Effects of Catchment, First-Flush, Storage Conditions, and Time on Microbial Quality in Rainwater Harvesting Systems

M. T. Amin[1], Tschung-il Kim[2], M. N. Amin[3], M. Y. Han[2*]

ABSTRACT: Rainwater collected from a rooftop rainwater harvesting (RWH) system is typically not considered suitable for potable uses, primarily because of poor microbial quality. The quality of stored rainwater, however, can be improved through basic design and maintenance practices during the construction and operation of an RWH system. This paper presents the microbial analysis of rainwater in two RWH systems installed at the Seoul National University Campus in South Korea. Rainwater samples were collected at different locations within each system and analyzed for total and fecal coliforms, *Escherichia coli*, and heterotrophic plate count bacteria. Within their storage tanks, water quality improved horizontally from inlet to outlet points, and higher quality was observed at the supply point (located about 0.5 m from the base of the tank) than at the surface or bottom of the tank. First-flush rainwater was found to be highly contaminated but rainwater quality improved following about 1 mm of precipitation. The catchment surface also had a significant effect on the quality of rainwater; samples collected from a rooftop exhibited better microbial quality than from a terrace catchment. Better water quality in underground tanks (dark storage conditions) compared to open weirs/filters (exposed to natural light) demonstrated the importance of storage conditions. Water quality also improved with longer storage, and a decrease of 70% to 90% in microbial concentrations was observed after about 1 week of storage time. The findings of this study demonstrate that the microbial quality of harvested rainwater can be improved significantly by the adoption of proper design and maintenance guidelines such as those discussed in this paper. *Water Environ. Res.*, **85,** 2317 (2013).

KEYWORDS: catchment, first-flush, microbial quality, rainwater harvesting, storage.

doi:10.2175/106143013X13706200598433

Introduction

Rainwater harvesting (RWH) is receiving attention worldwide, primarily as an alternative source of non-potable water supplies (Ghisi and Ferreira, 2007; Hatibu et al., 2006; Olem and Berthouex, 1989; Simmons et al., 2001) that results in water savings (Baguma et al., 2010; Nazer et al., 2010). The use of rainwater in domestic hot water systems can produce optimal environmental and economic results for urban water cycle management (Hartung, 2007; Spinks et al., 2006; Sturm et al., 2009). Other reasons for rainwater storage include mitigation of various water problems such as flooding and drought (Brewster and Buros, 1985; Chanan and Woods, 2006; Zhang et al., 2010), groundwater recharge (Keler et al., 2012; Murad et al., 2007), and urban water management (Daigger, 2009). The European Commission has recommended the use of rainwater in public and private buildings (EC, 1994). The infrastructure needed to use stored rainwater consists of the catchment area, a treatment facility, a storage tank, a supply facility, and associated pipes (Amin and Han, 2009a; Han and Mun, 2008).

Despite being an ancient practice in many parts of the world, RWH is currently used on a limited scale for household-level potable purposes (Amin and Han, 2007; Ariyananda, 2005; Dillaha and Zolan, 1985; Handia et al., 2003; Heyworth et al., 2006; Ibrahim, 2009; Pinfold et al., 1993; Thomas and Greene, 1993; UNEP, 1998). This is because the quality of stored rainwater usually does not meet drinking water quality standards (Gould, 1999; Lee et al., 2010; Lye, 2002; Zhu et al., 2004). A variety of factors affect the quality of harvested rainwater, including dry periods (Sazakli et al., 2007; Vazquez et al., 2003), catchment type (Nair et al., 2001; Nakata et al., 1995), and storage conditions (Chang et al., 2004; Forster, 1999). Weather patterns can also significantly influence the bacterial load in roof run-off (Evans et al., 2006).

Nevertheless, use of storage tanks can be regarded as a means of treatment because sedimentation can reduce contaminant loads in stored rainwater (Coombes et al., 2002; Spinks et al., 2005). An analysis of sludge samples by Spinks and colleagues identified sedimentation as a key component of the water quality improvement. Other factors that can improve rainwater quality include the use of filters and first-flush diverting devices to treat roof runoff prior to storage. Post-treatment practices such as disinfection (Amin and Han, 2009b, c; Amin and Han, 2011), membrane application (Kim et al., 2005, 2007), slow sand filtration, and hot water systems (Ahammed and Meera, 2006; Yaziz et al., 1989) can also improve rainwater quality prior to potable use.

Unless special care is taken, harvested rainwater can become contaminated during collection and storage (Meera and Ahammed, 2006). The effects of first-flush, catchment surfaces, storage conditions, and storage duration on the microbial quality of rainwater from two separate RWH systems were investigated.

[1] Alamoudi Water Chair, King Saud University, P.O. Box 2460, Riyadh 11451, Kingdom of Saudi Arabia.

[2*] Civil and Environmental Engineering Department, Seoul National University, Seoul, South Korea; e-mail: myhan@snu.ac.kr.

[3] Department of Civil and Environmental Engineering, College of Engineering, King Faisal University, P.O. Box 380, Al-Hofuf, Al-Ahsa 31982, Kingdom of Saudi Arabia.

Table 1—Description of two rooftop rainwater harvesting (RWH) systems used in study.

Description	Catchment type	Area (m^2)	Main tank size (m^3)	Auxiliary tank (m^3)	Filter details
RWH system 1 (dormitory building)	Concrete roof	2098	200	–	VF6-type with mesh size of 0.65 mm and capacity of 70.5 L/sec
RWH system 2 (engineering building)	Concrete roof	934	–	27	T-101-type with mesh size of 0.6 mm
	Green roof	934	–	–	
	Terrace	824	–	–	
	Concrete roof	960	250	–	WFF 100-type with mesh size of 0.28 mm and capacity of 1.5 L/sec; AFS 200

The findings of this study can assist in the proper design of RWH systems to improve water quality water at the supply point.

Materials and Methods

Experimental Site Description. This study was conducted at Seoul National University in South Korea. Rooftop RWH systems were installed at two locations supplying rainwater for toilet flushing. Table 1 summarizes and Figure 1 illustrates the primary features of both RWH systems.

The first (RWH system 1) included a 200-m^3 underground concrete storage tank to collect rainwater from a concrete roof catchment area of 2098 m^2 (Figure 1a). Rainwater from the rooftop passed through a VF6-type filter before entering the storage tank through a calm inlet (Figure 2a). The second (RWS system 2) had a main, auxiliary, and supply tank to collect rainwater from a catchment that comprised concrete and green roofing (ordinary grass) as well as a terrace (Figure 1b). Tank and catchment surface sizes are provided in Table 1. The main tank collected rainwater from the concrete surface after passage through a WFF 100-type filter (F1 in Figure 1b), whereas the auxiliary tank collected rainwater from concrete and green roofing as well as from a terrace catchment after passage through a screen assembly (S in Figure 1b). Harvested rainwater from the auxiliary tank flowed to the main tank through another filter (F2 in Figure 1b) before reaching the supply tank to provide water for toilet flushing.

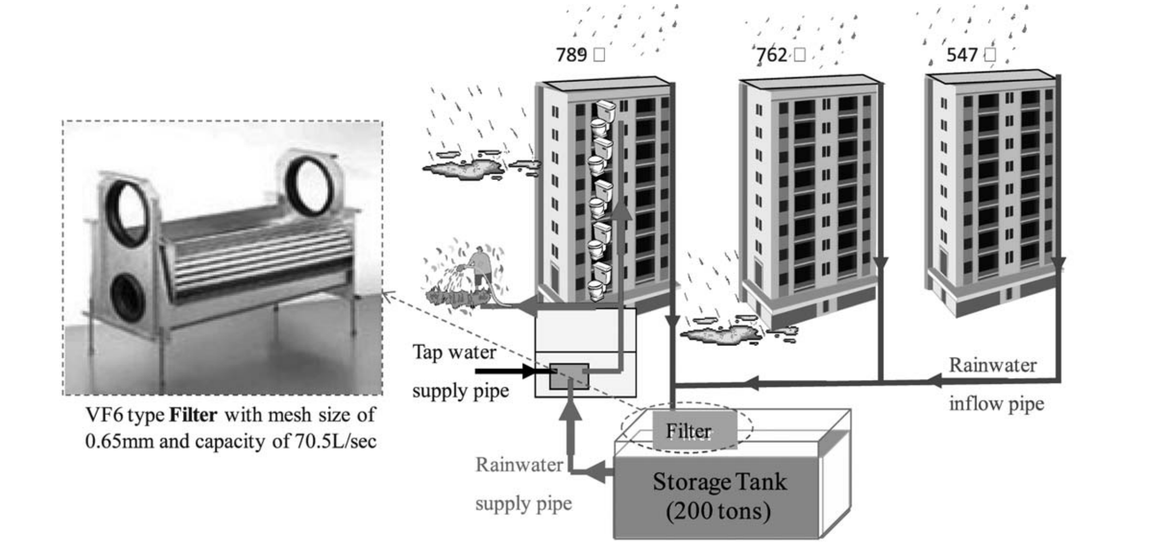
Sampling Locations and Procedures. Samples were collected at different locations within the RWH systems, including filters, weirs, screen assembly, and underground storage tanks. Bulk samples were obtained at the rooftop with 1-L glass beakers to represent direct precipitation (rain). Samples from storage tanks were collected with a 1-L acrylics water sampler, which included a brass messenger for activation as well as a lead collar for rapid descent and minimal drift caused by water currents. Samples from filters, weirs, and the screen assembly were collected in 0.5-L polyethylene sterile screw cap containers, chilled, and analyzed within 24 h.

Figure 2a shows the plan and cross-sectional view of the storage tank in RWH system 1. The tank was divided into two equal halves (inlet and outlet sections) by an intermediate wall, and rainwater flowed from the inlet to the outlet through a baffle. One sample ($S_1$1) was taken from the filter to represent the roof-intercepted sample; an additional sample was taken near the inlet point ($S_1$2, about 1 m from the calm inlet). Another sample was collected near the supply pump to represent the point-of-supply (PoS; about 0.5 m from the base of the tank) sample ($S_1$3). The difference in microbial quality between $S_1$2 and $S_1$3 represents the horizontal quality variation inside the storage tank. Two more samples, $S_1$4 at midway depth and $S_1$5 at the surface (2 m from the base) of the tank, were taken in the outlet section to represent vertical quality variation when compared with the PoS sample ($S_1$3).

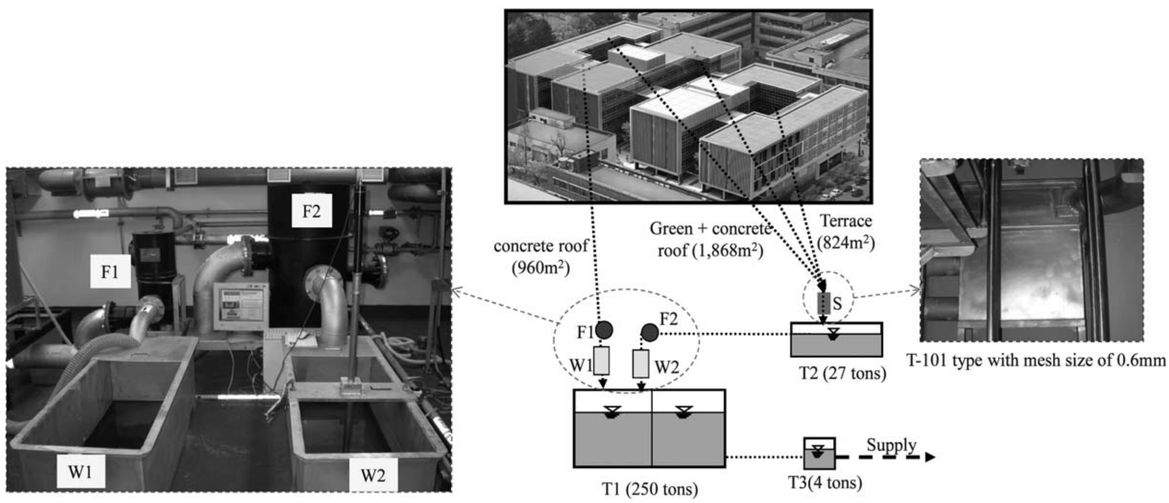
Figure 2b represents the plan and cross-sectional view of the main tank in RWH system 2. The tank was also divided into two halves (inlet and outlet sections) by an intermediate wall. Three and five vertical samples were taken in the inlet ($S_2$1 to $S_2$3) and outlet ($S_2$4 to $S_2$8) sections, respectively, to evaluate the vertical quality variations in the main tank at two places, as shown in Figure 5. The near-bottom samples (i.e., $S_2$1 and $S_2$4) were taken at heights of about 0.5 m and 0.2 m from the base of the main tank, respectively. For horizontal quality variation, samples in the inlet and outlet section were compared at respective depths ($S_2$3 versus $S_2$8, $S_2$2 versus $S_2$6, $S_2$1 versus $S_2$4), as shown in Figure 6. The PoS was 1.35 m above the base of the tank in the outlet section. The maximum level of rainwater in the tank, when full, was 4.25 m. For the auxiliary tank, only two samples ($S_2$13 and $S_2$14) were taken at the inlet and outlet sections to assess horizontal quality variation because the water flowed from the inlet point to the PoS (Figure 2c). All samples from the storage tanks to evaluate horizontal and vertical quality variations were collected immediately after the rainfall event.

Samples were also collected from open weirs ($S_2$9 from weir 1 and $S_2$10 from weir 2), filter 1 ($S_2$11 and $S_2$12), and the screen assembly ($S_2$15 and $S_2$16) to assess the effects of catchment, first-flush, and storage conditions. For the catchment effects, samples in the open weirs and storage tanks were compared (i.e., main versus auxiliary tank and weir 1 versus weir 2) (Figure 7). For determining the effects of first-flush, two samples (immediately after the rainfall event and following about 1 mm of rainfall) were collected before the rainwater entered filter 1 and the screen assembly (Figure 8). The effect of storage conditions was evaluated by comparing the samples at the PoS in the main ($S_2$5) and auxiliary ($S_2$14) tanks with samples from weirs 1 and 2, respectively (Figure 9). All three components (weirs, filter, and the screen assembly) were exposed to ambient light at room temperature conditions and were typically cleaned twice per year.

Bacteriological Analysis of Rainwater Samples. At the start of the study, five to six samples were collected over a 1.5-year period, mostly on a bimonthly basis. Analyses were conducted after the tanks were full, typically following multiple rainfall events over a 2-month period. Several physicochemical and biological parameters were evaluated twice during summer,



(a)



(b)

Figure 1—Schematic diagrams of two rooftop rainwater harvesting (RWH) systems for (a) RWH system 1 and (b) RWH system 2 (F= filter; W = weir; T = tank).

spring, autumn, and winter months. Investigated bacteriological water-quality parameters included total coliforms, fecal coliforms, *Escherichia coli*, and heterotrophic plate count bacteria (HPC). Water quality analyses were conducted in accordance with *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1999). Difco™ Lauryl Tryptose Broth (Becton, Dickinson and Company, Franklin Lakes, New Jersey) was used for the presumptive phase of total coliforms, fecal coliforms, and *E. coli*. Difco™ Brilliant Green Bile Broth (Becton, Dickinson and Company), Difco™ EC Medium (Becton, Dickinson and Company), and Bacto™ EC Medium with MUG (Becton Dickinson, Le Pont de Claix-Cedex, France) were used for the confirmation phase of total coliforms, fecal coliforms, and *E. coli*, respectively.

Results and Discussion

Basic physicochemical parameters (mean values) for rainwater samples from both RWH systems are shown in Table 2. Because most temperature readings were taken during winter months, the average temperature was 17 °C. This is significant because lower temperatures do not favor the growth of microorganisms (Hart and White, 2006; Sazakli et al., 2007).

The arithmetic mean of the pH and conductivity of the bulk sample (direct precipitation) was 5.6 (ranged from 4.5 to 6.9) and 35 (ranged from 10 to 72), as measured over an approximately 1-year period. The pH values of the rainwater throughout the study varied between 6.8 and 9.8, with the lowest value (6.84) measured in the storage tank of RWH system 1. The average (alkaline) pH values were >7.0, which could be a result of the concrete roof catchments and storage tanks (particularly for a

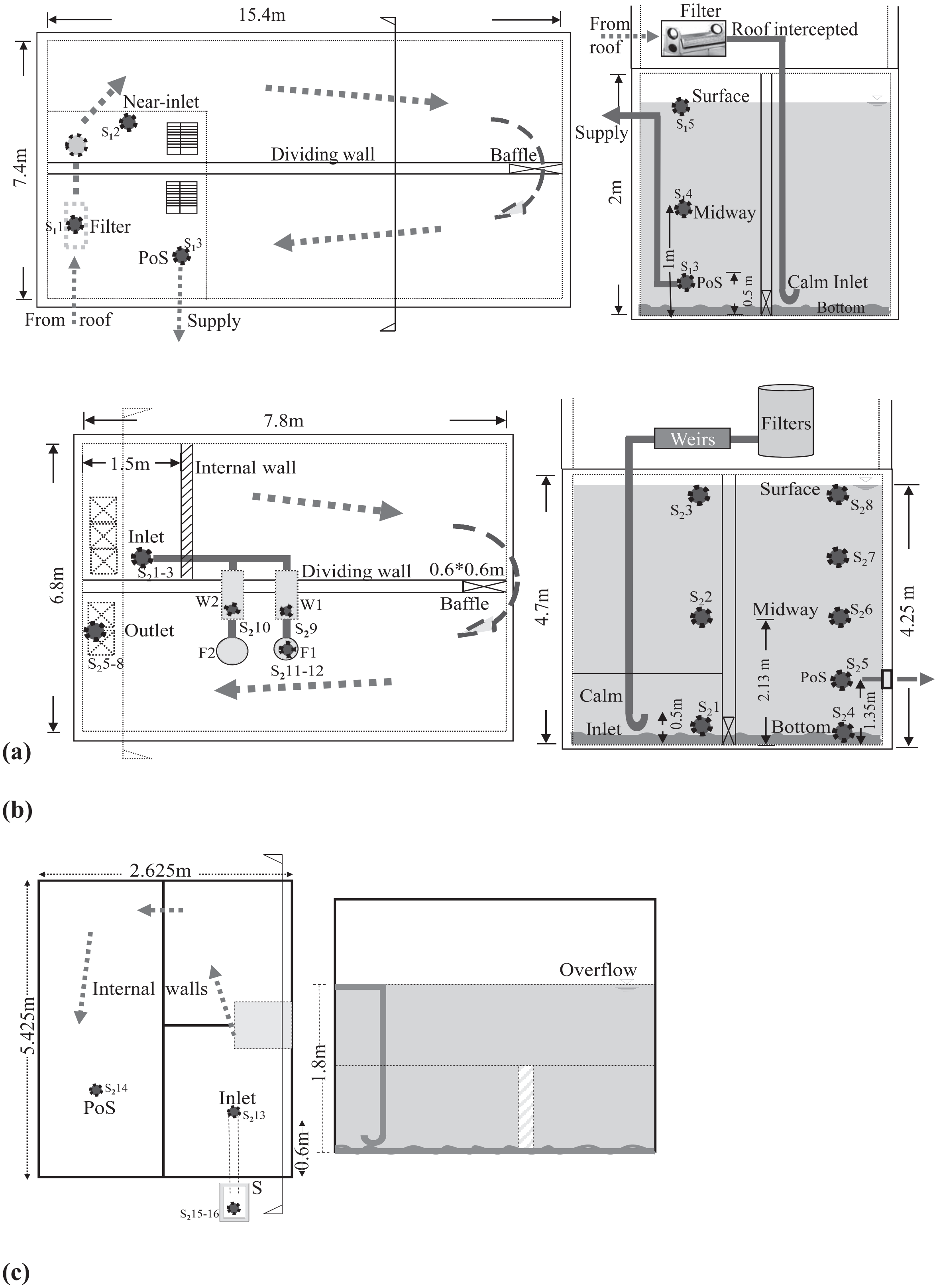


Figure 2—Plans and sections of different storage tanks of two rooftop rainwater harvesting (RWH) systems: (a) storage tank (T) of RWH system 1; (b) main tank (T1) of RWH system 2; and (c) auxiliary tank (T2) of RWH system 2 (PoS = point-of-supply; W = weir; T = tank).

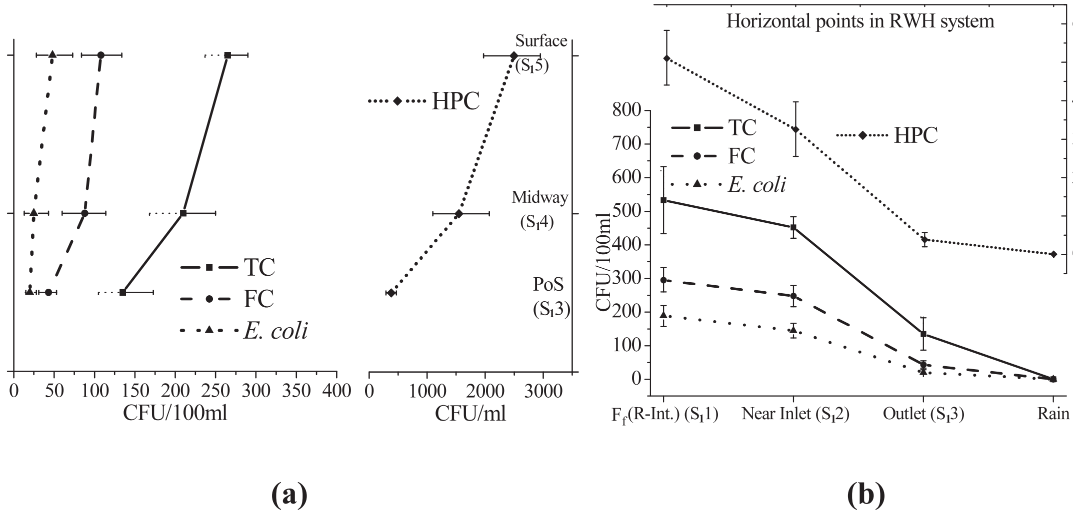


Figure 3—(a) vertical ($S_1$3 to $S_1$5 in Figure 2a) and (b) horizontal ($S_1$1 to $S_1$3 in Figure 2b) microbial quality variation in the storage tank of rooftop rainwater harvesting system 1 (Ff [R-Int.] = first-flush [roof-intercepted] sample in filter assembly; HPC = heterotrophic plate count bacteria; TC = total coliforms; FC = fecal coliforms; PoS = point-of-supply; CFU = colony forming units).

relatively new construction in RWH system 2). There is no maximum allowable pH for potable water in terms of public health. Eye irritation and exacerbation of skin disorders, however, have been associated with pH > 11, whereas redness and eye irritation have been reported at pH < 4, the severity of which can increase with decreasing pH (WHO, 1986). Also, water with high (>11) or low (<6.5) pH can lead to corrosion of plumbing fittings and pipes. Thus, the pH values of the rainwater evaluated in this study were safe from a public health perspective.

Microbial Quality Variation in Storage Tanks. *Horizontal and Vertical Quality Variation in the Storage Tank of Rooftop Rainwater Harvesting System 1.* Figure 3 represents the vertical and horizontal microbial quality variation in the outlet section and from the inlet to the outlet point inside storage tank of RWH system 1. Better vertical quality at PoS ($S_1$3) was observed than at the surface ($S_1$5) or at the midway level ($S_1$4) of the tank (Figure 3a). Concentrations of total coliforms, fecal coliforms, and *E. coli* at the PoS were almost 50% of their respective values at the surface of the tank; however, the concentration of HPC was 6 to 7 times lower at the PoS than at the surface of the tank. The percent improvement was calculated by comparing the measured values of microbial parameters with their initial concentrations. Notably, average values for all bacteriological parameters exceeded guideline values for public and private water supplies (0 CFU/100 mL for coliforms and *E. coli*) (Morris et al., 1996; Schwartz et al., 1997).

The microbial water quality improved horizontally in the system from the filter assembly (roof-intercepted sample or first-flush, $S_1$1) to the near-inlet point ($S_1$2) and to the PoS ($S_1$3)

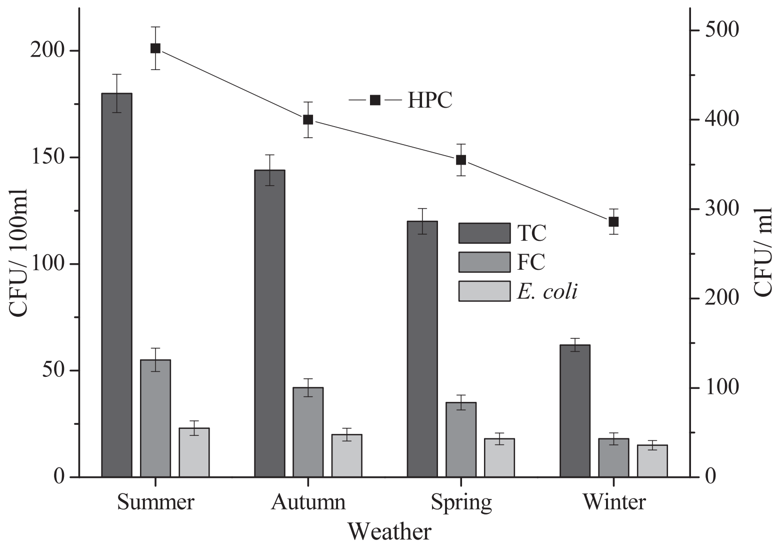


Figure 4—Seasonal variation for microbial indicators in rainwater samples at point-of-supply ($S_1$3) in storage tank of rooftop rainwater harvesting system 1 (HPC = heterotrophic plate count bacteria; TC = total coliforms; FC = fecal coliforms; CFU = colony forming units).

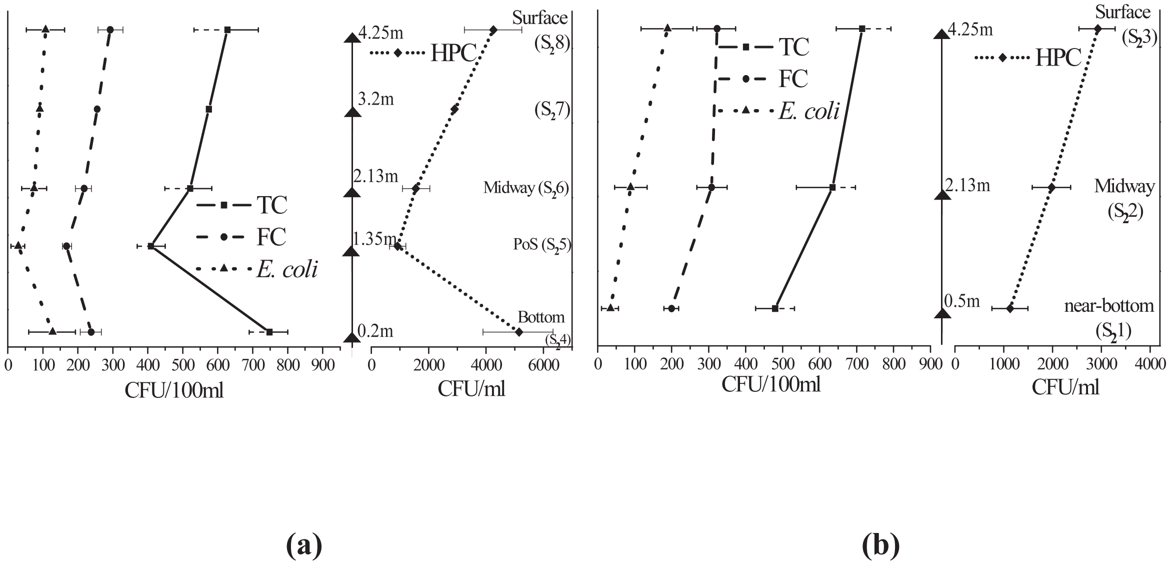


Figure 5—Vertical microbial quality variation at the (a) outlet (S_24 to S_28 in Figure 2b); and (b) inlet (S_21 to S_23 in Figure 2b) points in the main storage tank of rooftop rainwater harvesting system 2 (HPC = heterotrophic plate count bacteria; TC = total coliforms; FC = fecal coliforms; PoS = point-of-supply; CFU = colony forming units).

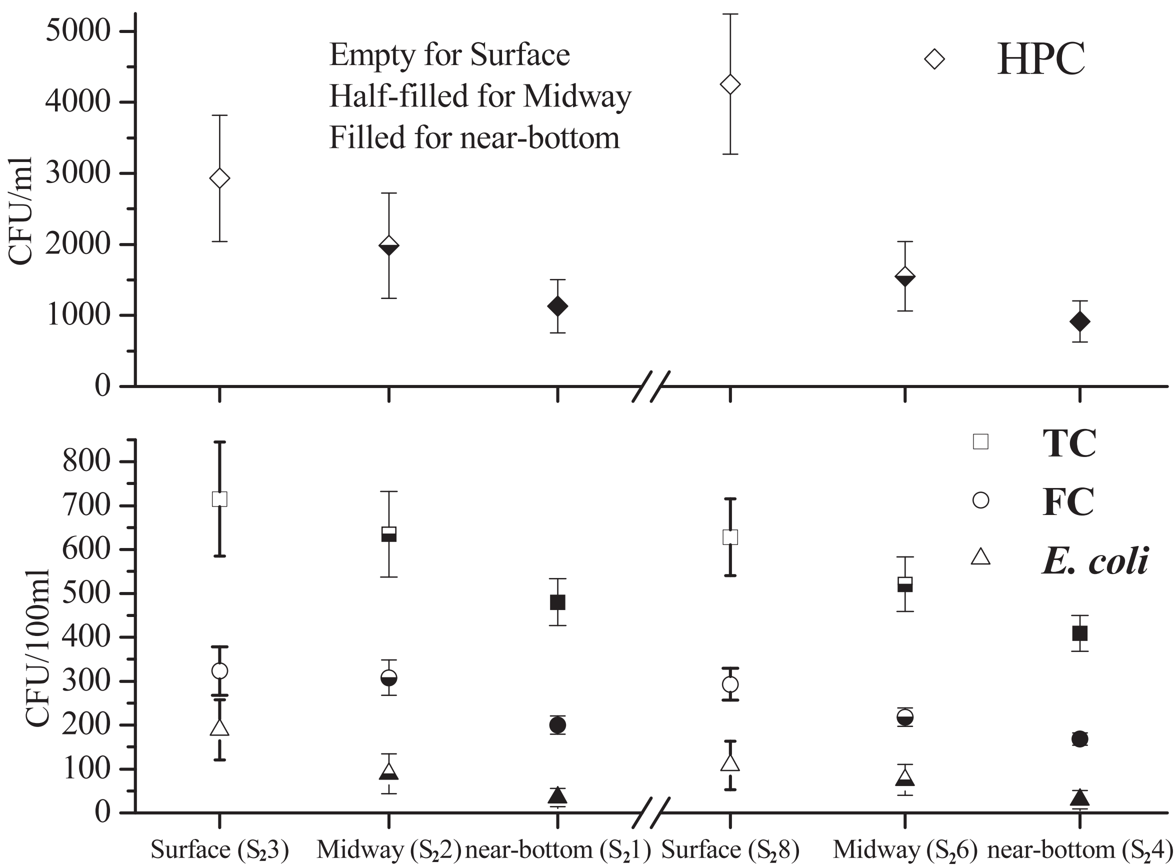
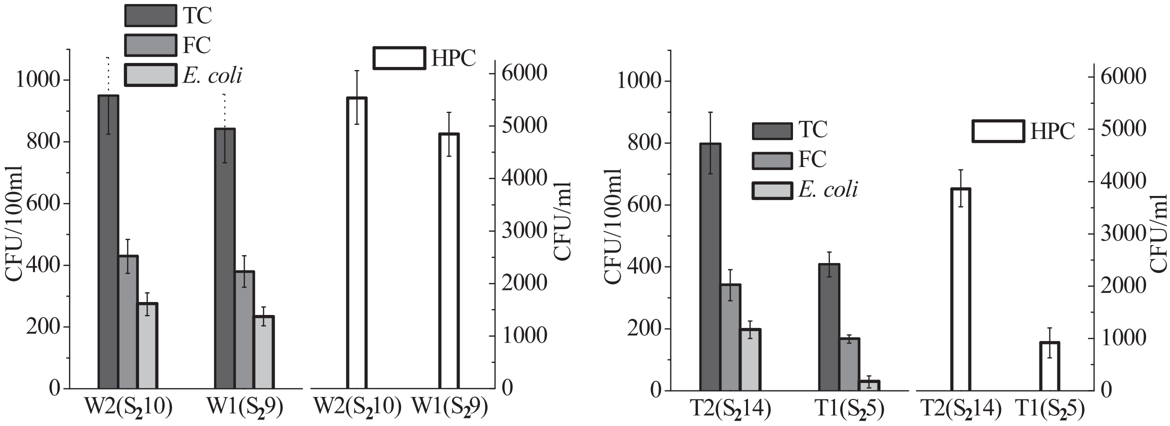


Figure 6—Horizontal quality variations from the inlet to the outlet points in the main tank of rooftop rainwater harvesting system 2 (HPC = heterotrophic plate count bacteria; TC = total coliforms; FC = fecal coliforms; CFU = colony forming units).

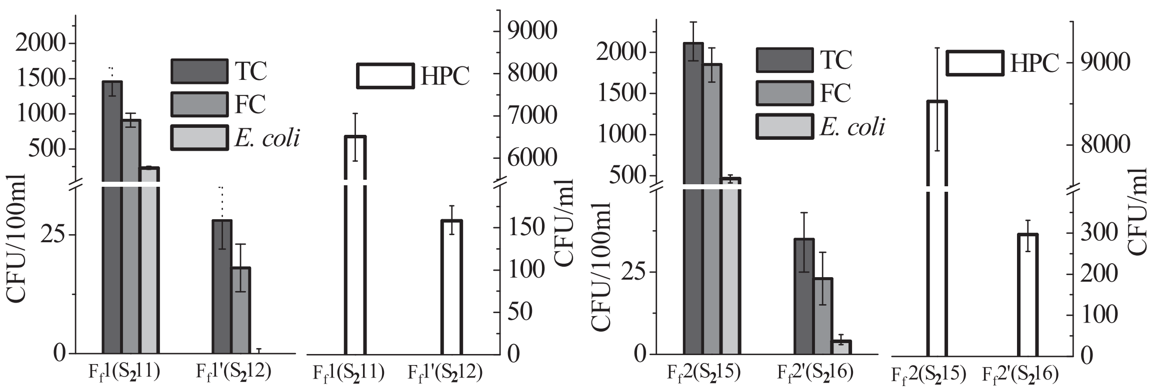


(a) (b)

Figure 7—Quality comparison between different catchments of rooftop rainwater harvesting system 2 from (a) open weirs, and (b) storage tanks (TC = total coliforms; FC = fecal coliforms; HPC = heterotrophic plate count bacteria; CFU = colony forming units).

(Figure 3b). The first-flush sample, which was collected from the filter assembly, was clearly more contaminated than stored rainwater in the tank. Total coliforms, fecal coliforms, and *E. coli* were all reduced by 15% to 20% from the filter assembly to the inlet point, whereas this reduction was about 40% for HPC. From the filter assembly to the PoS, total coliforms, fecal coliforms, and *E. coli* concentrations were reduced by almost 70%, 85%, and 90%, respectively; HPC reduction was almost 93%.

The range of error bars in Figure 3 shows the seasonal variation in microbial concentrations. That is, rainwater had higher levels of total and fecal coliforms in summer versus winter months. The difference was almost 50 to 80 CFU/100 mL for total coliforms, 20 to 50 CFU/100 mL for both fecal coliforms and *E. coli*, and up to about 1000 CFU/ mL for HPC (Figure 3a). The decrease in bacteria concentrations throughout the winter could be attributed to a number of factors. One possibility is that the colder air temperatures during winter (–15 to 15 °C) inhibited the growth of bacteria within the storage tank. Another could be the result of decreased activity of animals and birds at the catchment surface. Decreased fecal contamination of the catchment surface by birds and animals during these colder months would reduce the influx of fecally-contaminated rainwater into the storage tanks. In this regard, Hart and White (2006) and Sazakli et al. (2007) both reported the presence of fewer microorganisms during the winter and that the levels gradually increased during spring and autumn. The seasonal variation of the microbial parameters in storage tanks is also shown in Figure 4. The highest summer microbial concentrations can be attributed to dirty catchment surfaces as a result of yellow sand storms from China during summer months. The



(a) (b)

Figure 8—Quality improvements after first-flush in rooftop rainwater harvesting system 2 from (a) concrete roof catchment, and (b) concrete/green roof and terrace catchment (TC = total coliforms; FC = fecal coliforms; HPC = heterotrophic plate count bacteria; CFU = colony forming units).

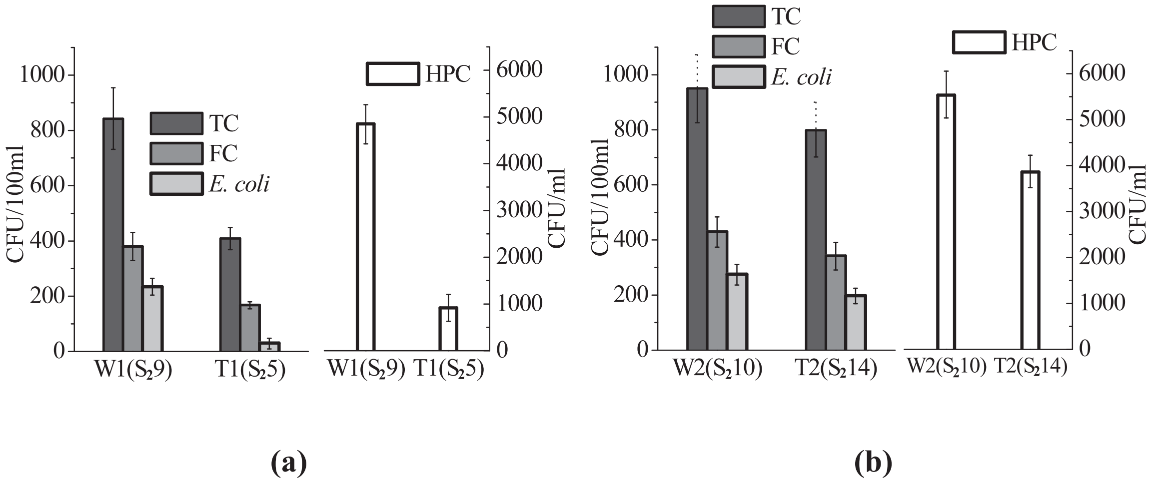


Figure 9—Effects of different storage conditions on microbial quality in rooftop rainwater harvesting system 2 for (a) concrete roof-intercepted versus main tank; and (b) concrete/green roof and terrace intercepted versus auxiliary tank (TC = total coliforms; FC = fecal coliforms; HPC = heterotrophic plate count bacteria; CFU = colony forming units).

effects of different seasons on bacterial populations have also been reported by previous researchers (e.g., Jones and Harrison, 2004; Lighthart, 2000).

Table 3 summarizes the results of an analysis of sludge (Table 3) settled at the bottom of the main tank. Coliforms were as high as 1600 CFU/100 mL and HPC exceeded 10 000 CFU/mL. This suggests that settlement could be a key contaminant removal process within storage tanks (Coombes et al., 2002), in addition to the action of biofilms at the tank-water interfaces (Islam et al., 2010). These findings are also supported by previous studies that compared the conglomeration of bacteria in a macro-layer at the interface between tank surfaces and stored rainwater (Coombes et al., 2005) to contaminants that settled to the bottom of the tank (Coombes et al., 2000; Spinks et al., 2005). Coombes et al. (2006) reported that the better microbial water quality at the PoS compared to the water surface was a result of the formation of a biofilm on the walls of tank, and that the biofilm might have entrapped coliforms and HPC bacteria with nutrients present in the stored rainwater.

The difference in microbial reduction from the filter assembly to the inlet point and then to the PoS clearly indicates that the majority of this reduction can be attributed to sedimentation and possibly the presence and action of biofilms within the storage tank. The bacterial contamination in the tanks appears to result primarily from the first-flush entry into the storage tank. The minimization of bacterial contamination in the rainwater tanks can be attributed to filtration and the presence of effective seals within the rainwater tanks that collectively minimize the entry of debris, soils, and leaves. Normal maintenance of the roof gutter systems could also have reduced the amount of contamination entering the rainwater tanks.

Microbial Quality Variation in the Storage Tanks of Rooftop Rainwater Harvesting System 2. Figures 5 and 6 represent the vertical and horizontal microbial quality variations in the main tank of RWH system 2. A similar trend of the microbial water quality variations seen in the storage tank of RWH system 1 was observed in system 2. Figure 5a shows the vertical quality variation in the outlet section of the main tank. Improved microbial quality was observed at the PoS ($S_2$5) than at the surface ($S_2$8) or the near-bottom point ($S_2$4) of the tank. Total coliform and *E. coli* concentrations were almost 45% and 75% lower at PoS than at the bottom point, respectively. The lowest and highest reductions (about 30% and 80%) were observed for fecal coliforms and HPC, respectively, from the bottom point to the PoS (Figure 5a). A similar trend for vertical microbial quality variation was observed in the inlet point of the main tank (Figure 5b). Total and fecal coliform concentrations were both almost 35% lower at the near-bottom point ($S_2$1) than at the surface ($S_2$3) of the tank. The *E. coli* and HPC reductions were almost 80% and 60% from the surface to the near-bottom point. Samples taken at the near-bottom points exhibited high concentrations of bacteria, which supports the assumption that contaminants settled to the bottom of tanks. It also indicates that biofilm action at the tank-water interfaces could have

Table 2—Physiochemical parameters in storage tanks of two rainwater harvest (RWH) systems (EC = electrical conductivity; DO = dissolved oxygen; NTU = Nephelometric Turbidity Units).

	Dormitory tank – RWS system 1			Main tank – RWH system 2			Auxiliary tank – RWH system 2		
Parameters	Min.	Max.	Avg.	Min.	Max.	Avg.	Min.	Max.	Avg.
Temperature (°C)	10	28	17.0	11	27	18	10	25	14.0
pH	6.84	8.2	7.04	7.7	9.85	8.71	6.68	9.7	8.56
EC (mS/cm)	42	56	45.0	75	109	88	152	428	286
DO (mg/L)	5.3	6.9	6.78	4.35	7.2	5.66	3.52	5.89	4.53
Turbidity (NTU)	1.4	10.8	3.4	0.41	8.56	5.7	1.31	11	4.90

Table 3—Sludge characteristics (CFU = colony forming units; HPC = heterotrophic plate count bacteria).

Parameter	Value
Particle size (μm)	38.78–64.0
Water content (%)	75.4 ± 5.06
Specific gravity	1.01–2.33
Percentage organic matter (%)	15–34.25
pH	6–8
Chemical oxygen demand (mg/L)	20–100
Total coliforms (CFU/100mL)	1200–1600
HPC (CFU/mL)	>10 000

contributed to the improvement of microbial water quality at the PoS (Coombes et al., 2000; Spinks et al., 2005).

Figure 6 illustrates the horizontal microbial quality variation from the inlet to the outlet sections in the main tank at three respective points (surface, midway, and PoS) within the tank. The microbial quality of rainwater improved horizontally from the inlet to the outlet sections at all three sampled heights. Total and fecal coliform concentrations were almost 12% to 18% and 10% to 30% lower in the outlet section than in the inlet section of the main tank. The maximum difference was recorded for points at midway height (i.e., $S_2$2 and $S_2$6). For *E. coli*, the maximum reduction from the inlet to the outlet was observed at the surface of the tank ($S_2$3 to $S_2$8), whereas an overall 15% improvement at the midway and near-bottom points from the inlet to the outlet sections of the main tank was observed. Heterotrophic plate count bacteria concentrations were reduced by almost 20% at both midway and near-bottom points from the inlet to the outlet section. An opposite trend of decreasing water quality, however, was observed at the surface of the tank where HPC concentration increased by almost 150% from the inlet to the outlet section ($S_2$3 to $S_2$8).

As described previously, the main tank was divided into two halves by an intermediate wall with water flows from the inlet to the outlet section passing through a baffle. Increased sludge accumulation in the inlet section could have accounted for the better microbial water quality near the PoS (in the outlet section), in conjunction with the intermediate wall and internal wall baffles that enhanced sedimentation. Horizontal microbial quality improvement was also observed as the water flowed from the inlet point to the PoS ($S_2$13 to $S_2$14) in the auxiliary tank of RWH system 2 (results not shown). The latter finding can also be attributed to the presence of internal walls in the auxiliary tank and increased sludge accumulation in the inlet versus outlet section of the auxiliary tank.

Quality Comparison of Different Sources (Catchment Surfaces) in Rooftop Rainwater Harvesting System 2. The microbial quality of rainwater collected from weir 1 ($S_2$9 from weir 1) to rainwater collected from weir 2 ($S_2$10 from weir 2) is compared in Figure 7a. Note that rainwater samples from weir 1 represented only the concrete roof catchment that passed through filter 1, whereas samples from weir 2 represented concrete/green roof and terrace surface. The latter passed through filter 2 after sedimentation in the auxiliary tank and filtration though the screen assembly. The quality in weir 1 was about 10% to 15% better for all microbial parameters compared with rainwater in weir 2. This variation appeared to reflect differences in the catchment materials for both weirs. The differences in microbial water quality also reflected the effects of cleaning and management, which were easier and more frequent for concrete surfaces. In the case of the concrete/green roof and terrace surfaces for weir 2, much of the pollution could have been the result of human activities (e.g., walking and smoking on the terrace surface), which could have transported and deposited dirt and traces of urine or bird/human feces.

The microbial quality of the rainwater sample taken at PoS ($S_2$5 in Figure 2b) in the main tank was also compared with that of the outlet sample taken at PoS ($S_2$14 in Figure 2c) in the auxiliary tank to evaluate the effects of different catchment surfaces. As shown in Figure 7b, the microbial quality of the rainwater in the auxiliary tank (collected from the concrete/green roof and terrace surface) was worse than in the main tank (where the rainwater from the auxiliary tank was further diluted with rainwater collected from concrete catchment only). Total and fecal coliform concentrations were almost 50% lower at PoS in the main tank than at PoS in the auxiliary tank, primarily as a result of the different catchment surfaces. This difference was up to almost 80% for *E. coli* and HPC (Figure 7b). In addition, the sample collected from the auxiliary tank was comparatively dirty in appearance and alkaline with very high turbidity value compared to the main tank sample, which was also alkaline but with intermediate turbidity (Table 2).

The effects of cleaning the dirty catchments were made apparent by comparing the microbial quality of rainwater sample taken immediately after the rainfall event (first-flush samples) with the sample taken after 1 mm of rainfall (F_f', or samples after first-flush). Figure 8 shows the results of comparing two samples ($S_2$11 and $S_2$12) taken from filter 1 (Figure 2b) as well as two samples ($S_2$15 and $S_2$16) from the screen assembly (Figure 2c). The high concentrations of HPC (7000 to 9000 CFU/mL) and the presence of total coliforms, fecal coliforms, and *E. coli* in the first-flush samples (F_f1 or $S_2$11 and F_f2 or $S_2$15) indicate that the catchment surfaces were contaminated by human activities on the rooftop/terrace. This effect was even more obvious in the case of the first-flush samples from the screen assembly attached to the auxiliary tank, the catchment of which comprised the concrete/green roof as well as terrace surface. The effect of the cleaned catchment was further reflected in samples collected following 1 mm of rainfall (F_f1' or $S_2$12 and $F_f\,2'$ or $S_2$16), where the microbial quality was greatly improved compared to the first-flush sample (Figures 8a and 8b), irrespective of the type of the catchment surface. However, only the sample from the concrete roof catchment after first-flush ($S_2$12 collected from filter 2) exhibited better microbial water quality than the sample from concrete/green roof and terrace surface after first-flush ($S_2$16 collected from the screen assembly). The latter finding was primarily a result of the relatively dirty terrace surface and green roofing, even following 1 mm of rainfall, as compared to the concrete roof catchment.

Finally, these results show that the type of catchment surface has a strong influence on the microbial quality of stored rainwater. Use of a suitable catchment surface in conjunction with regular cleaning/maintenance—especially during long, dry periods—can improve the microbial quality of rainwater when a first-flush diverting device is not attached to the RWH system (as was the case in the present study). The presence of birds or other animals (e.g., rats) can be the primary contributor of total and fecal coliforms in the tanks, which resulted primarily from the terrace catchment, in addition to human activities. Thus, the

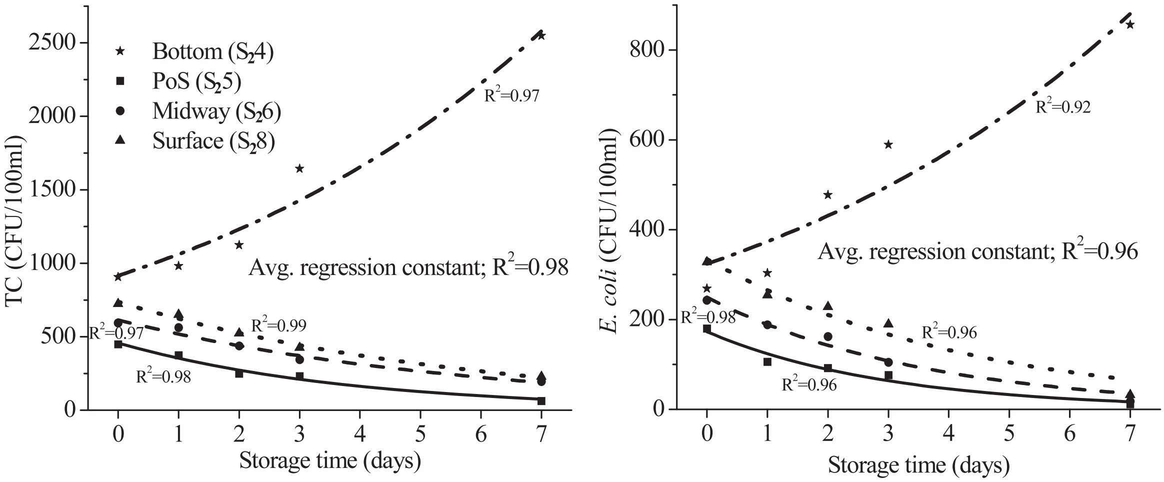


Figure 10—Total coliforms (TC) and *Escherichia coli* changes at outlet point with retention time in rooftop rainwater harvesting system 2 (TC = total coliforms; PoS = point-of-supply; CFU = colony forming units).

microbial quality of runoff can improve or worsen depending on the kinds of materials present as well as the catchment surface type (Ubba and Aghogho, 2000; Yaziz et al., 1989; Yufen et al., 2008).

First-Flush Effects on Microbial Quality in Rooftop Rainwater Harvesting System System 2. The effects of first-flush can be predicted from the results presented in Figure 8, where the microbial quality of two samples (one collected shortly after the rainfall event and the other after about 1 mm of rainfall) was compared. Figure 8a shows this comparison for the concrete roof-intercepted samples taken from filter 1 (F_f1 and F_f1'); Figure 8b shows the comparison for the concrete/green roof- and terrace-intercepted samples (F_f2 and F_f2') taken from the screen assembly attached to the auxiliary tank.

The first-flush of runoff water at the beginning of a storm event contained a high proportion of the pollutant load (Figures 8a and 8b). A likely cause of this finding could be the deposition and accumulation of pollutant materials on the roof during dry periods, either by natural or anthropogenic activities. The longer the dry period, the greater the probability of higher pollutant loads in the first-flush. The first-flush from the concrete/green roof and terrace catchment (F_f2 or $S_2$15) was highly contaminated with total coliform bacteria concentrations (as much as 2000 CFU/100 mL); however, their concentrations were slightly less but still in the range of 1500 CFU/100 mL for the roof-intercepted first-flush (F_f1 or $S_2$11). Fecal coliforms and *E. coli* concentrations in F_f2 were almost twice than their respective concentrations in F_f1, whereas HPC in F_f2 was almost 1.3 times greater than in F_f1. The microbial quality improvement was 98% after first-flush (following 1 mm of rainfall). Both samples after first-flush (i.e., F_f1' or $S_2$12 and F_f2' or $S_2$16 in Figures 8a and 8b), however, still contained total and fecal coliforms and HPC, which demonstrates that 1 mm of rainfall might not be sufficient to completely remove the contaminants that were deposited during the preceding dry period. Notably, the roof-intercepted sample was almost free of *E. coli* contamination after first-flush (F_f1' in Figure 8a) with acceptable turbidity and a neutral pH (results not shown).

Based on the above results, one potential reason for higher biological loading in RWH system 2 was the absence of a first-flush diverting device, although filtering devices were attached to both tanks. Although diverting the first millimeter of rainfall from entering the storage tanks (i.e., first-flush removal) can improve the microbial quality of stored rainwater, filtering alone might be insufficient to reduce total and fecal coliforms. Thus, the best practice would be to include filters that have a separate outlet for dirt and that can reject the first-flush.

Effects of Storage Conditions and Time on Microbial Quality in Rooftop Rainwater Harvesting System 2. One important factor that influences the microbial quality in RWH systems is the storage condition. The quality of rainwater samples taken at PoS inside the main ($S_2$5) and auxiliary tank ($S_2$14) was compared with samples taken from open weirs (i.e., weirs 1 [$S_2$9] and 2 [$S_2$10]), respectively, as shown in Figure 9. Both samples were subjected to different storage conditions in terms of light and enclosure. The rainwater inside weir 1 was introduced only from the concrete roof catchment, which was better in microbial quality than in weir 2 (Figure 7a) that collected rainwater from the concrete/green roof and terrace surface. Given the sedimentation, biofilm, and storage conditions, the water quality in weir 1 should be better than that at PoS because the main tank collected rainwater from both weirs 1 and 2. The quality of rainwater inside the main tank ($S_2$5 at PoS), however, was better than in the open weir ($S_2$9 in weir 1) (Figure 9a). The concentrations of both total/fecal coliforms and *E. coli*/HPC inside the main tank were almost 50% and 85% lower, respectively, than in weir 1. A potential reason for these findings could be the occurrence of natural treatment processes inside the main tank, including sedimentation, action of biofilms at the water-surface interfaces, and dark storage conditions. The rainwater in weir 1 was exposed to ambient light and other natural factors, such as the presence of flies, mosquitoes, and other insects as a result of the room conditions, which might have increased microbial growth. Thus, rainwater storage conditions could be one of the most important factors to consider during RWH system design.

The microbial quality of rainwater inside the auxiliary tank ($S_2$14 at PoS) was also better than in weir 2 ($S_2$10 in weir 2), although it is also passed through filter 2 before entering weir 2 from the auxiliary tank (Figure 9b). Concentrations of both total

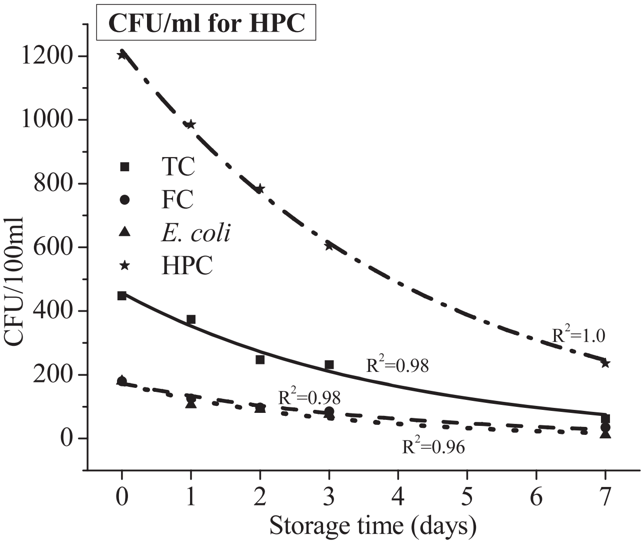


Figure 11—Microbial quality improvements with longer storage time at point-of-supply (PoS) (S_25) in main tank of rooftop rainwater harvesting system 2 (HPC = heterotrophic plate count bacteria; TC = total coliforms; FC = fecal coliforms; CFU = colony forming units).

coliforms/fecal coliforms and *E. coli*/HPC inside the auxiliary tank were almost 15% to 20% and 30% lower, respectively, than in weir 2. The similar dark storage conditions inside the auxiliary tank and the presence of insects in weir 2 can potentially explain this difference in microbial quality. The temperature difference (about 7 to 8 °C) between the tank water and rainwater in open weirs (results not shown) could have also influenced water quality. That is, the elevated temperatures in the open weirs could have increased the growth of total and fecal coliforms, and which is supported by Hart and White (2006) and Sazakli et al. (2007).

The storage time (detention time of rainwater in tank) also had a significant effect on microbial quality, as shown in Figures 10 and 11. Microbial quality variation inside the main tank was monitored over a 1-week period and significant improvements in quality were observed. All four parameters were analyzed at several depths in the inlet and outlet sections of the main tank, and selected results for total coliforms and *E. coli* at four vertical sampling points (surface, midway, PoS, and bottom) in the outlet section of the main tank are presented in Figure 10. Concentrations of total coliform bacteria and *E. coli* decreased with time at all sampling points except at the bottom (S_24) of the tank where both increased. The improvement in microbial quality at all other points again suggests the importance of sedimentation. The high concentrations of total coliforms and *E. coli* in bottom samples (Figure 10) further supports this conclusion. These changes in microbial water quality over time can be predicted by regression analysis based on exponential graph fittings. The total number of microorganisms at different sample points with respect to retention time can be predicted as follows (eq 1):

$$\text{number of microorganisms} = ae^{bt} \tag{1}$$

where t is the retention time in days and both a and b are the regression constants of the experimental data shown in Table 4.

The most critical microbial changes over time were observed at the PoS (S_25) inside the main tank, as shown in Figure 11. Significant water quality improvement can be seen at the PoS with increasing retention time as a result of sedimentation and naturally-occurring water quality improvement processes. These results indicate that the microbial quality of rainwater can be improved greatly with sufficient storage time. Because RHW storage times >1 week in wet seasons could be deemed impractical, microbial contamination can be appreciably reduced with proper maintenance of the catchment surface and use of a first-flush diverting device.

Conclusions

The effects of multiple parameters (catchment, first-flush, and storage) on microbial quality in two RWH systems were investigated to support the establishment of proper design and maintenance guidelines to ensure good quality water at the supply point. Inside the storage tank, relatively better water quality was observed at the PoS (about 0.5 to 1 m from the base of the storage tank) than at the surface or bottom of the tanks. In addition, longer flow paths and the presence of the internal walls/baffles can also be important design parameters for storage tanks. Because samples taken following about 1 mm of rainfall exhibited better microbial quality compared with first-flush samples, diverting the first-flush of rainfall from entering the storage tank can also improve stored rainwater quality. The selection of appropriate roof materials in conjunction with regular cleaning of the catchment surfaces to remove dust,

Table 4—Regression constants for different microbial parameters at different points inside main tank (CFU = colony forming units; PoS = point-of-supply; HPC = heterotrophic plate count bacteria).

Bacteria (CFU/100 mL)	Equation constants	Sampling points at outlet section of the main tank: Bottom	PoS	Midway	Surface
Total coliforms	*a*	915.53	456.75	614.41	737.77
	b	0.148	–0.257	–0.169	–0.170
Fecal coliforms	*a*	331.0	173.18	229.78	338.22
	b	0.149	–0.257	–0.189	–0.170
Escherichia coli	*a*	323.76	172.57	249.54	334.63
	b	0.143	–0.333	–0.279	–0.232
HPC (CFU/mL)	*a*	6930.45	1217.13	2148.44	5551.20
	b	0.074	–0.228	–0.161	–0.175

leaves, and bird droppings are also important. Further, the finding of better microbial quality of stored rainwater inside underground tanks than in the open weirs in this study signifies the importance of favorable dark storage/low temperature conditions compared to ambient light exposure and the presence of flies, mosquitoes, and other insects. Finally, the microbial quality of rainwater generally improved with storage time, especially when preceded by an extended dry period. Thus, collected rainwater should be stored (e.g., at least 1 week) before use to allow sufficient time for naturally-occurring water quality improvement processes to occur.

Acknowledgements

This study was supported by the Research Institute of Engineering Science of Seoul National University, South Korea. It is also a part of the *Projects & Research* axis of the Alamoudi Water Chair at King Saud University, Riyadh, Saudi Arabia.

Submitted for publication January 17, 2012; accepted for publication March 20, 2013.

References

Ahammed, M. M.; Meera, V. (2006) Iron Hydroxide-Coated Sand Filter for Household Drinking Water from Roof-Harvested Rainwater. *J. Water Supply Res. Technol. – AQUA,* **55** (7–8), 493–498.

Amin, M. T.; Han, M. Y. (2007) Scope/Need of Soft Path Water Resource Management in Developing Countries. *Water Sci. Technol. Water Supply,* **7** (5–6), 185–192.

Amin, M. T.; Han, M. Y. (2009a) Roof-Harvested Rainwater for Potable Purposes: Application of Solar Collector Disinfection (SOCO-DIS). *Water Res.,* **43** (20), 5225–5235.

Amin, M. T.; Han, M. Y. (2009b) Water Environmental and Sanitation Status in Disaster Relief of Pakistan's 2005 Earthquake. *Desalination,* **248** (1–3), 436–445.

Amin, M. T.; Han, M. Y. (2009c) Roof-Harvested Rainwater for Potable Purposes: Application of Solar Disinfection (SODIS) and Limitations. *Water Sci. Technol.,* **60** (2), 419–431.

Amin, M. T.; Han, M. Y. (2011) Improvement of Solar Based Rainwater Disinfection by Using Lemon and Vinegar as Catalysts. *Desalination,* **276** (1–3), 416–424.

American Public Health Association (APHA); American Water Works Association; Water Environment Federation (1999) *Standard Methods for the Examination of Water and Wastewater,* 20th ed.; American Public Health Association: Washington, D.C.

Ariyananda, T. (2005) Rainwater as Safe Drinking Water. Paper presented at Tokyo Asia Pacific Sky Water Forum; Sumida-City, Tokyo, Japan, Aug 1–8; Tokyo Asia Pacific Sky Water Forum Executive Committee and Sumida Ward: Tokyo, Japan.

Baguma, D.; Loisk, I. W.; Jung, H. (2010) Water Management, Rainwater Harvesting and Predictive Variables in Rural Households. *Water Resour. Manage.,* **24** (13), 3333–3348.

Brewster, M. R.; Buros, O. K. (1985) The Use of Non-Conventional Water Resource Alternatives in Water Short Areas. *Desalination,* **56,** 89–108.

Chanan, A.; Woods, P. (2006) Introducing Total Water Cycle Management in Sydney: A Kogarah Council Initiative. *Desalination,* **187** (1–3): 11–16.

Chang, M.; McBroom, M. W.; Beasley, R. S. (2004) Roofing as a Source of Nonpoint Water Pollution. *J. Environ. Manag.,* **73** (4), 307–315.

Coombes, P. J.; Dunstan, R. H.; Spinks, A.; Evan, C. A.; Harrison, T. (2005) An Overview of a Decade of Research into the Quality of Rainwater Supplies Collected from Roofs. *Proceedings of the 12th International Conference on Rain Water Catchment Systems;* New Delhi, India, Nov; International Rainwater Catchment Systems Association: New Delhi, India.

Coombes, P. J.; Dunstan, R. H.; Spinks, A.; Evan, C. A.; Harrison, T. (2006) Key Messages from a Decade of Water Quality Research into Roof Collected Rainwater Supplies. Paper presented at 1st National Hydropolis Conference 2006; Perth, Australia, Oct 8–11; Stormwater Industry Association: Beaumaris, Australia.

Coombes, P. J.; Kuczera, G.; Kalma, J. D.; Argue, J. R. (2002) An Evaluation of the Benefits of Source Control Measures at the Regional Scale. *Urban Water,* **4** (4), 307–320.

Coombes, P. J.; Kuczera, G.; Kalma, J. D.; Dunstan, R. H. (2000) Rainwater Quality from Roofs, Tanks and Hot Water Systems at Figtree Place. *Proceedings of the 3rd International Hydrology and Water Resource Symposium;* Perth, Australia, Nov 20–23; Engineers Australia: Barton.

Daigger, G. T. (2009) Evolving Urban Water and Residuals Management Paradigms: Water Reclamation and Reuse, Decentralization, and Resource Recovery. *Water Env. Res.,* **81** (8), 809–823.

Dillaha, T. A.; Zolan, W. J. (1985) Rainwater Catchment Water Quality in Micronesia. *Water Res.,* **19** (6), 741–746.

European Commission (EC) (1994) Recommendations for Using Rainwater in Public and Private Buildings (European Commission, Directorate General for Energy XVII) 1990–1994.

Evans, C. A.; Coombes, P. J.; Dunstan, R. H. (2006) Wind, Rain and Bacteria: The Effect of Weather on the Microbial Composition of Roof-Harvested Rainwater. *Water Res.,* **40** (1), 37–44.

Forster, J. (1999) Variability of Roof Runoff Quality. *Water Sci. Technol.,* **39** (5), 137–144.

Ghisi, E.; Ferreira, D. F. (2007) Potential for Potable Water Savings by Using Rainwater and Greywater in a Multi-Storey Residential Building in Southern Brazil. *Build. Environ.,* **42** (7), 2512–2522.

Gould, J. E. (1999) Is Rainwater Safe to Drink? A Review of Recent Findings. *Proceedings of the 9th International Rainwater Catchment Systems Conference;* Petrolina, Brazil, July 6–9; International Rainwater Catchment Systems Association: New Delhi, India.

Han, M. Y.; Mun, J. S. (2008) Particle Behavior Consideration to Maximize the Settling Capacity of Rainwater Storage Tanks. *Water Sci. Technol.,* **56** (11), 73–79.

Handia, L.; Tembo, J. M.; Mwiindwa, C. (2003) Potential of Rainwater Harvesting in Urban Zambia. *Phys. Chem. Earth,* **28** (20–27), 893–896.

Hart, C.; White, D. (2006) Water Quality and Construction Materials in Rainwater Catchments across Alaska. *J. Environ. Eng. Sci.,* **5** (1), S19–S25.

Hartung, H. (2007) Rainwater Utilization in Africa, Some Experiences. *Proceedings of the 1st International Rainwater Leadership Workshop;* International Water Association Rainwater Harvesting and Management Specialist Group (IWA WHM SG); Seoul National University Brain Korea 21 Sustainable Infrastructure Research Group (SNU BK21 SIR Group); and United Nations Environment Programme (UNEP): Seoul, Korea.

Hatibu, N.; Mutabazi, K.; Senkondo, E. M.; Msangi, A. S. K. (2006) Economics of Rainwater Harvesting for Crop Enterprises in Semi-Arid Areas of East Africa. *Agric. Water Manage.,* **80** (1–3), 74–86.

Heyworth, J. S.; Glonek, G.; Maynard, E. J.; Baghurst, P. A.; Finlay-Jones, J. (2006) Consumption of Untreated Tank Rainwater and Gastroenteritis among Young Children in South Australia. *Int. J. Epidemiol.,* **35** (4), 1051–1058.

Ibrahim, M. B. (2009) Rainwater Harvesting for Urban Areas: A Success Story from Gadarif City in Central Sudan. *Water Resour. Manage.,* **23** (13), 2727–2736.

Islam, M. M.; Chou, F. N.-F.; Kabir, M. R.; Liaw, C.-H. (2010) Rainwater: A Potential Alternative Source for Scarce Safe Drinking and Arsenic Contaminated Water in Bangladesh. *Water Resour. Manage.,* **24** (14), 3987–4008.

Jones, A. M.; Harrison, R. M. (2004) The Effects of Meteorological Factors on Atmospheric Bioaerosol Concentrations—A Review. *Sci. Total Environ.,* **326** (1–3), 151–180.

Keler, S.; Meyer, B.; Seeling, S.; Tressel, E.; Krein, A. (2012) Influence of Near-to-Nature Stormwater Management on the Local Water Balance Using the Example of an Urban Development Area. *Water Environ. Res.,* **84** (5), 441–451.

Kim, R. H.; Lee, S.; Kim, J. O. (2005) Application of a Metal Membrane for Rainwater Utilization: Filtration Characteristics and Membrane Fouling. *Desalination,* **177** (1–3), 121–132.

Kim, R. H.; Lee, S.; Jeong, J.; Lee, J. H.; Kim, Y. K. (2007) Reuse of Greywater and Rainwater Using Fiber Filter Media and Metal Membrane. *Desalination,* **202** (1–3), 326–332.

Lee, J. Y.; Yang, J. S.; Han, M. Y.; Choi, J. Y. (2010) Comparison of the Microbiological and Chemical Characterization of Harvested Rainwater and Reservoir Water as Alternative Water Resources. *Sci. Total Environ.,* **408** (4), 896–905.

Lighthart, B. (2000) Mini-Review of the Concentration Variations Found in the Alfresco Atmospheric Bacterial Populations. *Aerobiologia,* **16** (1), 7–16.

Lye, D. J. (2002) Health Risks Associated with Consumption of Untreated Water from Household Roof Catchment Systems. *J. Amer. Water. Res. Assoc.,* **38** (5), 1301–1306.

Meera, V.; Ahammed, M. M. (2006) Water Quality of Rooftop Rainwater Harvesting Systems: A Review. *J. Water Supply Res. Technol. – AQUA,* **55** (4), 257–268.

Morris, R. D.; Naumova, E. N.; Levin, R.; Munasinghe, R. L. (1996) Temporal Variation in Drinking Water Turbidity and Diagnosed Gastroenteritis in Milwaukee. *Am. J. Public Health.,* **86** (2), 237–239.

Murad, A. A.; Al Nuaimi, H.; Al Hammadi, M. (2007) Comprehensive Assessment of Water Resources in the United Arab Emirates (UAE). *Water Resour. Manage.,* **21** (9), 1449–1463.

Nair, J.; Gibbs, R.; Mathew, K.; Ho, G. E. (2001) Suitability of the H2S Method for Testing Untreated and Chlorinated Water Supplies. *Water Sci. Technol.,* **44** (6), 119–126.

Nakata, K.; Wansorn, S.; Takano, T. (1995) Lead Concentration in Rain Water Used for Drinking in the Area Surrounding Bangkok. *Asia Pac. J. Publ. Health,* **8** (1), 8–9.

Nazer, D. W.; Siebel, M. A.; Zaag, P. V.; Mimi, Z.; Gijzen, H. J. (2010) A Financial, Environmental and Social Evaluation of Domestic Water Management Options in the West Bank, Palestine. *Water Resour. Manage.,* **24** (15), 4445–4467.

Olem, H.; Berthouex, P. M. (1989) Acidic Deposition and Cistern Drinking Water Supplies. *Environ. Sci. Technol.,* **23** (3), 333–340.

Pinfold, J. V.; Horan, N. J.; Wirojanarud, W.; Mara, D. (1993) The Bacteriological Quality of Rainjar Water in Rural Northeast Thailand. *Water Res.,* **27** (2), 297–302.

Sazakli, E.; Alexopoulos, A.; Leotsinidis, M. (2007) Rainwater Harvesting, Quality Assessment and Utilization in Kefalonia Island, Greece. *Water Res.,* **41** (9), 2039–2047.

Schwartz, J.; Levin, R.; Hodge, K. (1997) Drinking Water Turbidity and Pediatric Hospital Use for Gastrointestinal Illness in Philadelphia. *Epidemiol.,* **8** (6), 615–620.

Simmons, G.; Hope, V.; Lewis, G.; Whitmore, J.; Gao, W. (2001) Contamination of Potable Roof-Collected Rainwater in Auckland, New Zealand. *Water Res.,* **35** (6), 1518–1524.

Spinks, A.; Berghout, B.; Dunstan, R.; Coombes, P.; Kuczera, G. (2005) Tank Sludge as a Sink for Bacterial and Heavy Metal Contaminants and its Capacity for Settlement, Re-Suspension and Flocculation Enhancement. *Proceedings of the 12th International Conference on Rain Water Catchment Systems;* New Delhi, India, Nov; International Rainwater Catchment Systems Association: New Delhi, India.

Spinks, A. T.; Dunstan, R. H.; Harrison, T.; Coombes, P. J.; Kuczera, G. (2006) Thermal Inactivation of Water-Borne Pathogenic and Indicator Bacteria at Sub-Boiling Temperatures. *Water Res,* **40** (6), 1326–1332.

Sturm, M.; Zimmermann, M.; Schutz, K.; Urban, W.; Hartung, H. (2009) Rainwater Harvesting as an Alternative Water Resource in Rural Sites in Central Northern Namibia. *Phys. Chem. Earth,* **34** (13–16), 776–785.

Thomas, P. R.; Greene, G. R. (1993) Rainwater Quality from Different Roof Catchments. *Water Sci. Technol.,* **28** (3–5), 291–299.

Uba, B. N.; Aghogho, O. (2000) Rainwater Quality from Different Roof Catchments in the Port Harcourt District, Rivers State, Nigeria. *J. Water Supply Res. Technol. – AQUA,* **49** (5), 281–288.

United Nations Environment Programme (UNEP) (1998) *Sourcebook of Alternative Technologies for Freshwater Augmentation in Some Asian Countries;* IETC Technical Publication Series; UNEP International Environmental Technology Centre: Osaka, Japan.

Vazquez, A.; Gostoya, M.; Pena, R. M.; Garcia, S.; Herrero, C. (2003) A Rainwater Quality Monitoring Network: A Preliminary Study of the Composition of Rainwater in Galicia (NW Spain). *Chemosphere,* **51** (5), 375–386.

World Health Organization (WHO) Working Group (1986) Health Impact of Acidic Deposition. *Sci. Total Environ.,* **52** (3), 157–187.

Yaziz, M. I.; Taunting, H.; Sapari, N.; Ghazali, A. W. (1989) Variations in Rainwater Quality from Roof Catchments. *Water Res.,* **23** (6), 761–765.

Yufen, R.; Xiaoke, W.; Zhiyun, O.; Hua, Z.; Xiaonan, D.; Hong, M. (2008) Stormwater Runoff Quality from Different Surfaces in an Urban Catchment in Beijing, China. *Water Environ. Res.,* **80** (8), 719–724.

Zhang, Y.; Grant, A.; Sharma, A.; Chen, D.; Chen, L. (2010) Alternative Water Resources for Rural Residential Development in Western Australia. *Water Resour. Manage.,* **24** (1), 25–36.

Zhu, K.; Zhang, L.; Hart, W.; Liu, M.; Chen, H. (2004) Quality Issues in Harvested Rainwater in Arid and Semi-Arid Loss Plateau of Northern China. *J. Arid Environ.,* **57** (4), 487–505.