman et al. 2010	Water savings: total water usage - potable water used
Su et al. 2009	Annual water supply deficit: ratio of total deficit volume to total demand
Zhang et al. 2010b; Zhang et al. 2009b	Volumetric reliability: percent of total demand met during the evaluation period
Zhou et al. 2010	Water shortage rate: the length of time in a year during which rainfall is limited Water loss rate: ratio of rainwater loss to annual precipitation

a 1,000L increase results in less than a 2% increase in potential water savings. Ghisi et al. (2007) and Domènech and Saurí (2011) used a similar definition, but required less than a 0.5% and 1% increase in potential water savings per additional 1,000L, respectively. Zhang et al. (2009b) and Zhang et al. (2010b) used a qualitative version of this definition with reliability as the parameter of interest instead of potential water savings. Imteaz et al. (2011b) identified the optimal storage volume as that for which the cumulative overflow volume approaches zero and/or the cumulative water savings approaches a constant value. A third definition was produced by Su et al. (2009), which simply stated that an optimal design should balance the volumetric reliability and the cost of the system.

The method by which the optimal storage volume is determined varies based upon the model being used. The model developed by Jones and Hunt (2010) relies on the user to run multiple design scenarios and choose the optimal storage volume based upon model outputs. Contrarily, the model presented by Guo and Baetz (2007) generates the optimal storage volume as a model output based upon user-defined criteria.

Evaluating RWH System Performance

There is a plethora of studies that employ models to evaluate the benefits of existing or hypothetical RWH systems (Table 23). Several of these studies investigate the relationship between model inputs and system performance; however, the results are somewhat contradictory as to which factors are most influential. Many studies have emphasized the importance of water demand, storage volume and contributing drainage area on system efficiency (Ghisi 2010; Zhou et al. 2010; Fewkes and Butler 2000), while others list climate *and* design parameters as factors impacting system performance (Coombes and Barry 2007; Islam et al. 2010b; Mun and Han 2012). Palla et al. (2011) asserts that design and operational aspects of a system influence performance more than climatic characteristics; however, substantial differences in system performance have been attributed to variations in climate and rainfall characteristics in other studies (Zhang et al. 2009b; Eroksuz and Rahman 2010; Imteaz et al. 2011b; Palla et al. 2012).

Many models use historical precipitation data for simulations, though the length of the record used has varied. Gires and de Gouvello (2009) used 5 years of data while Su et al. (2009) and Rahmen et al. (2010) used a 50- and 60-year record, respectively. Liaw and Tsai (2004) analyzed the relationship between the length of the rainfall record used and the resulting reliability and concluded that the variability associated with the estimated reliability decreased as the length of record increased. Palla et al. (2011) stated that rainfall records of at least 30 years should be used to ensure accurate estimates of performance while Su et al. (2009) recommends a minimum of 50 years to accurately reflect long-term trends.

The resolution of the precipitation data used for modeling has also been a topic of debate. Fewkes and Butler (2000) demonstrated that the accuracy with which a model predicted water savings efficiency decreased as the time interval increased from hourly to daily to monthly. Coombes and Barry (2007) evaluated the effect of varying time intervals on model results and concluded that a 6 minute time step allowed for water demand to occur during rainfall events, while daily time steps did not allow this and consequently underestimated annual rainwater yields. Liaw and Tsai (2004) also reported more accurate results with smaller time intervals, and showed that the impact of longer time intervals increased as storage volumes decreased; therefore, it is especially important to use shorter time intervals when modeling smaller RWH systems. While sub-hourly data may not be available, it is apparent that the highest resolution precipitation data should be used when available to maximize model accuracy. Daily rainfall data is typically considered ideal and is used for the majority of the studies in Table 23 (Ward et al. 2010b).

Conclusions and Recommendations

Models are a useful tool for predicting the benefits associated with RWH systems, such as potable water reduction, economic savings and stormwater runoff reduction. Modeling results can also offer valuable insight regarding the relationships between dependent and independent variables within a system. Understanding how rainfall characteristics, demand patterns and storage volumes impact the reliability of a system is crucial in designing systems that meet a user's goals and objectives.

Models can accurately predict the behavior and performance of systems, so long as the data inputs are accurate representations of a system's climate, design and operational conditions (Briggs and Reidy 2010). When using historical precipitation data, shorter time intervals and longer record lengths result in more accurate results (Liaw and Tsai 2004). Simulating water demands for a system can be extremely difficult due to climatic, social and habitual influences on water usage; therefore, incorporating methods of accounting for these influences will result in more precise simulations of usage. For example,

Table 23. Summary of various studies using models to evaluate RWH system performance.

References	Study Location	Study Details	Key Findings
Coombes and Barry 2007	Australia	• Compares 2 times steps (6-minute and daily) with 2 demand types (climate-dependent and average) • For climate-dependent analysis, behavioral simulation model used with probabilistic water demand model to simulate household water demands; average demand simulated with storage mass-balance model • Applies model to precipitation data from 8 Australian cities • Range of storage volumes analyzed: $1m^3$ to $10m^3$ • Water demand included all domestic water uses except drinking and cooking • Case A: 6 minute time step and climate-dependent demand • Case B: daily time step and climate-dependent demand • Case C: daily time step and average demand	• Climate-dependent water demands were higher during hot, dry conditions and lower during rainy conditions • Daily time steps underestimated annual rainwater yield (this underestimation was greater for systems with smaller storage volumes) • Smaller time steps allow water demand to occur during precipitation events, resulting in a reduction in overflow and increase in rainwater yield during low-intensity events • Annual rainwater yield was a function of storage volume, rainfall depth, seasonal distribution of rainfall and water demand
Coombes and Kuczera 2000	Australia	• Behavioral model developed that uses probabilistic framework to simulates behavior with respect to water demands • Based upon the premise that water usage is dependent upon daily temperature, days without rainfall and rainfall depth (people more likely to use water during hot and dry weather, people are less likely to use water during rainy days and the amount of water used is dictated by the amount of rainfall received) • Uses a daily time step and simulated exhouse demands (garden watering, car washing, irrigation, etc.) • Model inputs: daily rainfall depth, daily maximum temperature, monthly average exhouse water demand	• Model reliably predicted monthly ranges of exhouse water use and strong seasonal demand trends for a specific region in Australia • Model shows improved predictability from other models, as it accounts for behavioral responses to climate variables instead of linear regression • Users most likely to use water for exhouse demands on days without rainfall • On days without rainfall, water use patterns are influenced by normal usage patterns and air temperatures • On days with rainfall, amount of water used is influenced by the amount of rainfall received • Application is limited, as exhouse demand data is based upon monitoring data collected in a specific region of Australia

Table 23, cont. Summary of various studies using models to evaluate RWH system performance.

References	Study Location	Study Details	Key Findings
Eroksuz and Rahman 2010	Australia	• Continuous simulation daily water balance model used • Investigates water savings potential of multi-unit residential buildings in Sydney, Newcastle and Wollongong • Water demands: toilet flushing (36L/person/day), laundry (36L/person/day), hot water including shower, laundry and kitchen (62L/person/day) and outdoor irrigation (28L/person/day) • 50%, 20%, 10% and 20% of outdoor demand assumed to occur in summer, fall, winter and spring, respectively • Assumes roof to site area ratio of 0.5 • 10 storage volumes (10kL-100kL in 10kL increments) and 5 roof areas ($500m^2$-$2500m^2$ in $500m^2$ increments)	• When collecting runoff from smaller catchments, an increase in tank size does not increase water savings as much as when using a larger catchment • As catchment size increases, annual water savings increases and the rate of increase is larger for larger tank sizes • The storage volume for which an increase in volume results in little increase in water savings is considered the optimal size • The annual water savings is highly dependent upon annual rainfall
Fewkes and Warm 2000	UK	• Developed a behavioral, daily time step model to simulate a RWH system • System performance is predicted for various combinations of roof area, water demand, storage volume and rainfall characteristics • Performance curves are produced using an exponential best-fit equation • 11 cities in the UK were modeled using at least 15 years of historical precipitation data • Water demand is toilet flushing and assumed to occur at a constant daily rate • No rainfall losses (evaporation, leakage, etc.) were assumed	• All 11 performance and water efficiency curves were similar, suggesting system performance does not differ greatly due to regional rainfall fluctuations within the UK • Modeling results were within ±5% of other YAS model results and considered acceptable • A performance curve was generated for each input ratio (roof area x annual rainfall x annual demand); these curves represent system performance • These curves are a valuable design aid for the UK, but not applicable to other regions
Ghisi et al. 2007	Brazil	• Potential potable water savings were estimated for 195 cities via estimations of annual rainfall, number of people per dwelling, number of dwellings supplied with potable water and total roof area • Optimal rainwater tank sizes with respect to potable water savings were estimated for 9 cities via Neptume model (a water balance model that estimates potential potable water savings for a range of tank capacities applied to residential buildings); Rainwater tank sizes considered: 1000L - 30000L in increments of 1000L	• A good correlation did not exist between potential potable water savings and potable water demand; potable water savings generally higher in cities with lower demand • Higher potential savings during summer when temperatures and rainfall are higher

Table 23, cont. Summary of various studies using models to evaluate RWH system performance.

References	Study Location	Study Details	Key Findings
Gires and de Gouvello 2009	France	• Developed a behavioral model that includes parameters that characterize the reliability of RWH systems from the perspective of a water supplier (Table 22) • Model inputs: water demand, roof area, storage volume • Water demand was toilet flushing • Water usage variability was accounted for by using distribution data and assigning a usage to each day of the week instead of an average daily usage • Analyses performed for a range of roof areas (60-160m^2), number of building occupants (1-6), occupancy characteristics (families vs. singles/couples) and storage volumes (0.5-4m^3) • 5 years of historic precipitation data were used to apply the model to 63 French cities • Averages the results from YAS and YBS estimation methods	• Traditional models (which represent the homeowners' perspective) optimize storage volumes based upon regions with similar precipitation characteristics; this model optimizes storage volumes based upon household needs (represents the suppliers' perspective) • If RWH system can meet water demands without potable backup for 4 weeks, it is considered autonomous to a public water supplier • Reliability is an important parameter to supplier because they will be required to supply water when the RWH system cannot meet demand and because it impacts infrastructure and costs of a supplier • If the R1 and R2 parameters (Table 22) are too small and too large, respectively, the water supplier may still be required to supply water to households on occasion and thus cannot reduce their infrastructure • The R3 parameter is a good indication to suppliers of overall reliability of a system and the potential for infrastructure reduction: when R3 = 0-50%, system is not reliable; 50-70% is reliable, >70% is very reliable • R1, R2 and R3 should be used in conjunction with water savings efficiency to determine optimal storage volumes for RWH system that will benefit both homeowner and supplier
Imteaz et al. 2011a	Australia	• Developed daily water balance model for determining optimal storage volumes • Presents results for driest, average and wettest years of the simulation period (1st, 5th and 9th decile of total annual rainfall amount, respectively), based up the historical precipitation data entered into the model • Analyses were performed for ranges of storage volumes (1,000-10,000L), roof areas (50-300m^2), water demand (2-4 people, 185L/person/day) and reliability (60%, 70%, 80%)	• Various combinations of roof size, storage volume, climate conditions, number of building occupants and reliability can produce many different reliability values • For some variables, a threshold exists above which reliability will not change • In this study, it was not possible to acheive a 100% reliability for a 2 person household in Melbourne for a roof size less than 150m^2, even during the wettest year; additionally, tank sizes greater than 5000L had no impact on reliability, however, with a larger roof size and and optimal tank size, 100% reliability can be acheived in the driest year • For a 4 person household 100% reliability was not achievable for a roof size up to 300m^2 and storage volumes up to 10,000L

Table 23, cont. Summary of various studies using models to evaluate RWH system performance.

References	Study Location	Study Details	Key Findings
Imteaz et al. 2011b	Australia	• Used daily water balance model described in Imteaz et al. 2011a • The relationship between payback period and increase in potable water prices is investigated • Case study was performed in Melbourne, Australia on 2 RWH systems at Swinburne University of Technology • Catchment areas were 907m^2 and 2491m^2 for north and south tanks, respectively • Water demand: outdoor irrigation, applied twice weekly (north tank: 15,725kL/week, south tank: 6.6kL/week)	• The current storage volumes (185m^3 for north tank, 110m^3 for south tank) are not optimal for the given condition: the north tank should have a larger catchment area and the south tank should have a larger storage volume • Using actual daily data, instead of developing average daily data from monthly or annual data, provides more realistic results • It is important to perform optimization of storage volumes prior to constructing a RWH system to increase efficiency and financial viability • As potable water prices increase, the payback periods of tanks decrease
Imteaz et al. 2012	Nigeria	• Daily water balance model developed to estimate daily stormwater use, daily storage volume, daily overflow volume, daily potable water use and annual accumulations • Model inputs: daily rainfall, roof area, losses due to spillage, leakage and evaporation (assumed to be 15%) and water demand • Water demand scenarios: low demand (toilet flushing only, 1.8m^3/month/house) and high demand (toilet flushing and laundry, 2.45m^3/month/house) • Average roof area: 80m^2 • Model applied to Abeokuta, Nigeria to estimate household RWH potential	• Analysis performed for driest year (worst-case scenario) • Using average monthly data results in overestimation of optimal tank size • Using a daily time step is estimated to produce more realistic optimal storage volumes • For a single household in Abeokuta, a 7000L was modeled to acheive 100% reliability for a dry year assuming a low demand scenario and no backup water supply; a 10000L tank is required to meet 100% reliability under a high demand scenario • Significant potable water savings can be acheived via RWH in Nigeria, even during abnormally dry years
Islam et al. 2010b	Taiwan	• Investigated the potential for emergency water shortage elimination via dual-mode RWH implementation at an elementary school in 2 Taiwan cities - Taipei and Tainan • Dual-mode system consists of storage tank connected to overhead emergency tank, which supplies water for toilet flushing (12L/person/day for 450 people) during potable water shortage • Catchment area assumed to be 85% of total roof area (870m^2) • Modeled with spreadsheet-based behavioral model - run with YAS estimation method	• Optimal tank size was found to be 167m^3 based upon reliability and was estimated to provide 78% and 65% annual reliability for Taipei and Tainan • Optimal tank size provides 100% reliability for emergency shortage periods • System was more reliable for Taipei because it receives rainfall for 9 months per year vs. Tainan's 5 months per year • Economic analysis of the system indicated that RWH implementation was not economical advantageous at current potable water tariff rate (which includes government subsidy for potable water) • If potable water tariff reflected actual water costs, RWH would be feasible up to a storage volume of 200m^3

Table 23, cont. Summary of various studies using models to evaluate RWH system performance.

References	Study Location	Study Details	Key Findings
Kim and Yoo 2009	Korea	• Used a rainfall-runoff model (nonlinear rainfall loss module and linear measured rainwater to effective rainwater module) • Assumed all effective rainwater entered storage tank • Hydrological analyses uses 4 parameters: volumetric storage coefficient, drying rate of catchment, temperature modulation of dry rate, exponential loss parameter • Rainfall and temperature data requires as inputs	• As water demand increases, consumption increases, and number of days with available rainwater decreases • Efficiency of a RWH system is primarily a function of the runoff coefficient of the catchment • Systems with a higher benefit/cost ratio are considered more economically feasible • Low water demands from a system may result in degraded water quality due to increased detention time
Kim et al. 2012	South Kore	• Developed an analytical probabilistic model for simulating RWH systems • Mass balance equations were used for each part of the system (catchment, storage, infiltration) • Exponential distribution functions (cumulative and probability) were used to determine outflow from a system for various combinations of rainwater storage and infiltration facilities	• This study focuses on rainfall-runoff reduction, as opposed to water savings, as provides results for a given return period • Model estimates average runoff reductions achieved with various storage volumes • Good design tool when stormwater runoff mitigation is a primary concern
Liaw and Tsai 2004	Taiwan	• The YAS and YBS methods of simulating a RWH system were compared to determine their impacts on reliability results • 1-, 3-, 5-, 7- and 10-day time steps were compared to determine their impacts on the relationship between storage volume and reliability • Various rainfall record lengths were compared to determine the effect on variation in reliability results • A production theory was applied to aid in the determination of optimal storage volumes for various combinations of roof area and storage capacity for a given volumetric reliability	• The 4 primary parameters influencing the performance of RWH systems are: 1) release rule (YAS vs. YBS) and reliability, 2) time interval used in model, 3) length of precipitation record, and 4) runoff coefficient • The Rv parameter (Table 22) is more appropriate for estimating reliability than Re • The YBS method is recommended vs. YAS rule • As rainfall record increases, variation in the Rv parameter decreases and accuracy of performance simulation is improved • Differences in results for various time intervals decreases as storage volume increases; therefore, shorter time intervals should be used when storage volumes are small • RWH systems with smaller storage volumes are more sensitive to changes in runoff coefficients than those with larger storage volumes • For a given reliability, the catchment area increases as the storage volume decreases • The optimal point for a given reliability can be determined from the catchment area-storage capacity/reliability curve and the cost function • RWH systems should be designed to meet both hydrologic and economic criteria

Table 23, cont. Summary of various studies using models to evaluate RWH system performance.

References	Study Location	Study Details	Key Findings
Mun and Han 2012	Korea	• A water balance design model is applied to an existing RWH system to verify model accuracy • The operational and design parameters affecting the performance of a RWH system are investigated	• Primary design parameters affecting performance of RWH systems: rainfall, catchment area, tank volume, water demand and efficiency of rainwater collection • Operational parameters describing RWH system performance: rainwater use efficiency (RUE), water savings efficiency (WSE) and cycle number (Table 22) • A storage volume of 0.1*V/A (tank volume/catchment area) is recommended for regions experiencing frequent water shortages • The optimal storage volume is determined by comparing the rate of change in RUE to the increase in V/A values; recommended ranges of change in RUE values are given for combinations of V/A and D/A (water demand/catchment area) values • This design evaluation method was validated using monitoring data from an existing system • Expanding rainwater uses is recommended to improve RUE at little additional expense • This method can be applied to other locations using site-specific rainfall and design parameters
Palla et al. 2011	Italy	• Used behavioral model, daily time step (see Table 21) • 30 theoretical water demand/storage volume combinations (3 demand scenarios, 10 storage scenarios) were simulated for 3 precipitation regimes • Water demand was toilet flushing; 3 scenarios tested were low, medium and high occupancy households	• Demand fraction (annual water demand÷annual inflow) is primary controller of system performance (water savings efficiency and overflow ratio, see Table 22) • When demand fraction = 1, performance can be optimized via adjustment of storage volume • Sizing adjustments will have minimal impact at higher demand fractions (demand never fully met) and lower fractions (overflows not limited) • Precipitation characteristics have minimal effect on system performance • Detention time is a function of storage fraction (system storage volume÷annual inflow) and impacts water quality (longer storage fraction = worsening water quality); 2-4 days is ideal • The optimal RWH system has a demand fraction near 1 and a low storage fraction (0.02-0.04)

Table 23, cont. Summary of various studies using models to evaluate RWH system performance.

References	Study Location	Study Details	Key Findings
Palla et al. 2012	Italy	• Behavioral model was applied to 46 RWH systems under various climatic and operation conditions • Model is based upon daily water balance equations and YAS method • Water demand - toilet flushing at a constant daily rate • Non-dimensional parameters were used to compare performance of systems: demand fraction (annual demand÷annual inflow) and storage fraction (storage capacity÷annual inflow) • The effect of rainfall characteristics on system performance was investigated to determine the primary variables affecting system design; water savings efficiency and detention time are used to evaluate performance (Table 22)	• Cold and humid temperature zones produce the highest quantitative performance due to frequent rainfall and moderate inter-annual variability • As rainfall frequency decreases, the water savings efficiency decreases (especially for systems with storage fractions below 0.1) • Storage fractions greater than 0.1 (usually for systems that are large enough to meet at least the monthly demand) result in a decreased effect of rainfall characteristics on system performance • Antecedent dry weather period is significantly correlated to system performance - moderate ADWPs maximize quantitative performance • Long ADWPs increase water quality of stored rainwater due to longer detention times • In locations with long ADWPs, an increase in storage volume can maximize water savings efficiency while minimizing detention time
Rahmen et al. 2010	Australia	• A continuous simulation daily water balance model was developed and applied to two thoeretical multi-story residential buildings with catchment areas of 800m^2 and 1600m^2 • 3 floor arrangements were analyzed: 1) 4 floors, 16 apartments, 48 people, 2) 6 floors, 24 apartments, 72 people, and 3) 8 floors, 32 apartments, 96 people • 60-year historic rainfall record was used • Water demands: toilet flushing, laundry, irrigation, car washing • Irrigation demand was assumed to vary based upon rainfall conditions: 1) if it rained for 1 day, no irrigation would occur on that day but would resume the next day, 2) if it rained 1-7 days, no irrigation would occur during the rainy days or for the equal number of rainy days after rain ceased, and 3) if it rained 8-21 days, there would be no irrigation during rainy days or for the equal number of rainy days after rainfall ceased, up to a total of 7 days • Compared 2 approaches: Building Sustainability Index (BASIX) and non-BASIX (BASIX approach includes water efficient applieables, dual flush toilets and native, low-water-use landscaping)	• Indoor water demand increased as the number of floors increased • Outdoor water demand increased as the site area increased • As catcment area increases, backup water volume decreased • Backup water volumes increased as the number of floors increased • Water usage with the BASIX and non-BASIX approach varied greatly, predominantly due to the use of water efficient appliances (for indoor usage) and mulching and fertilizer effects (for outdoor usage) • Backup water volumes were 3-4 times higher for the non-BASIX approach compared to the BASIX approach • The BASIX approach had a larger reliability than the non-BASIX approach because water availability increases when water demand decreases

Table 23, cont. Summary of various studies using models to evaluate RWH system performance.

References	Study Location	Study Details	Key Findings
Su et al. 2009	Taiwan	• A continuous simulation model was developed to analyze the probabilistic relationships between RWH storage volumes and water supply deficit rates • Mass balance equations were used in the model to simulate hydrologic operation • Fifty years of daily rainfall data were used for model applications • Probability density functions were created for deficit rates for each storage volume; these PDFs were used to create cumulative probability density functions (CDFs) which were used to construct exceedence probability (EP) curves • The model was applied to evaluate the feasibility of meeting toilet flushing demands with a RWH system as a single building in Taipei	• Using the EP curves, a designer can choose an EP of failure and determine an optimal storage volume for a preset deficit rate • Average water supply deficit decreases and water supply increases as the storage volume increases; however, there is a threshold above which there is no more improvement with increasing volume due to local hydrological conditions (in this study that threshold was 90m^3) - this is essentially the 'upper limit' on water supply improvement that can be provided via the RWH system • As storage volume increases, the economic efficiency of the RWH system decreases
Vieritz et al. 2007	Australia	• Applied TANK model (Table 21) to Brisbane, Australia for 1889-2005 • Storage volume of tank = 5000L • Catchment area ranged from 50-250m^2, assumed catch loss of 20% • Used combination of internal and external water uses	• YAS vs. YBS can have significant effect on results, especially for storage volumes larger than 3000L • A larger water demand results in greater rainwater yield • Rainwater yields will not increase substantially when storage volume increases if connected to small roof areas
Ward et al. 2010b	Exeter, UK	• RainCycle model (Table 21) applied to two case studies • Case study 1: office building in Exeter, UK, single building feeds RWH system, water used to flush toilets, approx. 300 people, 1500m^2 catchment area, 25m^3 storage volume • Case study 2: housing development in Bude, UK, community RWH system, water used to flush toilets, approx. 415 people 3900m^2 catchment area, 255m^3 storage volume • 3 system design methods analyzed: 1) YAS continuous simualtion, 2) days of storage multiplied by average daily demand to get storage volume, and 3) rule-of-thumb method based upon a user-defined percentage of average annual rainfall or demand, whichever is lower.	• YAS method provided most accurate, conservative results compared to YBS for both daily and hourly time steps • Estimated storage volumes are often larger than necessary due to inaccurate estimates of catchment and collection efficiency • Estimation methods (#2 and #3) required larger storage volumes than continuous simulation method (#1) • Continuous simulation method provides more accurate assessment of cost-benefit anaysis with respect to estimated storage volume for a given water demand • When modeling community RWH systems, modeling as one large systems vs. modeling as separate individual systems can impact storage volumes results • Catchment area can limit the amount of demand met by the RWH systems • Low resolution rainfall data (i.e. monthly data averaged to produce daily or hourly data) can underestimate rainwater yield and cost savings; daily data is ideal

Table 23, cont. Summary of various studies using models to evaluate RWH system performance.

References	Study Location	Study Details	Key Findings
Zhang et al. 2009b	Australia	• Daily water balance model applied to 4 Australian cities with different climates (Melbourne, Perth, Sydney and Darwin) for an 80 year period (1927-2006) • Optimal tank sizes determined by the change in reliability resulting from an increase in size • RWH was used in addition to highly efficient domestic facilities for all case studies • Water demand: flushing toilets	• Darwin had highly-fluctuating rainfall that did not match up well with water demand patterns, resulting in larger optimal storage volume and increased overflow • Sydney had higher, more consistent rainfall and consequently resulted in the highest reduction in potable water use • Melbourne also had consistant rainfall patterns, resulting in smaller optimal storage volume • As rainfall consistency decreased, optimal storage volumes increased
Zhang et al. 2010b	Australia	• AquaCycle model applied to a rural residential development in Cranbook • 3 water demand scenarios were considered: garden irrigation, toilet flushing, toilet flushing & garden irrigation	• Toilet flushing produced the highest volumetric reliability, garden irrigation the second highest, combination of both the lowest • Combination demand reduced potable water use by 25%, garden irrigation reduced it by 20% and toilet flushing reduced it by 12%
Zhou et al. 2010	China	• Monte Carlo technique was used on measured data from Seoul to create rainfall data for a site in Zhoushan with no historical data • RWH model used the resulting precipitation data for simulation by a behavioral model • Various theoretical combinations of storage volume, catchment area and water demand were simulated and analyzed	• Efficiency of a RWH system is a function of annual precipitation, catchment area, storage volume and water demand • The optimal storage volume and catchment area of a system will improve rainwater yields and increase consumption

Coombes and Barry (2007), Coombes et al. (2000) and Rahman et al. (2010) accounted for fluctuating irrigation usage based upon climate and seasonal conditions.

Models can be a valuable tool for designers, allowing them to determine the optimal design characteristics of a RWH system. The use of a model can result in significant improvements in the hydrologic and economic efficiency of a system when compared to one-size-fits-all and rule-of-thumb sizing approaches. The numerous models available (Table 21), combined with the many metrics identified in Table 22 provide designers with countless methods of evaluating system performance. For every combination of catchment area, storage volume, water demand, etc., there are numerous optimal design solutions (Imteaz et al. 2011a); however, the use of various models can help a designer choose the solution that best meets the overall goals and objectives of the system (e.g. potable water savings, stormwater runoff reduction, or backup water supply during water shortages).

Future Research Needs

Future research needs that may serve to improve our understanding of modeling RWH systems are listed below, in no particular order:

- A need exists for more application and testing of existing models (as opposed to the development of new models) to identify needs in research knowledge (Elliot and Trowsdale 2007).
- For individual locations, it would be helpful to identify the precipitation data resolution (hourly, daily, monthly) required for ranges of storage fractions [storage volume÷(roof area x annual rainfall)] to produce results with acceptable accuracy (Fewkes and Butler 2000).
- Further investigation is needed on how differences in storage volumes and system reliability impact potable water suppliers, as most available research is conducted from the customers' viewpoint (Gires and de Gouvello 2009).
- Models are needed that focus on non-residential urban areas to assess potential infrastructure and cost reductions due to the implementation of RWH (Gires and de Gouvello 2009).
- There is still a need for the development of models that focus on the stormwater aspects of RWH systems, including the reduction of stormwater runoff (Kim et al. 2012).

Reducing Potable Water Consumption via Rainwater Harvesting

As one of the primary goals of RWH implementation is to decrease consumption of potable water, many studies have been conducted on the potential potable water savings that can theoretically be achieved via RWH. The use of a detailed behavioral model is not always required or utilized when a study is simply investigating the potential reduction in potable water usage, as opposed to the relationship between design parameters and system performance.

Site-Scale Analyses

Gardner and Vieritz (2010) conducted case studies on two RWH systems in Gold Coast and Brisbane, Australia. A single household was equipped with a 25kL storage tank that was connected to all household taps and appliances. Four years of monitoring data indicated that the RWH system, on average, was able to meet 45% of water demands without a backup supply. As 3 of the 4 years monitored were significantly drier than the Gold Coast's average annual rainfall, it was expected that this value would increase under normal rainfall conditions. The second case study was conducted at a 22-lot residential development where each house was equipped with a 20kL storage tank and all overflows were directed to 2 75kL community backup tanks. During the first 4 years of monitoring, approximately 88% of all water demands were met by harvested rainwater. Again, this monitoring took place during abnormally low-rainfall years, so this number is expected to increase when rainfall is more reflective of normal conditions. These results led Gardner and Vieritz (2010) to conclude that implementing RWH systems with large storage volumes can increase households' self-sufficiency with respect to meeting potable water demands, even during drought periods.

Coombes et al. (1999) conducted a similar study on a residential development in Newcastle, Australia. Figtree Place, a 27-lot development, incorporated many low impact development (LID) practices, including community RWH systems. Each 9-15kL underground system services 4-8 houses and collected rainwater is used for hot water systems and toilet flushing. Based upon preliminary monitoring results, potable water savings of approximately 45% and 65% are expected for internal and total potable water usage, respectively, when compared to development without LID practices. (Coombes et al. 1999).

Vialle et al. (2012) evaluated the potential for reducing potable water demand when RWH was used for flushing toilets in a 4-person private household in France. A 5m^3 tank was employed to meet a demand of approximately 30L/day by collected rainwater from a 204m^2 roof. During a 1-year monitoring period, a total of 48,239L was used to flush toilets. Approximately 87% of this demand was met by the RWH system. Monthly water saving efficiency values ranged from 52% to 100%. These results indicated that a RWH system can successfully reduce potable water consumption for a single household when used to flush toilets (Vialle et al. 2012).

A residence hall at Emory University was equipped with a 336,900L storage tank, 60,600L of which was used to meet toilet flushing demands for the building (Lynch and Dietsch 2010). This system was estimated to meet 89% of the hall's annual toilet flushing demand, saving the University over 2.5 million liters of potable water per year (Lynch and Dietsch 2010). Another residence hall was equipped with a 565,000L RWH system that was used for stormwater runoff mitigation and irrigation of a green roof and the surrounding landscape. Sized to meet irrigation demands for a 2-week drought period, this system is likely to save a tremendous amount of potable water as well (Lynch and Dietsch 2010).

Municipal-Scale Analyses

Abdulla and Al-Shareef (2009) conducted a study to evaluate the potential potable water savings if RWH was implemented in the residential portions of each of Jordan's 12 governorates. Data were collected for the following variables: rainfall, sources of potable water, annual water demand, population numbers, number and type of dwellings within each governorate and average area of each dwelling type. The volume of rainwater that could be potentially harvested annually was estimated by multiplying the annual rainfall depth by the total roof area within the municipality. A runoff coefficient of 0.8 was applied to the total volume, as it was assumed 20% of the rainwater was not conveyed to the storage tank. Potential water savings for the 12 governorates in Jordan ranged from 0.27% to 19.7%. The lowest savings potential was associated with the Aqaba governorate, which experiences the lowest annual rainfall and highest per capita demand for water. Assuming rainwater was collected from all dwellings within each governorate, a total of 15.44Mm^3 could be captured each year, which is approximately 5.8% of the total water demand in 2004 and 5.6% of the total demand in 2005. Based upon these results, Abdulla and Al-Shareef (2009) concluded that RWH could substantially supplement current potable water supplies in Jordan.

A study performed by Kim and Furumai (2012) investigated the potential water savings in a residential district of Chiba City, Japan. Chiba City has a total area of 562,000m^2 and a population of 5.518x10^3. Rainfall data were available for the city in 5 minute intervals for a total of 30 years and GIS data were used to classify buildings within the city based on their water usage. A basic mass-balance flow model, InfoWorks™CS, was used to model rainfall/runoff processes. RWH systems were assumed to have storage volumes equivalent to 30mm of rainfall, or 2.1m^3, 4.2m^3, 3.9m^3, 2.1m^3 and 18m^3 for residential houses, offices, commercial buildings, restaurants and public buildings, respectively. Modeling results indicated that rainwater could supply 34% of the total miscellaneous water demand within the city, though the utilization of rainwater was significantly different among the different building types. This finding was corroborated by Mikkelsen et al. (1999), who found that water consumption varied substantially among different types of dwellings.

Domènech and Saurí (2011) used a similar approach to evaluate potential water savings in Sant Cugat del Vallès, a suburb of Barcelona, Spain. GIS data were used to estimate the total area of rooftop surface available for collected rainwater. Twenty years of daily precipitation data were used as inputs to the RainCycle© model described in Table 21. Results from the model showed that if employed, RWH could meet approximately 16% of the municipality's potable water demand. The results also indicated that multi-family buildings often had a greater catchment area to irrigation area ratio, thus allowing a greater percentage of irrigation demands to be met by RWH systems than single-family homes.

Comparable analyses were conducted by Ghisi et al. (2007) in the southeast region of Brazil. A total of 195 cities were analyzed to determine the potential water savings associated with widespread RWH implementation. Rainfall, potable water demand, population numbers, number of dwellings, and roof area data were acquired for each city, and the total volume of rainwater was estimated using the same techniques as Abdulla and Al-Shareef (2009). The overall average potential water savings for the SE region was 41%, with average monthly savings for individual cities ranging from 12%-79%. Higher savings potential generally occurred between October and March when temperatures were warm and rainfall was greater. Furthermore, cities with lower potable water demands usually had a higher potential savings than those cities with higher demands, indicating that average potable water demand is not a good indicator of potential water savings via RWH (Ghisi et al. 2007).

Mikkelsen et al. (1999) estimated the volume of rainwater that could be produced from all building surfaces in Denmark to be approximately 229 million m^3/year. When calculated for households only, this number dropped to 91 million m^3/year. Mikkelsen et al. (1999) noted that the collection ratio (i.e. the amount of available rainwater vs. that actually collected) differed among dwelling types, with apartments having the highest ratio (94%) and detached houses having the lowest (55%). This was due to the difference in water consumption and effective roof area. Apartment buildings generally had a high water consumption relative to effective roof area, while detached houses had a lower consumption and a higher effective roof area. When collection ratios were applied to the volume of rainwater produced by household surfaces the volume decreased by approximately 30% to 64.5 million m^3/year. This could satisfy approximately 68% of household water demands for toilet flushing and laundry, but only 22% of total household water demand.

Using rainfall, GIS and citizen survey data, Lange et al. (2012) estimated the amount of rainfall that could be collected from household roofs during the drought and average rainfall seasons in the city of Ramallah, Palestinian Authority. Approximately 118,000m^3 and 298,000m^3 of rainfall could be collected in Ramallah during drought and average rainfall seasons, respectfully. Lange et al. (2012) extrapolated the study to the Lower Jordan River Basin, which includes portions of Israel, Jordan and Palestinian Authority and encompasses 9,379km^2. It was estimated that 3.04 million m^3 and 19.77 million m^3 of rainwater could be collected from household roofs during drought and average seasons, respectively. Water consumption data were not included in this study, so it was unknown how much the potable water demand could be reduced through the use of RWH.

Conclusions and Recommendations

Results from site-scale and regional-scale studies differed substantially in the estimated reduction of potable water demand due to RWH implementation. Site-scale studies produced substantially higher estimates of the amount of potable water demand that could be met with collected rainwater, with values ranging from 45% to 89% (Gardner and Vieritz 2010; Coombes et al. 1999; Vialle et al. 2012; Lynch and Dietsch 2010). Replacement values for regional- or municipal-scale RWH implementation ranged from 5.6% to 68% and varied based upon the type of water demand being met (toilet flushing demand vs. total water demand) (Abdulla and Al-Shareef 2009; Kim and Furumai 2012; Domènech and Saurí 2011; Ghisi et al. 2007; Mikkelsen et al. 1999).

The amount of rainwater that can be potentially harvested from a given site is dependent upon many factors, including available roof area, capture efficiency from the catchment area (i.e. runoff coefficient), rainfall depth and variability, water usage volume and patterns, and storage volume of the system (Aladenola and Adeboye 2010; Ghisi et al. 2007; Abdulla and Al-Shareef 2009; Kim and Furumai 2012). Thus, the substantial variation among study results is not surprising. Results from site-scale studies indicate that RWH could potential satisfy a large portion of a building’s water demands, though the extent to which this is feasible is governed by specific design, operational and environmental conditions (Palla et al. 2012; Gardner and Vieritz 2010). Results from regional studies were less promising, but in areas with favorable rainfall characteristics (low variability and high annual rainfall) and lower water demands, RWH could substantially supplement potable water supplies. In areas without these favorable conditions, RWH is not a likely source of water demand reduction. Zhang et al. (2009a) concluded that RWH could not meet a substantial fraction of potable water demand in Beijing, China due to its high population density (high water demands and relatively low effective roof area) and highly variable rainfall. Similarly, Han and Ki (2010) stated that potable water demand reduction via RWH was not feasible in Korea due to highly variable rainfall patterns.

Kim and Furumai (2012) pointed out the need for well-defined, detailed information when evaluating the potable water reduction potential associated with RWH implementation. The modeling section in this document supports this claim, as there are many factors affecting RWH system performance. Detailed modeling exercises for large-scale studies require tremendous resources, computing power, time and effort, which is most likely the reason for their scarcity. Thus, general, broader studies on widespread RWH implementation, such as those presented herein, are important in evaluating the potential water supply benefits; however, they must be interpreted with caution, as the majority used low resolution data and broad assumptions or extrapolation procedures to arrive at their conclusions. Furthermore, economic implications of widespread RWH implementation should not be neglected. A later section covers this topic in detail.

Economic and Social Aspects of Rainwater Harvesting

The implementation and operation of RWH systems are not just controlled by physical and environmental parameters; economic and social aspects of these systems play a major role in their adoption and use. This section discusses the economic implications of RWH implementation at both the site- and regional-scale, social perceptions of RWH and how they impact implementation and use, and the environmental and energy impacts of constructing and using these systems.

The majority of issues hindering RWH implementation involve the economic viability and public perception of RWH systems (Fewkes and Warm 2000). In a survey of Canadian residents, most participants felt that an overall indifference to water conservation was a substantial impediment to RWH use (Leidl et al. 2010). Ward et al. (2010) cited the lack of information regarding system design and sizing and cost effectiveness of systems as the primary reasons for people choosing not to implement RWH. Abdel-Shafy et al. (2010) stated that a lack of public awareness and professional marketing have caused RWH opportunities in Egypt to be neglected. High capital costs, liability concerns, restrictions on end uses of harvested water and lack of environmental commitment among citizens have also been noted as barriers to RWH adoption (Leidl et al. 2010). It is apparent that the economic and social aspects of RWH systems are crucial components of implementation and must be understood and addressed appropriately.

Economic Considerations

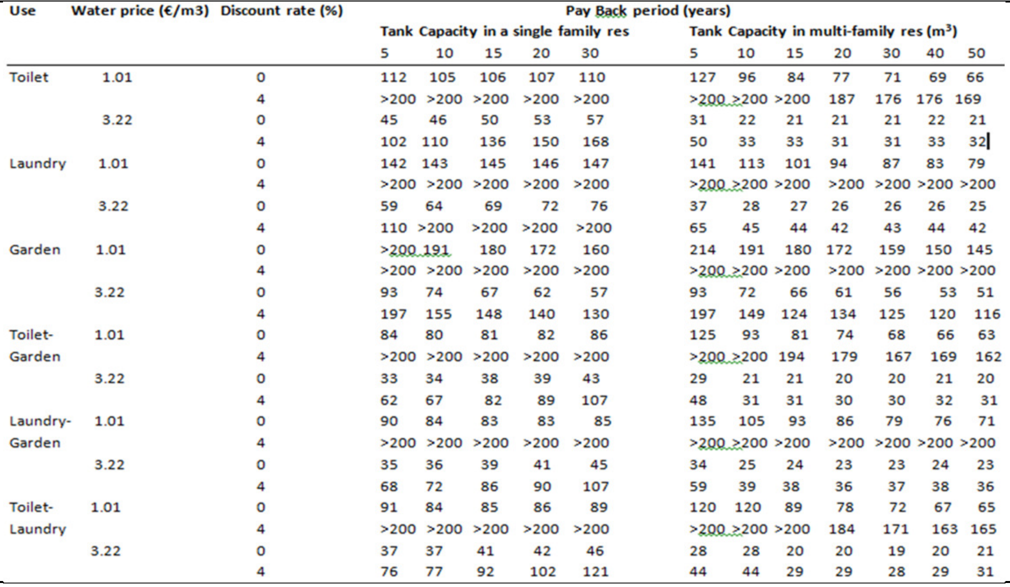
The majority of studies conducted on the economic aspects of RWH concluded that it is not economically advantageous when compared to existing potable water supplies (Kim and Yoo 2009; Islam et al. 2010b; Gardner and Vieritz 2010; Mikkelsen et al. 1999). Farreny et al. (2011b) performed a thorough economic analysis on 4 theoretical scenarios involving building- and neighborhood-scale RWH systems, both as new and retrofit construction (Table 24). It was concluded from this study that under current public water prices, none of the 4 scenarios considered were economically advantageous. Building-scale RWH systems were the least cost-effective (for both new and retrofit construction), as financial benefits from the systems never offset the costs. Farreny et al. (2011b) also determined that the neighborhood-scale/new construction scenario was most cost efficient of the 4 scenarios due to a relatively low payback period (27 years), though this conclusion was strongly dependent upon the condition of a small catchment area per dwelling. This supports a common notion that construction costs for retrofitting an existing building with RWH are often higher than when RWH is included as part of a new building (Abdulla and Al-Shareef 2009).

Domènech and Saurí (2011) also found that the financial benefits associated with single-family houses never offset the costs of a RWH system under a low-consumption water rate scenario, verifying conclusions drawn by Farreny et al. (2011b) (Table 24). Higher potable water price scenarios resulted in decreased payback periods (the time it takes for a project's net revenue to equal the capital cost), making community-scale RWH systems economically viable for all water demands except landscape irrigation. A high-consumption water rate scenario improved the cost effectiveness of the building-scale RWH scenario as well, but still yielded rather long payback periods (33-43 years, depending on the storage volume).

Neighborhood- or community-scale RWH systems tend to be more cost effective than building-scale systems. Farreny et al. (2011b) noted a substantial difference in the financial performance of the two scales and asserted that the costs of a RWH system are inversely related to its scale of use. Fletcher et al. (2008) and Mitchell et al. (2005) corroborated this finding as well. Domènech and Saurí (2011) found that RWH users in single family houses often perceived the cost of RWH to be much higher than users in multi-family buildings. This is most likely because the costs of a system in a multi-family building are divided among many families (Domènech and Saurí 2011). Furthermore, users in multi-family buildings were likely less involved in the construction of the system, whereas users in single family homes were more involved and more aware of the costs (Domènech and Saurí 2011).

Mikkelsen et al. (1999) compared the cost of RWH to the costs associated with potable water supplies in Denmark. Costs for RWH were estimated to be DKK 26-83/m^3 for apartment buildings. RWH costs for detached dwellings could potentially be as low as DKK 10/m^3, but only if the collection system was homemade. Compared to the production and total costs (including taxes and wastewater fees) of DKK 1-10/m^3 and DKK 35/m^3 for potable water, RWH was not an economically attractive alternative to public water supplies (Mikkelsen et al. 1999). Gardner and Vieritz (2010) also found that the cost of RWH was consistently higher than current public water sources. Optimizing storage volumes, decreasing capital costs (ex. not using a pump) or increasing potable water yields from RWH systems would decrease the costs per kL, though it is still unlikely to make RWH a competitive alternative with current potable water prices. RWH was, however, found to be economically competitive with newer urban supply options, such as desalination, potable reuse or dual reticulation and new dam construction (Gardner and Vieritz 2010).

Table 24. Summary of details and results for studies evaluating the cost effectiveness of RWH.

Alam et al. 2012	**Study Details**	• Compared the cost of RWH, conventional public water supply and private water supply in Sylhet City, Bangladesh • Assumed water demand of 25L/day • Assumed lifespan of ferrocement storage tank is 15 years
	Study Results	-----------------RWH System----------------- Construction cost: TK 6,000 Maintenance costs: TK 200/year Economic life: 15 years Total cost: TK 8,800 Annual cost: TK 587/year Cost per L: TK 0.06/L -----------Conventional Supply----------- Connection cost: TK 7,000 Water costs: Tk 0.15-0.25/L Total cost: TK 28,352 Annual cost: TK 1890/year Cost per L: TK 0.15/L ----------------Private Supply---------------- Pump installation cost: TK 6,000 Total cost: TK 37,929 Annual cost: TK 2,529/year Cost per L: TK 0.27/L
Domènech and Saurí 2011	**Study Details**	• The cost effectiveness of RWH in Sant Cugat del Vallès is analyzed using 2 existing RWH system (a single family system and a community system) • RainCycle model was used to simulate water savings potential for 20 year period • Social discount rate of 0% assumed • 2 discount rates considered: 0% and 4% • Payback period is used to determine cost effectiveness • Costs of gutter and downspouts were neglected • Maintenance costs assumed to be 50 euro per year (an additional 300€ per year assumed for multi-family buildings) • Annuall inflation rate of 3% used for maintenance costs and electricity costs; 4% annual increase rate used for water rates • Two water rate scenarios considered: low-medium consumption rate of 1.01€/m^3 and high consumption rate of 3.22€/m^3 • Multiple storage volumes considered: 5, 10, 15, 20, 30 m^3
Domènech and Saurí 2011	**Study Results**	

Use	Water price (€/m3)	Discount rate (%)	Pay Back period (years)											
			Tank Capacity in a single family res					Tank Capacity in multi-family res (m^3)						
			5	10	15	20	30	5	10	15	20	30	40	50
Toilet	1.01	0	112	105	106	107	110	127	96	84	77	71	69	66
		4	>200	>200	>200	>200	>200	>200	>200	>200	187	176	176	169
	3.22	0	45	46	50	53	57	31	22	21	21	21	22	21
		4	102	110	136	150	168	50	33	33	31	31	33	32
Laundry	1.01	0	142	143	145	146	147	141	113	101	94	87	83	79
		4	>200	>200	>200	>200	>200	>200	>200	>200	>200	>200	>200	>200
	3.22	0	59	64	69	72	76	37	28	27	26	26	26	25
		4	110	>200	>200	>200	>200	65	45	44	42	43	44	42
Garden	1.01	0	>200	191	180	172	160	214	191	180	172	159	150	145
		4	>200	>200	>200	>200	>200	>200	>200	>200	>200	>200	>200	>200
	3.22	0	93	74	67	62	57	93	72	66	61	56	53	51
		4	197	155	148	140	130	197	149	124	134	125	120	116
Toilet-Garden	1.01	0	84	80	81	82	86	125	93	81	74	68	66	63
		4	>200	>200	>200	>200	>200	>200	>200	194	179	167	169	162
	3.22	0	33	34	38	39	43	29	21	21	20	20	21	20
		4	62	67	82	89	107	48	31	31	30	30	32	31
Laundry-Garden	1.01	0	90	84	83	83	85	135	105	93	86	79	76	71
		4	>200	>200	>200	>200	>200	>200	>200	>200	>200	>200	>200	>200
	3.22	0	35	36	39	41	45	34	25	24	23	23	24	23
		4	68	72	86	90	107	59	39	38	36	37	38	36
Toilet-Laundry	1.01	0	91	84	85	86	89	120	120	89	78	72	67	65
		4	>200	>200	>200	>200	>200	>200	>200	>200	184	171	163	165
	3.22	0	37	37	41	42	46	28	28	20	20	19	20	21
		4	76	77	92	102	121	44	44	29	29	28	29	31

Table 24, cont. Summary of details and results for studies evaluating the cost effectiveness of RWH.

<table>
<tr><td>Farreny et al. 2011b</td><td>Study Details</td><td>• 2.6-ha neighborhood in high-density urban suburb of Barcelona, Spain
• Study approaches: 1) building-scale, retrofit construction; 2) building-scale, new construction; 3) neighborhood-scale, retrofit construction; 4) neighborhood-scale, new construction
• Neighborhood-scale approaches: 43 multi-story buildings, 558 dwellings, 2.83 people per household, construction involves shared conveyance, storage and distribution
• Building-scale approaches: 5 story building, 10 dwellings, roof area of 125m^2, construction involves conveyance, storage and distribution in each building
• Rainwater collected from roofs only
• Water demandis laundry; 20.5m^3/household/year for building-scale/retrofit scenario and 14.3m^3/household/year for all other scenarios
• Life cycle costing used - net present value and payback period calculated
• Costs (capital, operational and maintenance) and benefits (reduction in supply charges) were considered
• Discount rates of 0% and 3%, discount period of 60 years, no inflation
• Operational costs: electricity for pumping
• Maintenance costs: part replacement - pump (replaced every 15 years), filters (1/2 of filters replaced every 15 years), tank (assumed every 30 years)
• 2 benefit scenarios considered - steady water rate and increasing water rate</td></tr>
<tr><td>Farreny et al. 2011b</td><td>Study Results</td><td><table>
<tr><th></th><th colspan="4">----------Study Approach----------</th></tr>
<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td>Storage Volume (m^3)</td><td>8</td><td>6</td><td>275</td><td>275</td></tr>
<tr><td>Water Demand (m^3/yr)</td><td>205</td><td>143</td><td>8030</td><td>8030</td></tr>
<tr><td>Water Savings (%)</td><td>35.7</td><td>43.9</td><td>43.4</td><td>43.4</td></tr>
<tr><td>Overall Efficiency (%)</td><td>100</td><td>86</td><td>78</td><td>78</td></tr>
<tr><td>Overflow (%)</td><td>0</td><td>14</td><td>22</td><td>22</td></tr>
<tr><td>Empty Tank (days/year)</td><td>256</td><td>223</td><td>226</td><td>226</td></tr>
</table></td></tr>
<tr><td>Gardner and Vieritz 2010</td><td>Study Details</td><td>• Evaluated cost-effectiveness of RWH implementation in Australia
• Average cost of installing a 5kL system as part of new construction: $3150
• Additional expenses estimated to be $20/year over 10-year life span (includes energy costs for pumping, gutter screens, gutter cleaning, screens and filters, tank cleaning, pump maintenance)
• Using a discount rate of 8%, implementation costs calculated to be $2.16/kL and $3.06/kL in Sydney and Adelaide, respectively</td></tr>
</table>

Table 24, cont. Summary of details and results for studies evaluating the cost effectiveness of RWH.

<table>
<tr>
<td rowspan="2">Khastigir and Jayasuriya 2011</td>
<td>Study Details</td>
<td>• Cost effectiveness of RWH investigated in 3 geographical areas of Melbourne, Australia (Werribee, Berwick, Kinglake)
• Daily water balance model used to determine optimal storage volume
• Costs and benefits compared
• Costs include capital investment (cost of tank), installation (costs of accessories), operation and maintenance
• Cost assumptions: 5kL storage tank ($2000), pump ($400), garden plumbing ($400), toilet plumbing ($400), laundry plumbing ($500), concrete tank base ($200), first flush device ($600), gutter guard ($70), operation/maintenance ($100 total)
• Present value cost calculated as the sum of all costs listed above
• Benefits include amount of rebate issued by government
• Parameters calculated to compare cost effectiveness: volume of potable water saved, cost effectiveness ratio (net present value of cost ÷ net present value of effectiveness), payback period, levelized cost (net present value of total capital and operation/maintenance costs converted to equal annual payments)
• Multiple scenarios were investigated: varying tank sizes (1, 3, 5kL), inflation rates (3%, 4.2%, 5%), discount rates(5%, 5-10%) and water rates ($0.9 per kL, $0.9-1.4 per kL)
• Water demands: toilets, laundry, garden</td>
</tr>
<tr>
<td>Study Results</td>
<td>Water Savings (kL/year):
<table>
<tr><th></th><th colspan="3">-------Werribee-------</th><th colspan="3">-------Berwick-------</th><th colspan="3">-------Kinglake-------</th></tr>
<tr><th></th><th>1kL</th><th>3kL</th><th>5kL</th><th>1kL</th><th>3kL</th><th>5kL</th><th>1kL</th><th>3kL</th><th>5kL</th></tr>
<tr><td></td><td>30.6</td><td>44.8</td><td>50.1</td><td>38.8</td><td>53.4</td><td>58.2</td><td>47.3</td><td>61.0</td><td>64.2</td></tr>
</table>
Payback Period (years):
<table>
<tr><th></th><th colspan="3">-------Werribee-------</th><th colspan="3">-------Berwick-------</th><th colspan="3">-------Kinglake-------</th></tr>
<tr><th>Discount Rate</th><th>1kL</th><th>3kL</th><th>5kL</th><th>1kL</th><th>3kL</th><th>5kL</th><th>1kL</th><th>3kL</th><th>5kL</th></tr>
<tr><td>5%</td><td>49</td><td>36</td><td>28</td><td>33</td><td>25</td><td>19</td><td>27</td><td>21</td><td>18</td></tr>
<tr><td>7%</td><td>35</td><td>28</td><td>24</td><td>26</td><td>21</td><td>17</td><td>23</td><td>19</td><td>16</td></tr>
<tr><td>10%</td><td>27</td><td>22</td><td>19</td><td>21</td><td>17</td><td>15</td><td>18</td><td>16</td><td>14</td></tr>
</table>
</td>
</tr>
</table>

Khastigir and Jayasuriya (2010) did not compare the cost of RWH to public water supplies; however, they did investigate relationships between economic and design variables for RWH systems (Table 24). The price of potable water, discount (interest) rate, inflation rate and amount of rainfall were found to influence the payback period of a RWH system. As the rainfall amount increased, the payback period decreased, as less potable water was utilized; thus, RWH may be more economically feasible in areas with greater rainfall. Furthermore, the payback period for a given system decreased as the public water price increased, the inflation rate decreased, or the discount rate increased. These results highlight the important of selecting the optimal storage volume when designing RWH systems (especially in areas with low rainfall), as this will maximize the use of rainwater and minimize costs associated with the system, thus increasing its economic viability (Khastigir and Jayasuriya 2010).

Findings by Alam et al. (2012) and Herrmann and Hasse (1997) contradicted those previously discussed. Alam et al. (2012) compared the price of water supplied by RWH, conventional public water supplies and private water supplies in Sylhet City, Bangladesh (Table 24). The conventional and private sources of water were found to be 3 and 4.5 times more expensive than RWH, leading to the conclusion that RWH was an economically advantageous alternative to other water supply sources. It is anticipated that these results are applicable only to the unique site and situation described in the Alam et al. (2012) study. Hermann and Hasse (1997) concluded that local RWH systems were a more economically efficient method of solving the Oberfranken, Germany water crisis than the establishment of a long-distance water supply, though this is the only study found that compared RWH to the construction of a long-distance, high-capacity pipeline.

Government rebates and subsidies on potable water can potentially decrease the economic favorability of RWH systems; however, subsidies and rebates on the implementation of RWH increases the feasibility and cost effectiveness of these systems. Islam et al. (2010b) demonstrated that a RWH system with an optimal storage volume was not a cost effective option in Taipei, Taiwan given current construction costs and tariff rates. The current tariff rates do not reflect the actual price of water due to government subsidies, a common incidence with public water supplies. If the water price reflected the actual cost of water production, RWH would be economically feasible in Taipei for storage volumes up to 200m^3. If water prices were not altered, a government subsidy of 55% for the construction of a RWH system would be needed to make storage volumes up to 170m^3 cost effective (Islam et al. 2010b).

Social Perceptions

While economic aspects of RWH systems might be the primary issue influencing implementation, social attitudes and acceptability are important factors as well (Tam et al. 2010, Gardiner 2010). Gardiner (2010) identified and interviewed a total of 1,050 residents of South East Queensland, Australia. The residents belonged to 1 of 5 groups: 1) rural areas with RWH as sole source of water, 2) rebate-subsidized, retrofit RWH in urban areas, 3) development where RWH was required as part of new construction, 4) development that required retrofit systems to be installed for toilet flushing and laundry, and 5) development that required retrofit systems with optional internal connections.

Citizens that were required to install RWH systems possessed an attitude of indifference towards the system, while voluntary users viewed the system as a valuable resource. Consequently, owners of regulatory-required systems were less engaged with the system and less knowledgeable of its operational aspects than voluntary users. Usage patterns differed among systems with internal plumbing connections and those without, even if both groups were required to install the systems. Usage patterns of systems without internal connections were similar to those of voluntarily-installed systems, where collected water was more often used for discretionary purposes such as irrigation and car washing. Users of internally connected systems were also less likely to have an intimate knowledge of the system's operation and design, and often viewed the system as part of the overall plumbing infrastructure of the house (as opposed to an independent supply of water). (Gardiner 2010)

Gardiner (2010) identified 3 attitudinal groups among RWH owners: 1) environmentalists, 2) indifferent attitude and 3) viewed system as a personal, independent supply of water. A 2008 survey of 451 system owners investigated the underlying demographics, motivations and attitudes among these 3 groups and found substantial differences (Table 25). The majority of users that belonged to group 2 were new home builders or recently bought a house with an existing RWH system. This group did not see RWH as an asset or a personal resource, yet often saw RWH as a valuable community response to drought conditions. Members of group 3 highly valued their RWH systems and viewed it as a means of obtaining a non-regulated, independent water supply. (Gardiner 2010)

Gabe et al. (2012) found similar results regarding attitudes and behaviors among RWH users. Fourteen New Zealand residents were interviewed, all of which had recently applied for a RWH permit due to new regulations. Six of these residents used RWH as their only source of water, while the remaining 8 used rainwater for toilet flushing, outdoor irrigation and laundry only. The sole-supply users had to purchase potable water in the event of a dry system, while the dual-water users had a built-in backup supply. A substantial difference in perception among the two groups involved the monetary benefits of RWH (Gabe et al. 2012). Sole-supply users were exempted from water rates and felt RWH was a cost effective alternative to public water supplies. Dual-supply users did not receive rate exemptions and often felt that RWH was more expensive to maintain and operate. Sole-supply users were more careful with their use of water and generally perceived the need for purchasing backup water to be due to poor management or system failure. Members of both groups identified the freedom and environmental stewardship as benefits of employing RWH. Additionally, both groups valued the presence of their systems during potable water shortages or supply system failures. (Gabe et al. 2012)

Jones and Hunt (2010) identified public perception as one of the largest impacts that must be overcome when implementing RWH in humid regions. Despite persistent drought conditions in North Carolina, Jones and Hunt (2010) reported very little usage from retrofitted RWH systems. Habitual behavior was a substantial factor in the lack of usage, as users continued to use potable water sources even though ample rainwater was available from the RWH system. DeBusk et al. (2013) compared usage patterns in humid and arid regions and revealed that systems installed in humid regions are often used seasonally or periodically, resulting in less overall usage than systems in arid regions. DeBusk et al. (2013) suggested the establishment of secondary objectives, such as stormwater manamagent, for RWH systems in humid regions to improve their cost effectiveness and efficiency.

Energy Consumption and Environmental Impacts

Kenway et al. (2008) reported potable water specific energy rates of 0.07kWh/kL and 1.9kWh/kL for Brisbane and Adelaide, Australia, respectively. Contrarily, estimated energy rates for a community-scale RWH system with UV disinfection in Brisbane were 5kWh/kL. Hood et al. (2010) found energy rates for a sustainable development in the Gold Coast, to be 1.3 kWh/kL. Note that this development employed numerous water and energy conservation measures and did not include disinfection in the RWH systems, resulting rates lower than the Brisbane system (Hood et al. 2010). Based upon these results, it is apparent that the energy consumption associated with RWH implementation is greater than that of existing public water supplies; however, in areas using more energy-intensive methods of water production, it is possible that RWH may be more energy efficient. For example, Hall et al. (2009) found the rate for widespread implementation of household-scale RWH systems in South East Queensland to be comparable to that of a nearby reverse osmosis desalination plant.

Table 25. Common characteristics of 3 attitudinal groups with respect to RWH (Gardiner 2010).

	Environmentalists (25%)	**"Not Really Interested" (31%)**	**"My Independent Supply" (44%)**
Demographics	• Retrofitters • Lived in house >10 years	• Mandated tanks, internal connections • Under age 40 • Lived in house <3 years	• Retrofitters • Over age 50
Behaviors	• Would install RWH in new dwelling if they move	• Would not install RWH in new dwelling if they move • Would not pay more for a house with a RWH system	• Would install RWH in new dwelling if they move
Motivations	• Feel water restrictions should be long-term • Pro-legislation	• More likely not to see long-term water restrictions as necessary • Do not perceive need for RWH when there is adequate public water supply	• Against legislation for RWH • RWH allows freedom in gardening • Believe water bills are lower due to RWH
Tank Management	• Tank likely ~1m from house	• Tank likely against house	• Tank likely <3m from house • Like to have >5,000L tank • See no need for internal use of rainwater
Attitudes	• Proud of the RWH system • Careful with water use	• Not confident in system management • Maintenance and inspection of system rarely performed	• Proud of RWH system • Less careful with water use (uses system as if no restrictions exist) • Greater concern of health risks • RWH allows feeling of independence • Sees RWH as private water resource
Other	• Environmentally aware (recycle, compost, etc.)	• Do not regularly recycle, compost	

In addition to energy consumption, there are other environmental consequences associated with RWH. Angrill et al. (2012) performed a life cycle assessment on RWH in a Mediterranean climate to assess the environmental impacts of various construction methods and determine the most environmentally favorable approach. Eight theoretical scenarios were investigated to analyze the effect of 2 variables on environmental impacts: 1) urban density (diffuse vs. compact), and 2) tank location (underground, below-roof, distributed over roof and community-scale). Environmental impacts were assessed for 7 impact categories: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), human toxicity potential (HTP), ozone depletion potential (ODP) and photochemical ozone creation potential (POCP).

The storage component of a RWH system comprised the greatest environmental impacts for the majority of assessment categories for both diffuse and compact density scenarios. This is due primarily to the installation of the storage tank (excavation, construction/production of the tank, structural reinforcements, etc.). The materials stage of the system's life cycle was the greatest contributor of impacts for both density scenarios when compared to the transportation, construction, use and deconstruction stages. In 6 of the 7 assessment categories, the compact density scenario produced less environmental impacts when compared to the diffuse density scenario, with the latter contributing approximately 3 times greater impacts than the former in some categories. (Angrill et al. 2012)

Angrill et al. (2012) determined that the most environmentally favorable design, regardless of urban density, involved the storage tank being distributed over the roof surface. This scenario produces the least environmental impacts due to several reasons: 1) the need for structural support was reduced due to the weight of the storage volume being distributed over the roof surface, 2) catchment components such as gutters, conveyance piping, etc., were not needed, and 3) gravity was used to distribute the collected water to the end uses, as opposed to pumping. When compared to alternative water sources such as conventional distribution networks and alternative technologies, RWH systems with this design could be an environmentally comparable solution. (Angrill et al. 2012).

Conclusions and Recommendations

The economic benefits of RWH have been heavily studied, with many researchers concluding that RWH is not a cost effective alternative to existing potable water supplies (Kim and Yoo 2009; Islam et al. 2010b; Gardner and Vieritz 2010; Mikkelsen et al. 1999). This is often due to the presence of government subsidies on public water supplies, which decrease the amount consumers must pay for potable water (Islam et al. 2010b; Kim and Yoo 2009; Leidl et al. 2010). It is unlikely that RWH will be a financially advantageous source of water until the price of potable water is increased to more closely reflect the actual price of water production (Kim and Yoo 2009; Rahman et al. 2010; Farreny et al. 2011b; Domènech and Saurí 2011). Kim and Yoo (2009) estimated the price of water must be 5 times higher than current rates to warrant the implementation of RWH. Perhaps the inclusion of external benefits, such as the deferment of water infrastructure needs, social impacts, stormwater mitigation and other non-monetized impacts, in economic analyses would improve RWH's relative performance when compared to existing water supply sources (Farreny et al. 2011b; Gardner and Vieritz 2010; DeBusk et al. 2013).

The numerous scenarios under which RWH can be implemented make it difficult to draw broad conclusions regarding the economic benefits. The type of construction (retrofit vs. new), design variations (tank placement, size of storage tank, materials used, treatment methods), cost differences (relative cost of materials between different locations, monetary exchange rates) and analysis methods (in/exclusion of certain system aspects, underlying assumptions, discount and interest rate variations, life span variations) can have substantial impacts on the results of an economic analysis. As such, caution should be used when interpreting and applying results. If possible, site-specific analyses should be conducted when RWH implementation is being considered to ensure assumptions and variables reflect the actual conditions of the site as much as possible.

To date, the majority of RWH systems have been designed to meet potable water reduction goals. Consequently, energy rates and environmental impacts associated with these systems are often larger than those of alternative water sources (Gardner and Vieritz 2010; Angrill et al. 2012). As the implementation of RWH increases and technologies improve, it is likely that more emphasis will placed on reducing the energy consumption and environmental impacts of these systems. To facilitate this transformation, further research is needed to determine how these variables differ among various design and operational scenarios.

Numerous benefits associated with RWH have been identified by the majority of users, including independence from the public water supply system, water supply insurance in the event of a water shortage or potable system failure, environmental stewardship, and the reduction in potable water usage; however, there is a substantial difference in opinion among people voluntarily using RWH and those who are required to use it via government mandates and individual attitudes have been shown to play an important role in how systems are used and maintained (Gardiner 2010; Gabe et al. 2012; White, 2010). Gardiner (2010) stated that RWH users tend to view their systems in one of three ways:

1. A personal water supply, independent of the public water source and exempt from water use regulations,
2. A form of environmental stewardship that reduces their burden on the public water supply system, or
3. An extension of the public water infrastructure, necessary only during times of drought or supply system failure.

Voluntary RWH users are generally associated with the first or second viewpoint, while many mandated users are best described by the third (Gardiner 2010). These attitudinal differences result in distinctive water usage patterns and system management practices (Gardiner 2010). Given the current low prices for potable water, it is possible that those viewing RWH as only a temporary method of enduring potable water restrictions will neglect their systems once restrictions are lifted (Gardiner 2010). It is apparent that a change in the way these people view RWH is essential to facilitate widespread implementation, improve the ecological sustainability of urban areas and increase the resilience of potable water supplies in the face of global climate change (Domènech and Saurí 2011).

Future Research Needs

Future research needs that may serve to improve our understanding of the economic and social aspects of RWH systems are listed below, in no particular order:

- Economic analyses on RWH systems should be expanded to include externalities such as long-term infrastructure impacts and stormwater mitigation (Farreny et al. 2011b).
- Neighborhood-scale systems should be further investigated to identify administrative obstacles hindering implementation (Farreny et al. 2011b).
- Research should be conducted to investigate planning procedures and legal frameworks that can be adopted to facilitate RWH implementation into current and future urbanization schemes (Farreny et al. 2011b).
- Comparative studies are needed to analyze the strengths and weaknesses of various alternative water sources to facilitate the development of effective policies to promote RWH (Domènech and Saurí 2011).

- Further research is needed on the energy consumption and social perceptions of mandated RWH systems (Gardner and Vieritz 2010).
- Other aspects of RWH systems that should be further analyzed include: 1) energy savings via thermal regulation provided by storage tanks distributed across the roof surface, 2) an analysis of RWH systems that incorporate social and economic factors, 3) a comparison of environmental impacts between RWH and various water supply technologies, and 4) a comparison of impacts between RWH strategies for new and existing buildings (Angrill et al. 2012).

Stormwater Management and Rainwater Harvesting

RWH systems can be effective tools for managing stormwater runoff. They can reduce the volume and rate of stormwater entering the storm sewer network by intercepting and storing runoff from catchment areas (Basinger et al. 2010; Zhang et al. 2009a; Zhang et al. 2009b; Ahmed et al. 2011a; Fewkes and Warm 2000; Guo and Baetz 2007; Kim et al. 2012). This section discusses models for RWH systems that incorporate stormwater management components and design modifications that may improve the mitigation potential of these systems.

Stormwater Modeling Tools

Mitchell et al. (2008) developed the Reuse Analysis Tool (RAT) behavioral model that simulates the inflows, outflows, and storage behavior of a RWH system based upon rainfall-runoff relationships. RAT incorporates the rainfall-runoff calculations from Model for Urban Stormwater Improvement Conceptualisation (MUSIC), an existing model commonly used for stormwater analyses in Australia. Runoff data generated from the MUSIC model serves as the inflow to the behavioral portion of RAT. Continuous simulations route the inflow through the RWH storage tank via mass balance equations and determine outflow from the system. The primary difference between RAT and the other RWH models previously discussed is the incorporation of a rainfall-runoff component. This allows users to apply RWH to catchment areas other than roof surfaces and estimate the stormwater mitigation benefits from a given scenario. (Mitchell et al. 2008)

Graddon et al. (2011) combined two modeling environments, urbanCycle and urbanNet, to create a powerful model capable of simulating water quality, various supply/demand scenarios, storage and treatment requirements, water recycling and effects of usage restrictions, to name a few. The urbanCycle portion of the model utilizes hierarchal networks that can simulate RWH implementation at the building- or neighborhood-scale. urbanNet balances supply and demands and simulates storage behavior through the use of linear programming. Together, these two models can simulate an infinite number of RWH scenarios (including multiple spatial scales, non-rooftop catchment areas, prioritized demand and supply, wastewater incorporation and many more) and allow designers to optimize system design based upon various user-defined goals). (Graddon et al. 2011)

The model developed by Jones and Hunt (2010) only simulates a rooftop catchment area, but calculates model outputs that can be useful for determining the stormwater management benefits of a building-scale RWH system, including total volume captured, overflow frequency, first flush volume captured and annual nitrogen removed. The total volume captured parameter indicates what percentage of the total annual runoff generated by the catchment area is captured by the RWH system. This is the volume that is kept from entering the stormwater network during a precipitation event. The first flush volume is the amount of runoff corresponding to the poorest water quality, usually the first 1” of rainfall. The percentage of this volume captured is a good stormwater quality variable, as this water is not being released to the storm sewer but being captured and treated by the RWH system. Overflow frequency is defined as the percentage of rainfall events that exceed the capacity of the storage volume. This aspect of the system can be a design consideration when stormwater mitigation is priority. Finally, the model generates the annual mass of nitrogen removed, which is estimated by multiplying the average nitrogen concentration in roof runoff by the volume of runoff captured by the system. Again, this is a good water quality indicator for stormwater management, as that amount of nitrogen is bypassing the stormwater system and receiving treatment by the RWH system. (Jones and Hunt 2010)

Designing for Optimal Stormwater Mitigation

As stated by DeBusk et al. (2013), in order for a RWH system to provide stormwater mitigation, there must be room within the storage tank to capture runoff from a precipitation event. Otherwise, this water leaves the system as overflow which provides no volume or peak flow rate reductions. There are several design techniques that can be employed to increase the stormwater mitigation potential (maximize capture efficiency and minimize overflow) of these systems, including dual storage, infiltration facilities and usage revisions.

Hermann and Schmida (1999) and Brodie (2008) both discuss the incorporation of dual storage facilities into RWH systems to increase capture efficiency and stormwater mitigation. Dual storage can be created by dividing a storage tank into two portions, designated as the detention storage volume and retention storage volume. The retention storage volume comprises the bottom portion of the storage tank and water is extracted from this section to meet user demands. The detention storage volume comprises the top portion of the storage tank and serves as a temporary holding space for runoff. The two storage volumes are separated by a small orifice that allows the water in the detention portion to slowly drain out between rain events. With this design the detention storage is often emptied prior to the next rain event, allowing the RWH system to reliably capture runoff from a large percentage of rain events. (Hermann and Schmida 1999; Brodie 2008).

Infiltration facilities (such as infiltration trenches, French drains, or bioretention cells) can be added to a RWH system to collect overflow, first flush diversion or dual storage release water (Hermann and Schmida 1999; Kim and Yoo 2009; Kim et al. 2012). In this context, infiltration practices accept, treat and infiltrate water than would otherwise enter the storm sewer network. Benefits from their inclusion in RWH systems include groundwater recharge, restoration of the hydrologic cycle in urban environments, water quality improvement, runoff volume reduction and peak flow mitigation. Although they require favorable soils and sufficient space, infiltration facilities can substantially increase the capture efficiency and stormwater mitigation potential of a RWH system.

Modifying or increasing usage of harvested rainwater can increase the stormwater mitigation potential of RWH systems. Having multiple usage demands ensures a continuous use of water, thereby maximizing rainfall capture by creating more room in the storage tank for upcoming rain events (Gardner and Vieritz 2010; Domènech and Saurí). Incorporating demands that align with local rainfall patterns can substantially increase the efficiency of the system in terms of both stormwater mitigation and water conservation (Zhang et al. 2009b). Finally, designing RWH systems so that rainwater usage is convenient and automated can maximize capture efficiency in areas where water is not commonly perceived as a limited resource (DeBusk et al. 2013).

Conclusions and Recommendations

RWH systems have great potential in terms of urban stormwater mitigation, but must be designed and operated correctly for this potential to be realized. The modeling tools discussed herein can be used to optimize a RWH system design to meet stormwater objectives (i.e. decrease overflow frequency/volumes and increase runoff capture efficiency). Increasing usage of harvested rainwater is crucial in increasing the stormwater mitigation efficiency of a RWH system. Designating multiple water demands that align with local rainfall patterns, facilitating drainage of the system (or a portion of the system) between rain events and designing the system for convenient, automated use can substantially increase usage of a system. Directing overflow or drainage from the system to an infiltration facility is another way of enabling a system to mitigate runoff volumes and rates. This approach also has the added benefit of groundwater recharge and mitigation of the urban hydrologic cycle.

Future Research Needs

There is very little research on the stormwater management benefits of RWH, as water conservation is often the primary goal of implementation. Fortunately, researchers are starting to identify stormwater management as an ancillary benefit of these practices and modeling tools have been developed to help designers optimize systems for stormwater mitigation. More modeling studies are needed to understand the relationships between design characteristics and usage patterns. Emphasis should be placed upon neighborhood- or community-scale systems to evaluate the effect of widespread RWH implementation on stormwater runoff from a development. Multiple locations should be considered, as rainfall characteristics are likely to affect the design aspects necessary for improving stormwater mitigation. Monitoring on actual systems is also needed to calibrate models and verify modeling results.

Using Legislation and Incentive Programs to Promote Rainwater Harvesting

The implementation of subsidies, rebates and legislation has been shown to significantly increase RWH adoption in many countries (Gardiner 2010). This section discusses the benefits and challenges associated with RWH policy implementation and summarizes the policies that have been successful in promoting RWH implementation around the world.

Policy Approaches

There are essentially two approaches to RWH policies: voluntary, incentive-based programs and mandated regulations. Government subsidies and rebate programs can be particularly effective in promoting RWH implementation. As opposed to regulations that require compliance, subsidies target individuals with an appreciation for RWH and provide an incentive for them to pursue adoption of RWH practices (Domènech and Saurí 2011). These people may be more likely to adequately maintain and operate RWH systems, thus maximizing the water savings benefits provided by the system. As subsidy recipients may be more environmentally conscious than other citizens, advertisements, workshops and awareness campaigns may be necessary to reach populations not as involved with water conservation issues (Domènech and Saurí 2011). Baguma and Loiskandl (2010) found citizens were more likely to implement RWH when subsidies were awarded for specific aspects of the installation, such as hardware, excavation or storage tanks, than if cash subsidies were offered.

From a government perspective, regulations can be cheaper to implement than subsidies, making them a popular choice among municipalities (Domènech and Saurí 2011). Although regulations may be more appealing to governing agencies, there are consequences associated with their use. Gardiner (2010) found that users of mandated systems possessed an attitude of indifference towards the system, while voluntary users viewed the system as a valuable resource. Consequently, owners of regulatory-required systems were less engaged with the system and less knowledgeable of its operational aspects than voluntary users (Gardiner 2010). While regulations may result in a greater number of systems being installed, those systems may not always be used most efficiently due to user attitudes and perceptions.

Table 26 summarizes RWH policies that have been implemented around the globe.

Table 26. Summary of existing rainwater havesting legislation and incentive programs.

Country/Region	References	Details
Australia	Domènech and Saurí 2011; Farreny et al. 2011	• Rebates (up to $500) given to all homeowners who install RWH • Households with connections to the storm sewer network are charged a surface water fee
Australia (South Australia)	Domènech and Saurí 2011	• All new buildings must use RWH or an alternative source for non-piped water
Australia (Victoria)	Hurlimann 2011; Khastigir and Jayasuriya 2011	• Target 155 - voluntary campaign encouraging citizens to consume less than 155L of water per day • Each water bill includes information on methods of conserving water, shows household consumption and target values
Australia (Queensland)	Ahmed et al. 2009; Gardiner 2010; Gardner and Vieritz 2010	• Home Water Wise Rebate Scheme • Rebates for citizens using rainwater for nonpotable uses • In South East Queensland, a development code requires dwellings built after 2007 with roof areas of at least 100m2 must install a 5kL RWH system for toilet, laundry and external uses • In 2006, South East Queensland citizens could receive up to $1000 rebate for RWH installation; rebate raised to $1500 in 2008 but required internal plumbing connections to toilet or laundry facilities
Bangladesh	Islam et al. 2010a	• Every new building must have RWH
Belgium (Flanders region)	Domènech and Saurí 2011	• New buildings with roof area greater than 100m2 must install RWH and stormwater attenuation systems
Bermuda	Lye, 1992	• Bermuda Public Health Act (1949) - stipulates characteristics of catchment areas and storage tanks of RWH systems • Water Storage Regulation (1951) - requires 4/5 of roof surface to be adequately guttered; requires storage tank cleaning every 6 years • Food Regulations Act (1960) - specifies storage requirements for restaurants, bakeries and other commercial buildings
Brazil	Domènech and Saurí 2011; Gomes et al. 2010	• Program of Training and Social Mobilization for Living with the Semi-Arid: One Million Rural Cisterns (P1MC) • Federal government has financial support program that includes homeowner education about system usage via 2-day
China (Gansu)	Zhu et al. 2004	• 121-Project - promotes RWH system installation for agricultural irrigation
Denmark (select municipalities)	Albrechtsen 2002; Mikkelsen et al. 1999	• Wastewater fee exemption for houses with RWH (WW fee is calculated based upon household water consumption) • When using rainwater, only toilet flushing and laundry uses allowed indoors
France	Gires and de Gouvello 2009; Vialle et al. 2012	• Legislation was passed in 2008 to allow the use of rainwater in buildings for toilet flushing, floor cleaning and laundry (prior to this rainwater use was limited to outdoor activities)

Table 26, cont. Summary of existing rainwater havesting legislation and incentive programs.

Country/Region	References	Details
Germany	Domènech and Saurí 2011; Farreny et al. 2011; Nolde 2007	• Citizens with RWH systems are exempted from stormwater taxes • Households with connections to the storm sewer network are charged a surface water fee
India (Bangalore, New Delhi, Kerala, Rajasthan & others)	Domènech and Saurí 2011	• Regulations similar to those in Belgium are in place for at least 15 states and cities • Chennai mandates rooftop RWH for groundwater recharge purposes
Jordan	Abdulla and Al-Shareef 2009; Domènech and Saurí 2011; Lange et al. 2012	• Water and Irrigation Ministry Policy • All new homes requried to have water collection storage tanks • Homeowners no longer get financial assistance to dig a well • RWH is encouraged during the winter season • There is no program specifically targeting RWH, but a broader Policy to encourage citizens to utilize all water resources
Palestinian Authority	Lange et al. 2012	• Encourages RWH as part of water emergency plan
Spain (Catalonia, several municipalities)	Domènech and Saurí 2011	• New buildings containing a specific garden area are required to install RWH systems • Sant Cugat del Vallès (a suburb of Catalonia) requires RWH systems for buildings with >300m^2 of garden • In Sant Cugat del Vallès, residents voluntary implemented RWH receive a subsidy up to 1,200€ (but not exceeding 50% of total cost)
Sri Lanka	Domènech and Saurí 2011	• National RWH policies in place
U.S. Virgin Islands	Lye, 1992; Hamdan 2009	• RWH is required to obtain a residential building permit • All buildings must have at least 37L of storage for each square foot of roof area • Every building must have its own storage tank
United States	Domènech and Saurí 2011; Lynch and Dietsch 2010	• New buildings in Tucson, AZ, Santa Fe County, NM and several Caribbean Islands must have RWH systems • Hays County and San Antonio, TX have rebate and tax exemption programs to promote RWH • States of AZ, CA, NM and TX have tax incentives and environmentally-friendly building codes to promote RWH

Challenges to Policy Implementation

Public health and liability are major concerns for entities considering policy implementation and agencies often opt for conservative legislation (Leidl et al. 2010). For example, RWH systems in Australia have not been utilized for drinking purposes as much as they could be due to a lack of understanding about microbial and chemical contamination risks and management practices (Ahmed et al. 2011a). This was the case in France as well where, until 2008, French citizens were not allowed to use harvested rainwater for any indoor demands (Gires and de Gouvello 2009). Policies restricting end uses of harvested rainwater limit the water savings potential and economic efficiency of these systems; thus, it is important for policies to address the health risks associated with RWH while still allowing maximum use of the system (Ahmed et al. 2011a). This requires the integration of public education, engineering and public health research (Fry et al. 2010).

Public Education – A Crucial Policy Component

Ward et al. (2010b) cited the lack of information regarding system design and sizing and cost effectiveness of systems as the primary reason for people not choosing to implement RWH in the UK. It is not surprising that citizens would be hesitant to invest in a system if they are unsure of its financial benefits. Abdel-Shafy et al. (2010) stated that a lack of public awareness and professional marketing have caused RWH opportunities in Egypt to be neglected. In each of these cases, the implementation of a public education program could increase information flow to residents for a fraction of the cost it would take to establish a subsidy program.

The lack of guidelines and public education has also been tied to poor water quality within the system. Baguma et al. (2010a) surveyed 77 households in Uganda (where RWH is promoted but no guidelines exist on its use) and found that the lack of knowledge among residents regarding system maintenance and operation procedures was significantly correlated with poor water quality. It was predicted that the dissemination of adequate information to those households would facilitate the implementation of maintenance practices, thereby decreasing health risks associated with use of the system via improved water quality (Baguma et al. 2010a; Baguma et al. 2010b). Again, a public education program could address this lack of knowledge and promote management strategies that minimize risk. Successful information conveyance could potentially expand the end uses of rainwater which could, in turn, lead to greater potable water replacement and stormwater mitigation (Ahmed et al. 2011a).

Conclusions and Recommendations

Incentive and regulatory programs have been shown to significantly increase the implementation of RWH systems and are essential mechanisms to facilitate widespread use (Bagume and Loiskandl 2010; Abdulla and Al-Shareef 2009). Policies should be carefully constructed and implemented to protect human health while still allowing maximum use and application of these systems. Public education programs should always accompany policies, as lack of knowledge has been cited as a critical barrier to RWH adoption and use (Baguma et al. 2010a).

Future Research Needs

Future research needs that may serve to improve our understanding of RWH policies are listed below, in no particular order:

- Further study is needed on innovative and effective methods of conveying information on RWH design, operation and maintenance to prevent health hazards (Baguma et al. 2010a).
- More research should be conducted on the opinions and practices of households operating under various RWH policy programs (Domènech and Saurí 2011).
- Investigation into multiple ‘classes’ of water is needed, as this approach may be appropriate for determining acceptable end uses for RWH systems (Lye, 1992).

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