Effect of Roof Material on Water Quality for Rainwater Harvesting Systems

Report

by
Carolina B. Mendez
Brigit R. Afshar
Kerry Kinney, Ph.D.
Michael E. Barrett, Ph.D.
Mary Jo Kirisits, Ph.D.

Texas Water Development Board
P.O. Box 13231, Capitol Station
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1 Executive summary

The pressing need for sustainable freshwater supplies has increased the use of roof-based rainwater collection systems for potable applications. Although rainwater harvesting systems can be simple and inexpensive to construct, various sources of contamination within the collection system can negatively affect water quality. In addition to environmental factors (e.g., seasonal variations) that affect rainwater quality, harvested rainwater quality is affected by the roofing material on the catchment surface. The main objective of this research was to provide information to the rainwater harvesting community in Texas regarding the impact of roofing material on harvested rainwater quality.

In this study, five pilot-scale roofs (asphalt fiberglass shingle, Galvalume® metal, concrete tile, cool, and green) and three full-scale residential roofs (two asphalt fiberglass shingle and one Galvalume® metal) were equipped with rainwater sampling devices to collect the "first flush" and water after the first flush. The harvested rainwater was collected from multiple rain events and analyzed for the following parameters: pH, conductivity, turbidity, total suspended solids (TSS), total coliform (TC), fecal coliform (FC), nitrate, nitrite, total organic carbon (TOC), dissolved organic carbon (DOC), selected synthetic organic compounds, and selected metals.

Generally, the first flush contained the highest concentrations of microbial and chemical contaminants in comparison to the subsequent collection tanks, indicating that the quality of harvested rainwater improved with roof flushing. However, the rainwater harvested after the first flush did contain some contaminants at concentrations above United States Environmental Protection Agency (USEPA) drinking water standards (i.e., turbidity, TC, FC, iron, and aluminum). This indicates that harvested rainwater must be treated prior to potable use.

Based on the pilot- and full-scale studies, none of the roofing materials emerged as clearly superior to the others in terms of the quality of the rainwater harvested after the first flush. From our limited data set, green roofs do not appear to be the best candidates for rainwater harvesting for indoor domestic use if the harvested rainwater is disinfected with chlorine. Although the rainwater harvested after the first flush from the green roof consistently had the lowest values of TSS, turbidity, nitrite, aluminum, iron, copper, and chromium, it also had the highest values of DOC; if disinfected by chlorination, the high DOC concentrations could lead to high concentrations of disinfection by-products.

While metal and tile roofs are commonly used for rainwater harvesting in developed countries, our limited data set suggests that asphalt fiberglass shingle and cool roofs also might be considered for this purpose given the quality of harvested rainwater that they produced; additional studies of asphalt fiberglass shingle and cool roofs are needed to provide a robust data set on harvested water quality.

2 Introduction

Water scarcity has become a serious problem due to increased urbanization, frequent droughts, and changing climate patterns. Rainwater harvesting systems are one way to address the worldwide increase in demand for safe water. In the United States, water conservation has resulted in the construction of 100,000 residential rainwater harvesting systems (Lye, 2002). Although rainwater harvesting systems can be simple and inexpensive to construct, various sources of contamination within the collection system can negatively affect water quality.

Contamination in harvested rainwater is affected by roof type, including roofing materials, slope, and length (Kingett Mitchell, 2003; Yaziz et al., 1989). Due to the acidic nature of ambient rainwater, chemical compounds from roofing materials may leach into the harvested rainwater (King and Bedient, 1982). Specifically, heavy metals such as cadmium, copper, lead, zinc, and chromium have been detected in rooftop-harvested rainwater (Quek and Förster, 1993; Lye, 1992; Yaziz et al., 1989). A study conducted in Texas investigated the effect of roofing materials on the quality of rooftop-harvested rainwater (Chang and Crowley, 1993) from 4 roof types and showed that a wooden shingle roof yielded the worst water quality and a terra cotta clay roof yielded the best. In the same study, it was reported that 7 metal concentrations in harvested rainwater exceeded the United States Environmental Protection Agency (USEPA) surface water quality standards (Chang and Crowley, 1993). In addition, Simmons et al. (2001) examined harvested rainwater quality from 125 residential roofs in New Zealand and found that less than 2.4% of the samples exceeded drinking water standards for zinc and copper. The same study showed that 14% of the samples exceeded drinking water standards for lead, which was attributed to the roofs in the study that were coated with lead-based paint. Other studies showed that older roofs leach more metals, suggesting that the age of the roof can negatively impact the quality of harvested rainwater (Chang et al., 2004). Although several additional studies in other countries have examined the effect of roofing material on harvested rainwater quality, domestic studies of the effect of roofing material on harvested rainwater quality might be more useful because roofing materials, coatings, and building practices vary globally.

In addition to leaching chemicals, rooftops also can release contaminants that accumulate during dry and wet deposition, such as organic compounds (Chang et al., 2004). Studies have detected a range of organic compounds in ambient rainwater samples, including polycyclic aromatic hydrocarbons (PAHs) and pesticides, with concentrations exceeding USEPA drinking water standards (Basheer et al., 2003; Polkowska et al., 2000). Ambient rainwater also is susceptible to contamination by microbial aerosols; urban aerosols have recently been shown to contain up to 1,800 different types of bacteria, which is comparable to the diversity of bacteria found in soils (Brodie et al., 2006). Deposition of fecal microorganisms on rooftops from animals such as birds, lizards, and squirrels is problematic as well (Ahmed et al., 2008; Crabtree et al., 1996). Researchers have detected total coliform (TC), fecal coliform (FC), *Salmonella* spp., *Campylobacter, Escherichia coli, Cryptosporidium,* and *Giardia* in rainwater storage tanks (Ahmed et al., 2008; Texas Commission on Environmental Quality [TCEQ], 2007; Lye, 2002; Simmons et al., 2001; Gould, 1999; Crabtree et al., 1996; Lye, 1987). This is an indication that rainwater harvesting systems have the potential to transmit microorganisms that can cause gastrointestinal illness in humans. Leaf litter and bacterial and algal growth in gutter seams also contribute to elevated microbial concentrations in roof runoff. Additionally, previous studies have shown that contamination in roof runoff is affected by the length of time between rain events (Yaziz et al., 1989), season (Jones and Harrison, 2004; Lighthart, 2000; Förster, 1998), land use (Bucheli et al., 1998), roof orientation to sunlight and wind direction (Evans et al., 2007; Evans et al., 2006), rainfall pH, rainfall intensity, and rainfall quantity (Yaziz et al., 1989).

The main objective of this research was to provide information to the rainwater harvesting community in Texas regarding the impact of roofing material on harvested rainwater quality. In Task 1, we identified roofing materials that are commonly used in Texas and those that are commonly recommended in Texas for rainwater harvesting. In Task 2, we examined the quality of rainwater harvested from pilot-scale roofs constructed with traditional materials (i.e., asphalt fiberglass shingles, galvanized metal, concrete tiles) and alternative materials (i.e., green and cool roofs). In Task 3, we examined the quality of rainwater harvested from three existing full-scale residential roofs (i.e., asphalt fiberglass shingle and galvanized metal).

3 Task 1. Survey of roofing materials commonly used in Texas

A survey was conducted to determine which residential roofing materials are most commonly used in Texas and what products are used to adhere, seal, or coat roofing materials. To complete this task, contact information for 71 roofing contractors was collected from the National Roofing Contractors Association (NRCA) and the Midwest Roofing Contractors Association (MRCA); the list of contractors is summarized in the Appendix (Table 9-1). Forty-five percent of the contractors agreed to participate, yielding a total of 23 residential and 9 commercial roofing contractors who participated in the survey. A summary of the survey questions and answers are provided in the Appendix (Table 9-2). According to the survey, all commercial and residential roofing contractors confirmed that self-adhesive asphalt fiberglass shingles are the most commonly used residential roofing material in Texas, being used on more than 80% of residential roofs (Jason Wright, personal communication, 2008); nails also are used to fasten the shingles. According to the survey, the second most commonly used residential roofing material in Texas is a type of metal roof called Galvalume®, which is usually fastened with nails. In addition to asphalt fiberglass shingle and metal roofs, it was reported that concrete roofing tiles are used in Texas. The top of the concrete tiles is fastened with nails. When asked what roofing materials should be recommended for rainwater harvesting, more than 80% of the contractors said that metal roofs should be used.

To investigate the chemical composition of each roofing material, several material safety data sheets (MSDS) were retrieved from manufacturers that were recommended by the commercial and residential contractors. According to the MSDS by Tamko, asphalt fiberglass shingles contain (by weight) <30% asphalt, <65% limestone, <40% mineral granules, <8% fiberglass, and <2.4% formaldehyde (Tamko, 2007).[1] This chemical composition is comparable to that listed in the MSDS by GAF-Elk, which states that asphalt fiberglass shingles contain (by weight) 10-30% asphalt, 25-45% limestone, 20-45% granules, and a fiberglass mat (1-3%) (GAF-Elk, 2008). In the toxicological information section of the Tamko MSDS, it is reported that shingles may contain small amounts of PAHs; some PAHs have been classified as carcinogenic (Barone et al., 1996), including benzo(a)pyrene, which has been identified in asphalt fumes.

According to the MSDS by MonierLifetile Manufacturing, concrete tile is composed of (by weight) 20-30% cement, 50-60% sand and aggregate, 0-5% limestone, and 0-8% acrylic polymer

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[1] Note that the amount of each material listed is shown as “less than” a threshold value. Thus, these threshold values do not add up to 100%.

(MonierLifetile, 1999). In addition, concrete tiles contain a mixture of metal pigments, including cobalt, chromium, and titanium, each ranging between 0-3% (MonierLifetile, 1999).

According to the MSDS by Dofasco, Galvalume® sheets contain (by weight) approximately 95% iron, <1.65% manganese, <1.1% chromium, and <0.12% nickel (Dofasco, 2007). In addition, Dofasco reports that the Galvalume® coating is composed of approximately 43% zinc and 55% aluminum. Variations of this chemical composition are reported by other manufacturers; BlueScope Steel reports that Galvalume® sheets contain (by weight) 1-10% zinc, 1-10% aluminum, and the remainder is composed of iron (BlueScope Steel, 2003); the United States Steel Corporation (USS) reports that Galvalume® sheets contain (by weight) <92% iron and a variety of alloying elements, including aluminum, copper, silicon, sulfur, and manganese, at <1.15% each (USS, 2004). These three manufacturers report that chromium is used as a metallic coating for surface treatment. As a result, it is possible that Galvalume® roofs might leach several types of metals.

Based on the composition of the roofing materials described above, we selected a range of volatile and semi-volatile organic compounds and metals for analysis in rainwater runoff for Tasks 2 and 3.

4 Task 2. Pilot-scale test roofs

Based on the results of Task 1, three roofing materials were selected for the construction of pilot-scale roofs: GAF-Elk's asphalt fiberglass shingle, Berridge's Galvalume® standing seam metal (in which the panels are seamed together to run vertically from the roof's ridge), and MonierLifetile's concrete tile. Three wooden frames were installed at the Lady Bird Johnson Wildflower Center (Austin, Texas), with roofs (8 feet [ft] x 4 ft) at an 18.4°-angle from the horizontal (Figure 4-1). In addition, the runoff was sampled from a pilot-scale green roof and a pilot-scale cool roof that were already in place at the Lady Bird Johnson Wildflower Center. The flat green roof contained a substrate, drainage layer, and membrane root barrier as described previously by Simmons et al. (2008) for a Type E green roof. The flat cool roof consisted of a white, acrylic-surfaced, 2-ply atactic polypropylene (APP) modified bituminous membrane (Simmons et al., 2008). All of the pilot-scale roofs were exposed to the same natural environment and were therefore subject to the same atmospheric deposition, ultraviolet radiation, temperature changes, and rainfall intensity. Although all five roofs were exposed to the same environment, the lack of a slope on the green roof and the cool roof could have affected the quality of harvested rainwater because slope has previously been shown to affect harvested rainwater quality (TCEQ, 2007; Kingett Mitchell, 2003).

Figure 4-1. **Pilot-scale roofs. (From left to right: asphalt fiberglass shingle, Galvalume®, concrete tile)**

It is recommended that the first flush divert a *minimum* of ten gallons (gal) for every 1,000 square feet (ft^2) of collection area (TWDB, 2005), where the collection area is the area of the roof footprint. Since the roof collection areas used in this task were approximately 30.4 to 36.6 ft^2 (metal, shingle, and tile roofs: 7.6 ft by 4 ft; cool and green roofs: 6.56 ft by 5.58 ft), we diverted slightly more than 0.5 gal (2 liters [L]) to ensure that the minimum recommendation for first flush volume was met. The collection tank volumes were determined based on the estimation that 1 inch (in) of rain will result in 0.5 gal of collected water for every square foot of roof footprint area (TWDB, 2005). Therefore, we estimated that the metal, shingle, tile, and cool roof systems could collect at least 7.6 gal (about 28.8 L) for a 0.5-in rain event. Assuming 34% rainwater retention for the Type E green roof (Simmons et al., 2008), we estimated that the green roof could collect at least 6 gal (about 22 L) for a 0.5-in rain event. The average rainfall in the Austin area was approximately 1 in for the majority of rain events in 2009.

To collect rainwater, the base of each roof was equipped with a sampling device that was inserted into an aluminum gutter (Figure 4-2). This insert consisted of a clean 3-in diameter polyvinyl chloride (PVC) pipe (potable quality) cut lengthwise in half and fitted with end caps. Three-quarter-in diameter PVC pipe was used to direct the collected rainwater from the sampling insert to a passive collection system that consisted of a 2-L tank to collect the “first flush” and two 10-L polypropylene tanks in series to collect water after the first flush (henceforth called the first flush, first and second tanks). Once the capacity of the tanks was reached during a rain event, any additional rain exited the system through an overflow spout. In addition, the site was equipped with a separate sampler to collect ambient rainwater (without roof exposure) to assess background pollutant concentrations in the rainwater (Figure 4-3). This sampler consisted of an 18-in diameter polyethylene funnel attached to a 10-L polypropylene tank; the ambient sampler was kept closed until the night before a rain event.

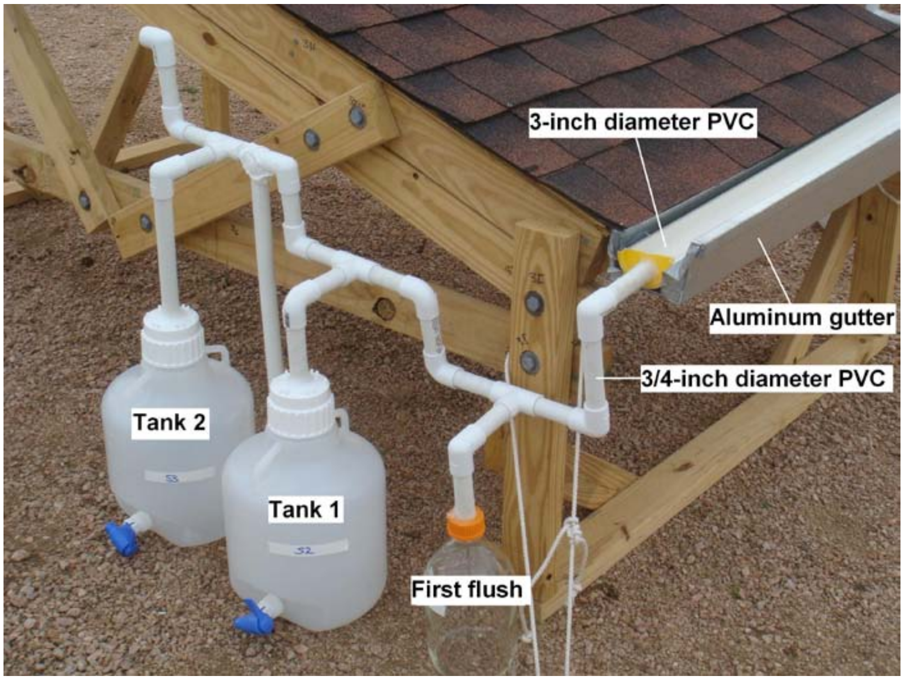

Figure 4-2. **Sampling device for pilot-scale roofs.**

Figure 4-3. **Ambient sampling device.**

The construction of three new pilot-scale roofs was completed on April 9, 2009. Samples were collected from rain events on April 18, 2009, June 11, 2009, July 23, 2009, and September 11, 2009 (Table 4-1). Samples were retrieved immediately after each rain event and analyzed in the laboratory. Between events, each sampling tank was thoroughly washed with Alconox detergent, rinsed thoroughly with deionized water, and autoclaved. The remaining pieces of the field sampler (e.g., PVC piping and funnel) were scrubbed and rinsed with deionized water on site.

Table 4-1. Description of rain events for pilot-scale roof studies.

Date	Rainfall (in)	Temperature(°F)	Number of preceding dry days
4/18/2009	1.4	63-82	4
6/11/2009	1.2	71-98	8
7/23/2009	1.1	74-101	14
9/11/2009	1.3	72-80	5

For the first 3 rain events, the ambient rain, first flush, and first and second tanks were analyzed in triplicate for pH, conductivity, turbidity, total suspended solids (TSS), dissolved organic carbon (DOC), metals (total metals = dissolved + particulate), total coliform (TC), and fecal coliform (FC). Nitrate (NO_3^-) and nitrite (NO_2^-) were measured once for each sample. For the fourth rain event, the first flush and ambient rain samples were analyzed for pesticides and PAHs (Appendix: Table 9-3)**.** Table 4-2 summarizes the analytical methods that were used, and Table 4-3 lists the preservation methods and storage times for each type of sample.

Table 4-2. Analytical methods.

Parameter	Meter/method type	Source
pH	Potentiometry Corning pH meter 230	*Standard Methods* (1998)
Conductivity	Radiometer Copenhagen conductivity MeterLab CDM230	Copenhagen radiometer
Turbidity	Hach turbidity meter model 2100A	Hach (2003)
TSS	Filtration	*Standard Methods* (1998)
TC	M-endo broth	*Standard Methods* (1998)
FC	FC agar	*Standard Methods* (1998)
Nitrate	Colorimetric; chromotropic acid	Hach (2003)
Nitrite	Colorimetric; diazotization	Hach (2003) EPA method 8507
PAHs and pesticides	Methods SW8270 and SW8081/8082 (Appendix: Table 9-3)	DHL Analytical Laboratories
DOC	Tekmar Dohrmann Apollo 9000	*Standard Methods* (1998)
Metals	Inductively coupled plasma mass spectrometry	*Standard Methods* (1998)

Table 4-3. Sample preservation and storage.

Parameter	Preservation	Maximum holding time
pH	None required	N/A
Conductivity	None required	N/A
Turbidity	None required	N/A
TSS	None required	N/A
TC	Store at 4°C	6-8 hours
FC	Store at 4°C	6-8 hours
Nitrate	Acidify to pH < 2; store at 4°C	28 days
Nitrite	Store at 4°C	48 hours
PAHs and pesticides	Store at 4°C	7 days
DOC	Acidify to pH < 2; store at 4°C	14 days
Metals	Acidify to pH < 2; store at 4°C	14 days

N/A: not applicable; analysis was conducted immediately.

As an example rain event, the data from the April 18, 2009 event are shown graphically (Figures 4-4 through 4-15). Since pH, conductivity, turbidity, TSS, DOC, metals, TC, and FC were measured in triplicate, the average of the triplicate measurements (with error bars representing standard deviation or 95% confidence limits) are shown in the plots. Since single measurements were made on each sample for nitrate and nitrite, no error bars are shown for those analytes. These average data from each rain event are tabulated (Tables 4-4 through 4-21) such that the minimum, median, and maximum values for the 3 rain events are shown.

Figure 4-4 shows the pH of the harvested rainwater from the April 18, 2009 event, and Table 4-4 summarizes the median, minimum, and maximum pH values for the three rain events. The pH of the harvested rainwater increased from the first flush through the first and second tanks. The pH of rainwater is approximately 5.7 (TWDB, 2005), and our ambient rain samples had pH values from 5.5 to 6.7. For all rain events, the pH of the harvested rainwater was higher than that of ambient rainfall, ranging from 6.0 to 8.2.

For all rain events, the rainwater harvested after the first flush[2] from the tile roof consistently yielded higher pH values, while the metal and shingle roofs consistently yielded lower pH values. However, all pH values were in the near-neutral range. These values are comparable to other studies of harvested rainwater including Yaziz et al. (1989), which reported pH values of 5.9 to 6.9, and Simmons et al. (2001), which reported pH values of 5.2 to 11.4.

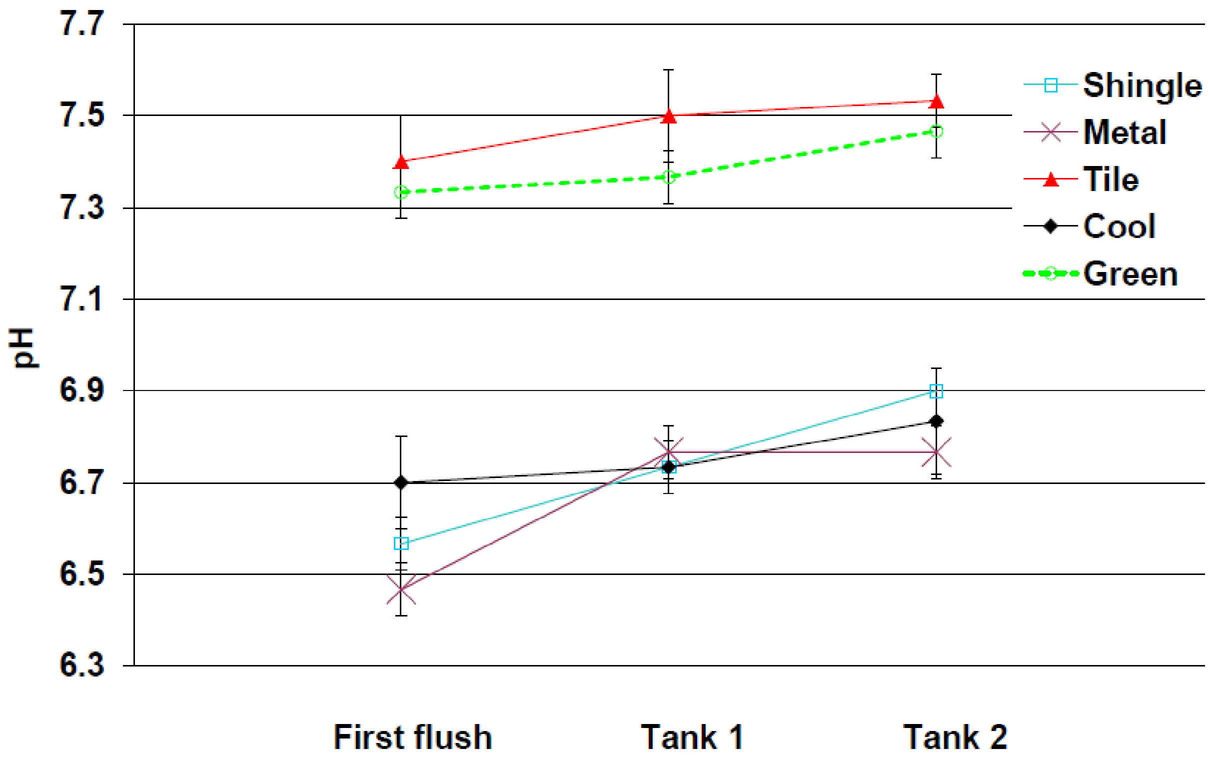

Figure 4-4. **pH in harvested rainwater from pilot-scale roofs for April 18, 2009 event. Ambient rainwater had average pH=5.5. Error bars represent standard deviations from triplicate analyses.**

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[2] It is most important to examine the quality of the rainwater harvested after the first flush since the first flush is diverted from use. Thus, the discussion in this report generally focuses on the harvested rainwater quality in the first and second tanks (Fig. 4-2).

Table 4-4. **pH in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Shingle	6.6 (6.4-7.1)	6.7(6.7-6.9)	6.7(6.7-6.9)
Metal	6.9(6.5-7.6)	6.7(6.6-6.8)	6.0(6.0-6.8)
Tile	7.6(7.4-8.2)	7.7(7.5-8.1)	7.7(7.5-7.7)
Cool	7.1(6.7-8.1)	7.2(6.7-8.0)	7.1(6.8-7.2)
Green	7.3(7.3-7.6)	7.4(7.1-7.6)	7.5(7.0-7.5)
Ambient rain	6.0(5.5-6.7)		

Figure 4-5 shows the conductivity of the harvested rainwater from the April 18, 2009 event, and Table 4-5 summarizes the median, minimum, and maximum conductivity values for the 3 rain events. The conductivity of the harvested rainwater decreased from the first flush through the first and second tanks. Conductivity values in the first flush through the second tank were higher in the April 18, 2009 rain event. For all rain events, rainwater harvested after the first flush from the metal roof yielded lower conductivity values as compared to the other roofing materials, while the green roof yielded higher conductivity values. Conductivity values in the ambient rain ranged from 18 microSiemens per centimeter (µS/cm) to 61 µS/cm, which are similar to those measured by Yaziz et al. (1989), ranging from 6 µS/cm to 33 µS/cm.

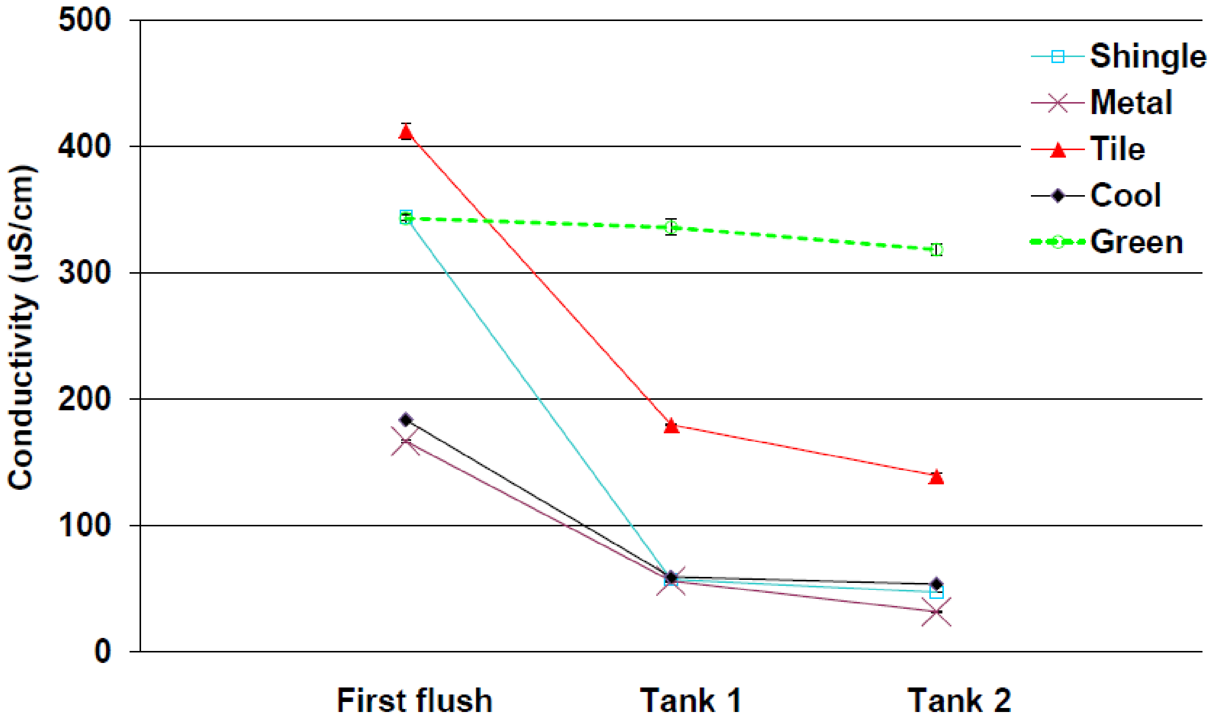

Figure 4-5. **Conductivity in harvested rainwater from pilot-scale roofs for April 18, 2009 event. Ambient rainwater had average conductivity=61 µS/cm. Error bars represent standard deviations from triplicate analyses.**

Table 4-5. Conductivity (µS/cm) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Shingle	221(170-344)	41(23-57)	34(18-47)
Metal	86(55-167)	22(10-56)	14(9-31)
Tile	73(68-413)	41(27-180)	39(18-139)
Cool	100(84-184)	35(19-59)	25(11-53)
Green	284(271-343)	253(118-336)	237(137-319)
Ambient rain	23(18-61)		

Figures 4-6 and 4-7 show turbidity and TSS of the harvested rainwater from the April 18, 2009 event, and Tables 4-6 and 4-7 summarize the median, minimum, and maximum turbidity and TSS values for the 3 rain events. Turbidity decreased dramatically from the first flush through the first and second tanks, with final values of turbidity that were on the same order as that of ambient rain. Turbidity readings in the first flush through the second tank ranged from 2 nephelometric turbidity units (NTU) to 105 NTU for all rain events, which are comparable to the 4 to 94 NTU reported in Yaziz et al. (1989). For all rain events, rainwater harvested after the first flush from the metal, tile, and cool roofs yielded higher turbidity values as compared to other roofing materials, up to 36 NTU, which might be attributed to their smoother surfaces. The lowest turbidity values were found in rainwater harvested after the first flush from the green roof, ranging from 3 NTU to 11 NTU, which is an indication that green roofs can effectively filter out particles. It is important to note, however, that all roofs yielded higher turbidity values than the 1 NTU maximum recommended for potable use of harvested rainwater (TWDB, 2006), which is the same as the USEPA's guideline for filtered surface water (USEPA, 2009). In comparison to the turbidity values, similar trends were seen for TSS. TSS decreased dramatically from the first flush through the first and second tanks, with final values of TSS that were close to that of ambient rain. Yaziz et al. (1989) reported 53 to 276 milligram per liter (mg/L) TSS in harvested rainwater and 10 to 64 mg/L TSS in ambient rainwater. Our values were similar to these, with values of 1 to 118 mg/L TSS in the harvested rainwater after the first flush and 7 to 46 mg/L TSS in ambient rainwater. Similar to turbidity trends, the metal, tile, and cool roofs yielded higher TSS (4 to 118 mg/L) in the harvested rainwater after the first flush as compared to the other roofing materials, and green roofs yielded lower TSS (1 to 25 mg/L) in the harvested rainwater after first flush.

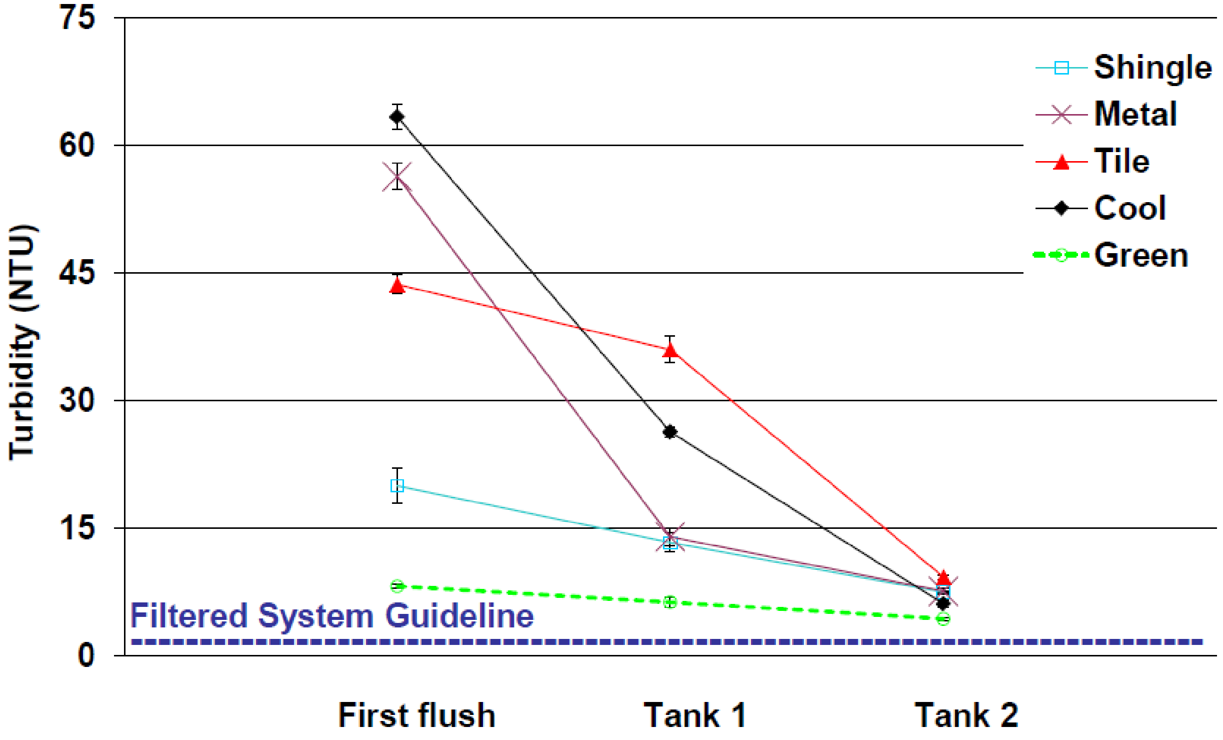

Figure 4-6. **Turbidity in harvested rainwater from pilot-scale roofs for April 18, 2009 event. Ambient rainwater had average turbidity=4 NTU. Error bars represent standard deviations from triplicate analyses. Filter system guideline adapted from USEPA, 2009.**

Table 4-6. **Turbidity (NTU) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Shingle	33(20-41)	16(13-24)	11(8-14)
Metal	96(56-102)	14(12-30)	8(7-9)
Tile	51(44-64)	36(28-36)	6(2-9)
Cool	67(63-105)	20(2-26)	6(2-13)
Green	8(5-15)	6(4-11)	3(3-4)
Ambient rain	4(4-8)		

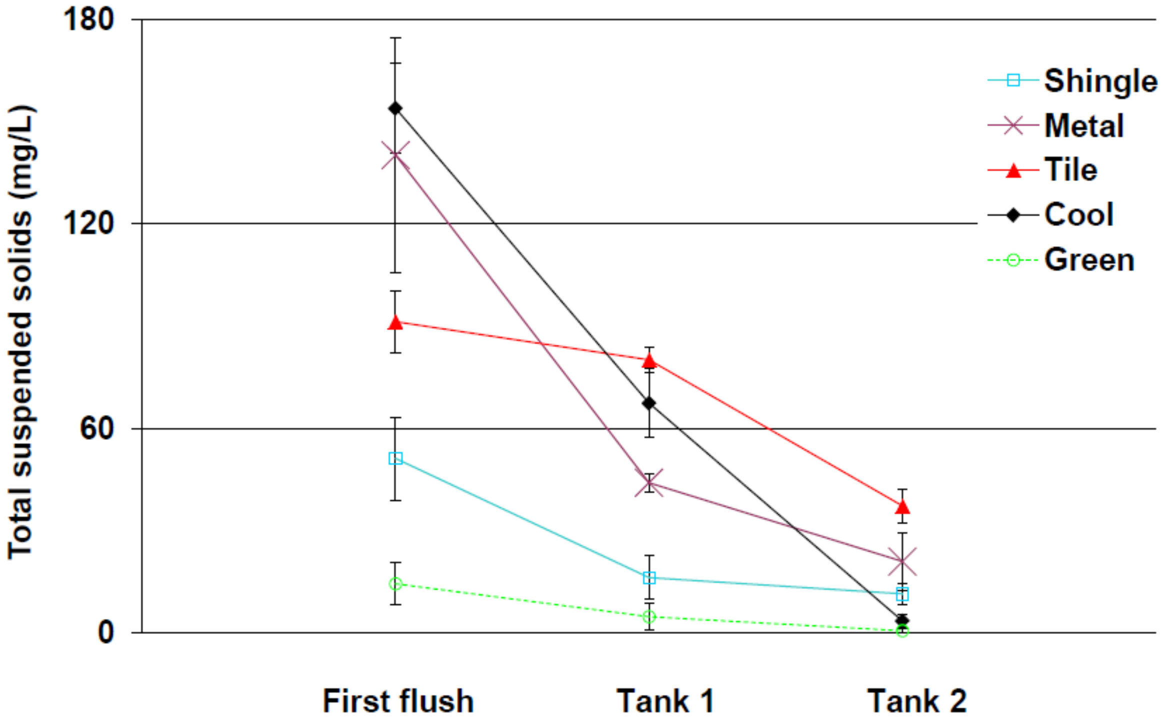

Figure 4-7. **TSS in harvested rainwater from pilot-scale roofs for April 18, 2009 event. Ambient rainwater had average TSS=7 mg/L. Error bars represent standard deviations from triplicate analyses.**

Table 4-7. **TSS (mg/L) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Shingle	108(51-123)	44(16-54)	34(12-43)
Metal	251(140-260)	71(44-87)	21(20-44)
Tile	159(91-164)	70(16-80)	34(4-37)
Cool	202(154-238)	93(67-118)	43(4-46)
Green	22(14-32)	19(5-25)	5(1-15)
Ambient rain	24(7-46)		

Figure 4-8 shows the nitrate concentrations in the harvested rainwater from the April 18, 2009 event, and Table 4-8 summarizes the median, minimum, and maximum nitrate concentrations for the 3 rain events. Nitrate concentrations decreased dramatically from the first flush to the first and second tanks. Nitrate concentrations in the rainwater harvested after the first flush ranged from 0 to 3.3 mg/L NO_3^--N for all rain events, which are below the USEPA drinking water maximum contaminant limit (MCL) of 10 mg/L NO_3^--N. Other studies reported higher nitrate concentrations in harvested rainwater, including 420 mg/L NO_3^--N in anthropogenically influenced areas of Florida (Deng, 1998).

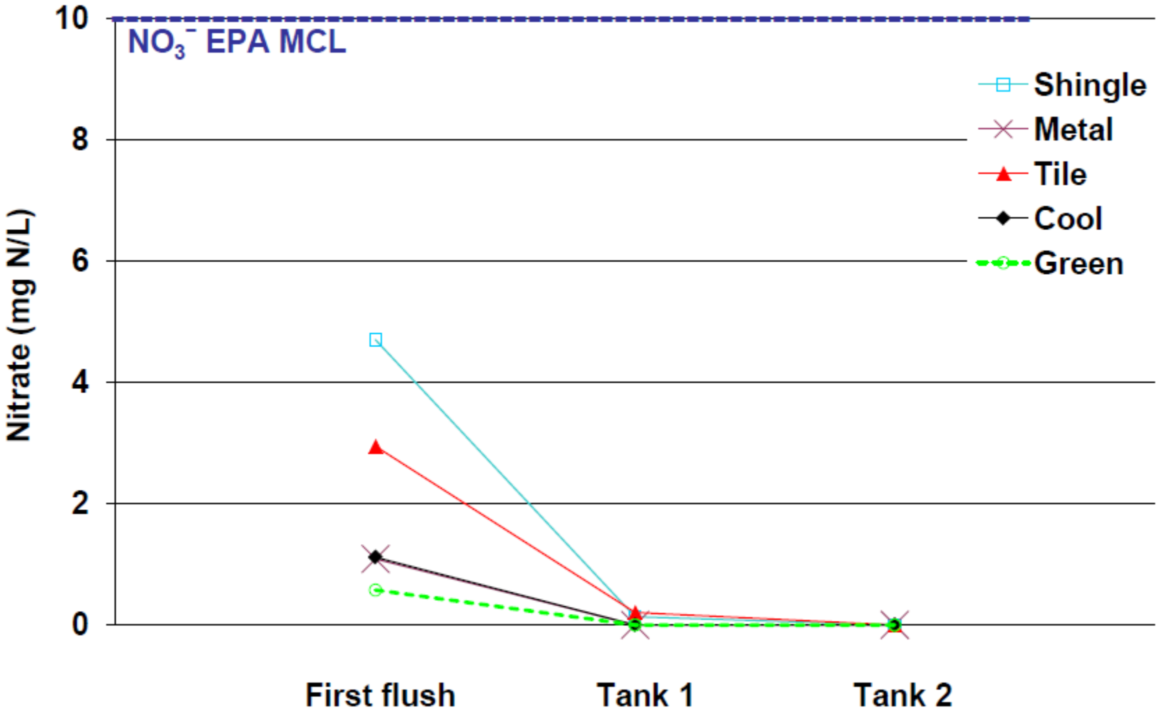

Figure 4-8. **Nitrate in harvested rainwater from pilot-scale roofs for April 18, 2009 event. Ambient rainwater had nitrate=0 mg/L NO_3^--N.**

Table 4-8. **Nitrate (mg/L NO_3^--N) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Shingle	5.4(4.7-5.4)	1.8(0.1-1.8)	0.8(0.0-1.4)
Metal	2.8(1.1-3.7)	1.9(0.0-2.0)	0.9(0.0-1.8)
Tile	3.6(2.9-3.7)	1.8(0.2-2.2)	1.3(0.0-1.3)
Cool	4.7(1.1-4.8)	1.7(0.0-2.0)	1.3(0.0-1.5)
Green	2.5(0.6-3.5)	1.8(0.0-3.3)	1.7(0.0-2.0)
Ambient rain	1.4(0.0-2.4)		

Figure 4-9 shows nitrite concentrations in the harvested rainwater from the April 18, 2009 event, and Table 4-9 summarizes the median, minimum, and maximum nitrite concentrations for the 3 rain events. Similar to nitrate, the nitrite concentrations decreased from the first flush to the first and second tanks. Nitrite concentrations in rainwater harvested after the first flush ranged from 0.00 to 0.04 mg/L NO_2^--N, which are well below the EPA drinking water MCL for nitrite (1 mg/L NO_2^--N). In the April 18, 2009 rain event, only the first flush of the metal roof yielded a nitrite concentration higher than the drinking water regulation; this was not reproduced in subsequent rain events, which showed 0.02 to 0.09 mg/L NO_2^--N in the first flush from the metal roof.

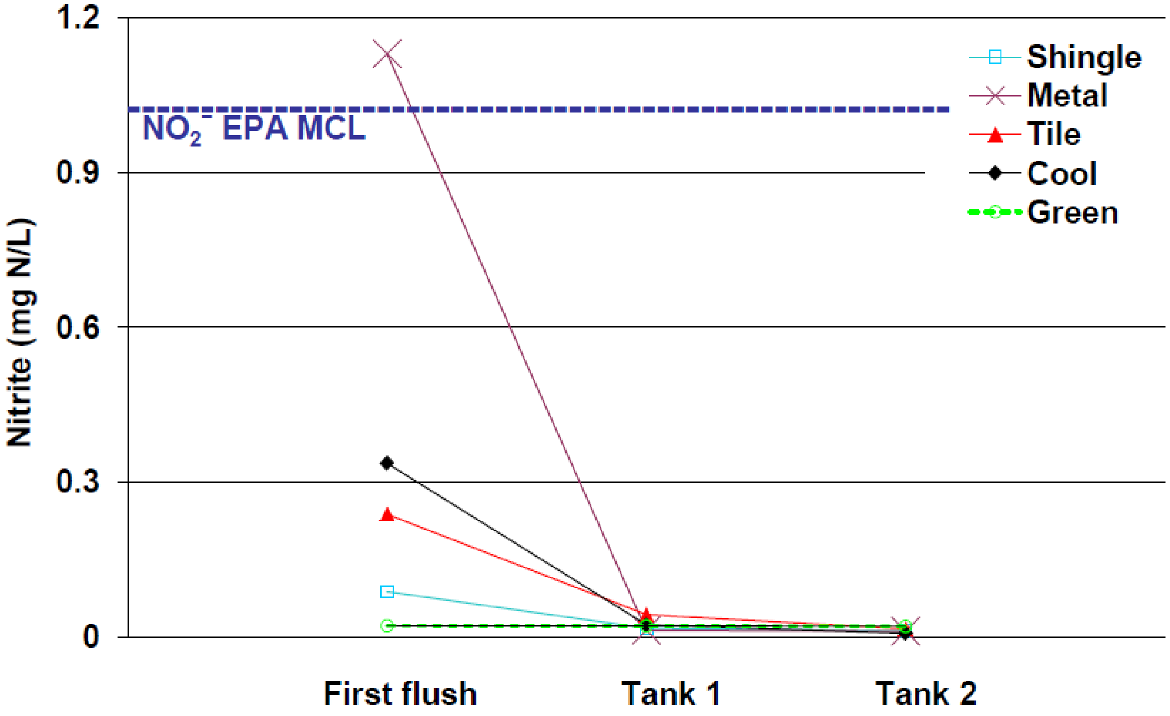

Figure 4-9. **Nitrite in harvested rainwater from pilot-scale roofs for April 18, 2009 event. Ambient rainwater had nitrite=0.009 mg/L NO_2^--N.**

Table 4-9. **Nitrite (mg/L NO_2^--N) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Shingle	0.09(0.07-0.21)	0.03(0.02-0.04)	0.02(0.01-0.03)
Metal	0.09(0.02-1.13)	0.02(0.02-0.03)	0.02(0.01-0.02)
Tile	0.05(0.02-0.24)	0.03(0.02-0.04)	0.02(0.02-0.03)
Cool	0.08(0.02-0.34)	0.02(0.00-0.04)	0.01(0.01-0.03)
Green	0.05(0.02-0.05)	0.02(0.01-0.04)	0.02(0.01-0.03)
Ambient rain	0.01(0.00-0.02)		

Figure 4-10 shows the DOC concentrations of the harvested rainwater from the April 18, 2009 event, and Table 4-10 summarizes the median, minimum, and maximum DOC concentrations for the 3 rain events. DOC concentrations in the rainwater harvested after the first flush ranged from 2.3 mg/L to 37.3 mg/L. Most of the data showed that DOC concentrations decreased from the first flush through the first and second tanks. The shingle roof, however, showed an increasing trend in DOC concentration from the first flush to the first tank, which was consistent in all rain events. The green roof consistently yielded the highest DOC concentration in the second tank, while the metal and cool roofs consistently yielded the lowest DOC concentration in the second tank. If the water were disinfected by chlorination prior to potable use, higher DOC concentrations (i.e., from the green roof) would be likely to produce higher concentrations of disinfection by-products.

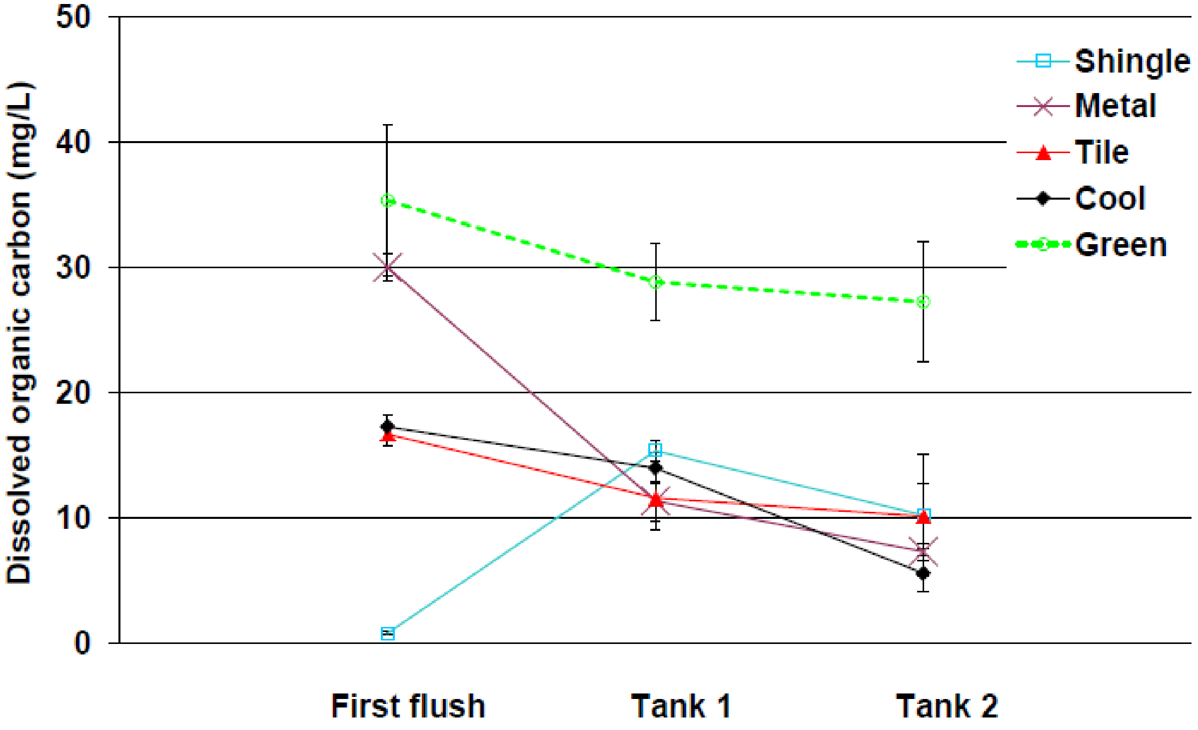

Figure 4-10. **DOC in harvested rainwater from pilot-scale roofs for April 18, 2009 event. Ambient rainwater had average DOC=4.7 mg/L. Error bars represent standard deviations from triplicate analyses.**

Table 4-10. **DOC (mg/L) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Shingle	0.6(0.1-0.8)	11.3(10.2-15.4)	10.3(10.1-13.4)
Metal	11.9(5.3-30)	3.1(2.8-11.4)	2.7(2.4-7.4)
Tile	9.3(0.4-16.7)	4.5(3.3-11.6)	3.4(3.2-10.1)
Cool	14.6(8.2-17.3)	8.7(2.4-14)	5.6(2.3-5.8)
Green	18.2(17.6-35.3)	28.8 (13.5-37.3)	27.3(7.8-35.1)
Ambient rain	4.4(3.4-4.7)		

Figures 4-11 and 4-12 show the TC and FC in the harvested rainwater from the April 18, 2009 event, and Tables 4-11 and 4-12 summarize the median, minimum, and maximum TC and FC for the 3 rain events. TC and FC counts decreased from the first flush to the first and second tanks.

The second tanks always had detectable TC and often had detectable FC, indicating that treatment would be needed prior to potable use. Green roofs showed lower coliform concentrations in harvested rainwater after the first flush for the first two rain events (April 18, 2009 and June 11, 2009), with TC concentrations from 7 to 12 colony forming units per one-hundred milliliters (CFU/100mL) and FC concentrations of <1 CFU/100mL. This was not true of the third rain event (July 23, 2009), which showed much higher coliform concentrations in the harvested rainwater from the green roof after the first flush; in that event, TC concentrations from 833 to 1300 CFU/100mL and FC concentrations from 270 to 390 CFU/100mL were observed. There is no clear explanation for the inter-event variability in FC and TC concentrations in the harvested rainwater from the green roof.

Ambient rainwater for all rain events contained TC concentrations from 547 to 648 CFU/100mL and FC concentrations of 3 to 33 CFU/100mL. Another study (Yaziz et al., 1989) found no TC or FC in ambient rain collected in the open from one meter from the ground. Our ambient sample also was collected approximately one meter from the ground, but the sampler was left open overnight to collect early morning rain events. The higher TC and FC concentrations in our ambient sample may be due to overnight contamination, including airborne deposition or birds that might have visited the sampler.

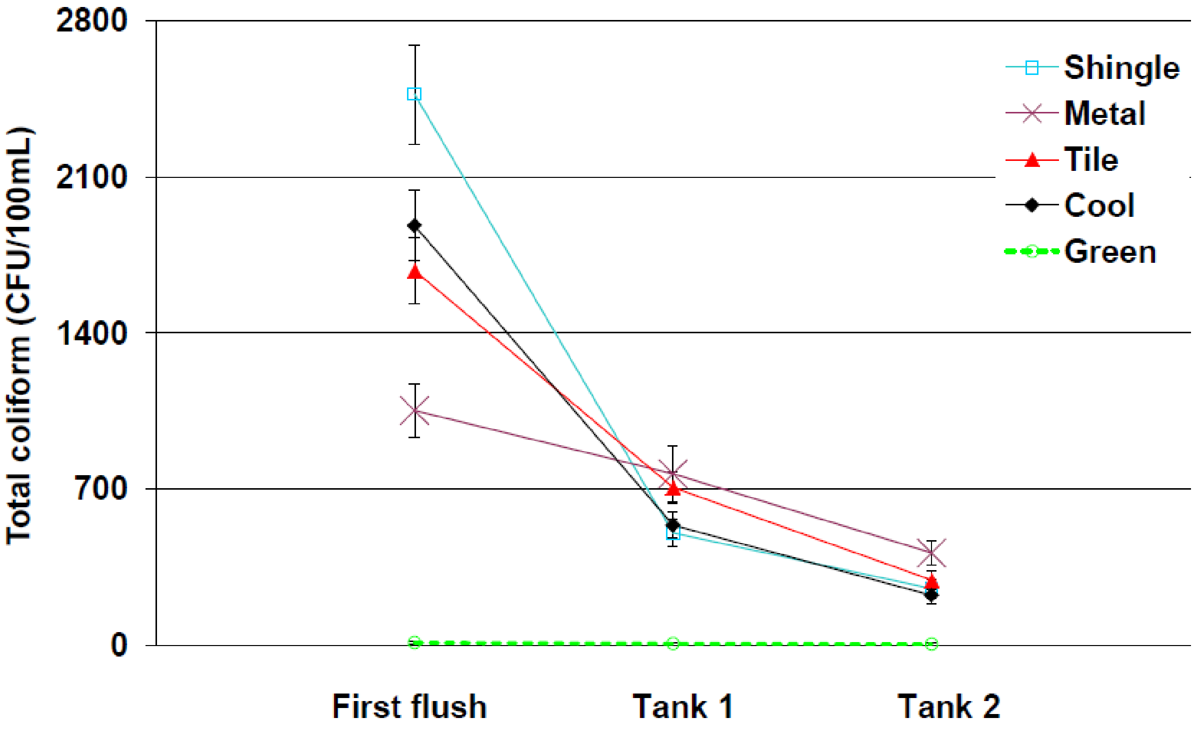

Figure 4-11. **TC in harvested rainwater from pilot-scale roofs for April 18, 2009 event. Ambient rainwater had average TC=648 CFU/100mL. Error bars represent 95% confidence intervals from triplicate analyses.**

Table 4-11. **TC (CFU/100mL) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Shingle	2433(1500-2470)	800(506-1367)	256(177-733)
Metal	767(450-1053)	550(167-770)	416(117-500)
Tile	1517(1017-1680)	883(709-983)	567(293-783)
Cool	1882(1767-3283)	917(540-1333)	226(150-867)
Green	15(13-1233)	12(9-1300)	8(7-833)
Ambient rain	550(547-648)		

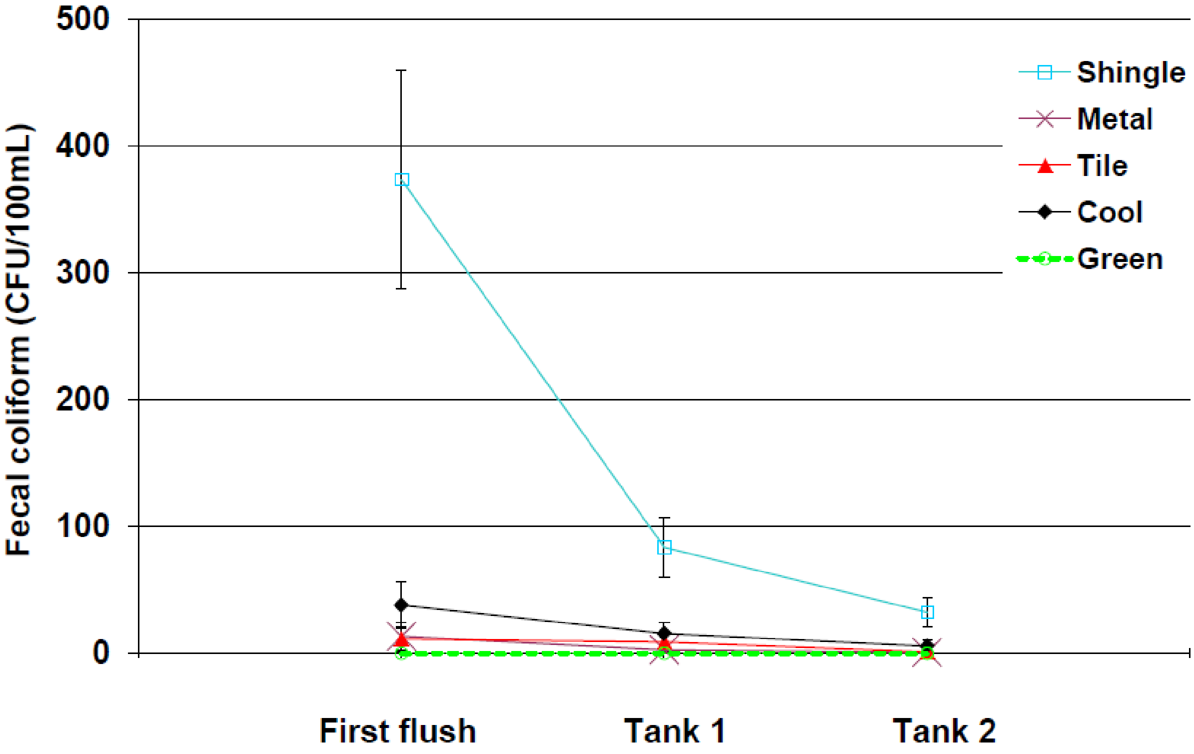

Figure 4-12. **FC in harvested rainwater from pilot-scale roofs for April 18, 2009 event. Ambient rainwater had average FC=15 CFU/100mL. Error bars represent 95% confidence intervals from triplicate analyses.**

Table 4-12. FC (CFU/100mL) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof Type	First flush	Tank 1	Tank 2
Shingle	113(32-373)	83(10-87)	25(9-32)
Metal	13(7-17)	4(<1-8)	<1(<1-6)
Tile	11(10-30)	9(5-20)	<1(<1-8)
Cool	35(25-38)	16(10-22)	7(6-8)
Green	<1(<1-550)	<1(<1-390)	<1(<1-270)
Ambient rain	15(3-33)		

A total of 9 metals were analyzed in the harvested rainwater, including arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), selenium (Se), iron (Fe), zinc (Zn), and aluminum (Al). Tables 4-13 to 4-21 summarize the median, minimum, and maximum metal concentrations for the 3 rain events, and they are compared with the USEPA MCLs or action levels in Table 4-22. Most of the data showed that metal concentrations decreased from the first flush through the first and second tanks, with final metal concentrations that were close to those of ambient rain. As, Cd, and Se were often undetectable: 18 out of 48 samples were below the detection limit of <0.29 microgram per liter (µg/L) As, 20 out of 48 samples were below the detection limit of <0.14 µg/L Se, and 40 out of 48 samples were below the detection limit of <0.10 µg/L Cd. By contrast, Fe and Al concentrations in the harvested rainwater often exceeded EPA secondary MCLs for drinking water (Table 4-22).

Metal concentrations in the harvested rainwater from our pilot-scale roofs were lower than values reported in other studies. For instance, Simmons et al. (2001) reported metal concentrations up to 4500 µg/L Cu (above USEPA action level), 140 µg/L Pb (above USEPA action level), and 3200 µg/L Zn from galvanized iron roofs. In addition, Chang et al. (2004) reported that more that 50% of the harvested rainwater samples from terra cotta clay and wood shingle roofs exceeded the secondary USEPA drinking water standard for Zn and the USEPA action level for Cu. A possible reason for the lower metal concentrations in rainwater harvested from our pilot-scale roofs is that they are relatively new materials in comparison to the roofs in other studies. Overall, as shown in Table 4-22, the rainwater harvested after the first flush from all pilot-scale roofs in our study did not violate any of the primary MCLs or action levels for metals.

Table 4-13. As (µg/L) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Shingle	1.40(0.86-4.20)	<0.29(<0.29-0.67)	0.35(<0.29-0.65)
Metal	0.91(0.58-0.97)	<0.29(<0.29-0.34)	<0.29(<0.29-0.30)
Tile	0.84(0.53-2.69)	0.53(<0.29-1.33)	0.42(<0.29-0.50)
Cool	0.68(0.49-1.06)	<0.29(<0.29-0.42)	<0.29(<0.29-0.17)
Green	4.27(2.98-8.45)	7.75(4.01-7.92)	7.91(3.48-8.38)
Ambient rain	0.14(0.12-0.27)		

Table 4-14. Cd (µg/L) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Shingle	<0.10(<0.10-0.14)	<0.10(<0.10-<0.10)	<0.10(<0.10-<0.10)
Metal	0.17(<0.10-0.34)	<0.10(<0.10-<0.10)	<0.10(<0.10-<0.10)
Tile	<0.10(<0.10-0.20)	<0.10(<0.10-<0.10)	<0.10(<0.10-<0.10)
Cool	<0.10(<0.10-0.16)	<0.10(<0.10-<0.10)	<0.10(<0.10-<0.10)
Green	<0.10(<0.10-<0.10)	<0.10(<0.10-<0.10)	<0.10(<0.10-<0.10)
Ambient rain	<0.10(<0.10-<0.10)		

Table 4-15. Cr (µg/L) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Shingle	3.63(1.60-5.00)	0.20(0.17-1.70)	0.53(0.16-0.66)
Metal	4.24(3.15-12.52)	0.44(0.29-1.61)	0.66(0.16-0.85)
Tile	3.07(1.82-6.59)	1.10(0.48-2.93)	0.83(0.21-0.89)
Cool	1.16(0.69-3.15)	0.53(0.28-0.57)	<0.12(<0.12-0.44)
Green	1.52(0.91-1.61)	0.82(0.46-1.94)	0.86(0.57-1.71)
Ambient rain	0.26(<0.12-0.27)		

Table 4-16. Cu (µg/L) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Shingle	338.60(283.13-600.30)	34.44(24.43-45.75)	25.71(16.47-72.16)
Metal	9.26(5.12-9.88)	2.51(1.01-4.84)	2.15(1.10-2.58)
Tile	12.11(7.84-36.85)	4.99(3.82-19.05)	5.27(2.52-14.35)
Cool	7.92(6.87-12.80)	2.98(1.54-5.16)	1.28(<0.63-2.11)
Green	8.14(4.10-9.01)	6.07(4.97-6.98)	7.73(3.94-12.39)
Ambient rain	0.98(0.68-11.70)		

Table 4-17. Pb (µg/L) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Shingle	2.95(1.02-5.19)	0.85(0.37-0.87)	0.56(0.51-1.19)
Metal	3.94(3.85-6.40)	1.02(0.37-1.08)	0.69(<0.12-2.27)
Tile	7.54(3.22-13.62)	2.13(1.12-8.72)	1.29(0.49-2.89)
Cool	4.97(4.66-11.51)	1.44(1.22-2.49)	0.56(0.50-1.28)
Green[a]	8.79(6.22-39.69)	5.06(3.04-5.39)	3.52(1.72-4.22)
Ambient rain	0.69(0.66-0.94)		

[a] Note: The elevated lead concentration might have come from the solder in the scupper gutter.

Table 4-18. Se (µg/L) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Shingle	0.70(0.28-1.33)	0.16(<0.14-0.21)	<0.14(<0.14-0.21)
Metal	0.52(0.27-0.91)	0.21(<0.14-0.24)	<0.14(<0.14-0.19)
Tile	0.33(0.22-1.16)	0.22(<0.14-0.37)	0.17(<0.14-0.27)
Cool	0.64(0.38-0.90)	0.16(<0.14-0.23)	<0.14(<0.14-0.22)
Green	0.39(0.30-0.39)	0.35(0.26-0.50)	0.30(0.28-0.50)
Ambient rain	0.15(<0.14-0.16)		

Table 4-19. Fe (µg/L) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Shingle	1346.67(348.63-2105.00)	280.13(107.83-342.47)	272.33(201.40-480.93)
Metal	1290.67(742.07-1687.67)	274.40(87.63-323.93)	222.20(40.94-563.00)
Tile	1101.33(747.83-1488.33)	496.07(219.93-761.57)	230.43(75.57-364.47)
Cool	1469.67(520.77-3535.00)	455.27(428.03-721.43)	118.97(114.13-341.80)
Green	85.78(46.59-222.30)	54.47(44.29-78.61)	56.92(54.24-71.65)
Ambient rain	270.80(193.70-1056.00)		

Table 4-20. Zn (µg/L) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Shingle	112.63(82.12-160.57)	34.87(8.25-81.95)	28.22(20.90-84.77)
Metal	753.50(665.57-852.13)	158.83(128.77-272.73)	118.47(77.46-362.13)
Tile	262.80(228.07-542.47)	127.23(96.23-313.67)	91.27(55.60-118.17)
Cool	347.20(271.43-483.33)	121.57(37.93-121.97)	45.45(41.49-98.70)
Green[a]	347.70(286.40-786.37)	377.03(252.83-525.17)	308.13(248.83-353.27)
Ambient rain	21.35(4.56-108.97)		

[a] Note: The elevated zinc might have come from the solder in the scupper gutter.

Table 4-21. Al (µg/L) in harvested rainwater from pilot-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Shingle	1908.67(435.43-3349.00)	334.33(226.37-374.87)	310.43(230.23-717.80)
Metal	1211.67(850.37-2049.67)	275.13(121.47-472.87)	337.67(73.97-554.87)
Tile	1506.00(764.63-1780.00)	659.13(267.20-939.50)	318.03(139.77-532.13)
Cool	1510.33(961.60-3756.00)	619.23(447.70-847.33)	151.73(150.90-513.17)
Green	224.97(134.73-282.13)	154.57(149.17-182.07)	169.10(112.93-181.87)
Ambient rain	350.83(157.80-558.83)		

Table 4-22. Comparison of metal concentrations (µg/L) in harvested rainwater from pilot-scale roofs with MCLs.

Metal	Primary USEPA MCL (µg/L)	Range of metal concentrations in first and second tanks of all roof types (µg/L)
Arsenic	10	<0.29 to 8.38
Cadmium	5	<0.10
Chromium	100	<0.12 to 2.93
Selenium	50	<0.14 to 0.50
	USEPA Action Level (µg/L)	
Copper	1300	<0.63 to 72.16
Lead	15	<0.12 to 8.72
	Secondary USEPA MCL (µg/L)	
Iron	300	40.94 to 761.57
Zinc	5000	8.25 to 525.17
Aluminum	50-200	73.97 to 939.50

Figures 4-13, 4-14, and 4-15 show Al, Fe, Cu, Zn, Pb, and Cr concentrations in the harvested rainwater from the April 18, 2009 event. The As, Cd, and Se data are not presented graphically since more than half of the samples had concentrations below the detection limits. For all rain events, rainwater harvested after the first flush from the green roof consistently showed the lowest concentrations of Al, Fe, Cr, and Cu. For all rain events, the highest Zn concentrations were seen in the harvested rainwater after the first flush from the green and metal roofs; elevated Zn concentrations from the green roof might have been from the solder in the scupper gutter. For the April 18, 2009 rain event, Al and Fe concentrations were highest in the harvested rainwater after the first flush from the tile roof; this was not consistent in the other rain events, which showed the highest Al and Fe concentrations in the harvested rainwater after the first flush from the shingle and cool roofs. For all rain events, the shingle roof showed the highest Cu concentrations. The April 18, 2009 rain event showed the highest Pb concentrations in the harvested rainwater after the first flush for the green roof; this was not representative of subsequent rain events, which showed lower Pb concentrations. For the green roof, elevated Pb concentrations might have been from the solder in scupper gutter. In general, the tile and metal roofs yielded the highest Cr concentrations in the harvested rainwater after the first flush, but the levels were very low (0.16 to 2.93 µg/L); Cr was expected in the rainwater harvested from the tile and metal roofs since it is used as metallic coating and pigment for these roofs (Dofasco, 2007; MonierLifetile, 1999).

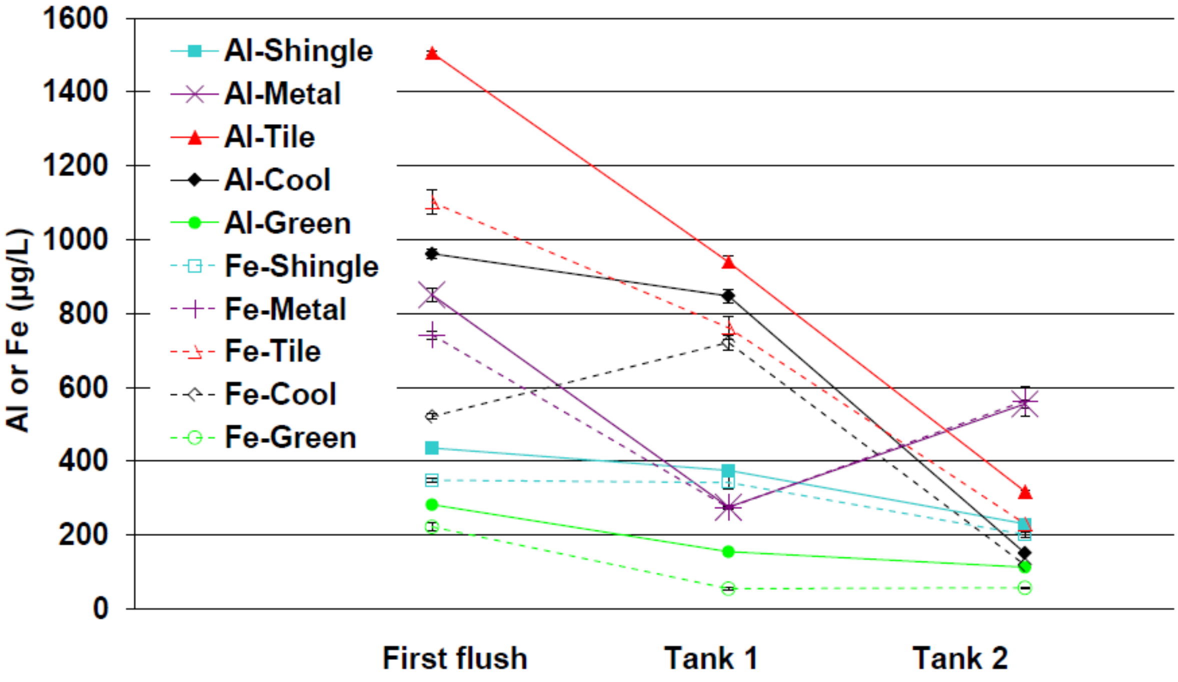

Figure 4-13. **Al and Fe in harvested rainwater from pilot-scale roofs for April 18, 2009 event. Ambient rainwater had average Al=157.80 µg/L and Fe=193.70 µg/L. Error bars represent standard deviations from triplicate analyses.**

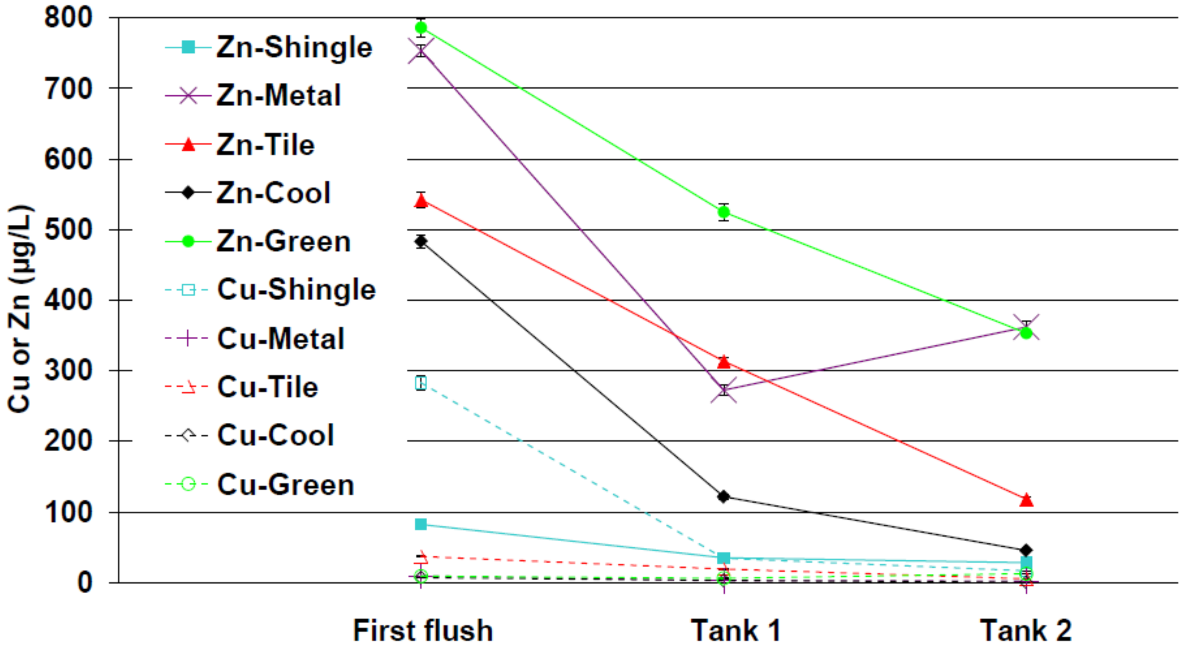

Figure 4-14. **Cu and Zn in harvested rainwater from pilot-scale roofs for April 18, 2009 event. Ambient rainwater had average Cu=0.68 µg/L and Zn=21.35 µg/L. Error bars represent standard deviations from triplicate analyses.**

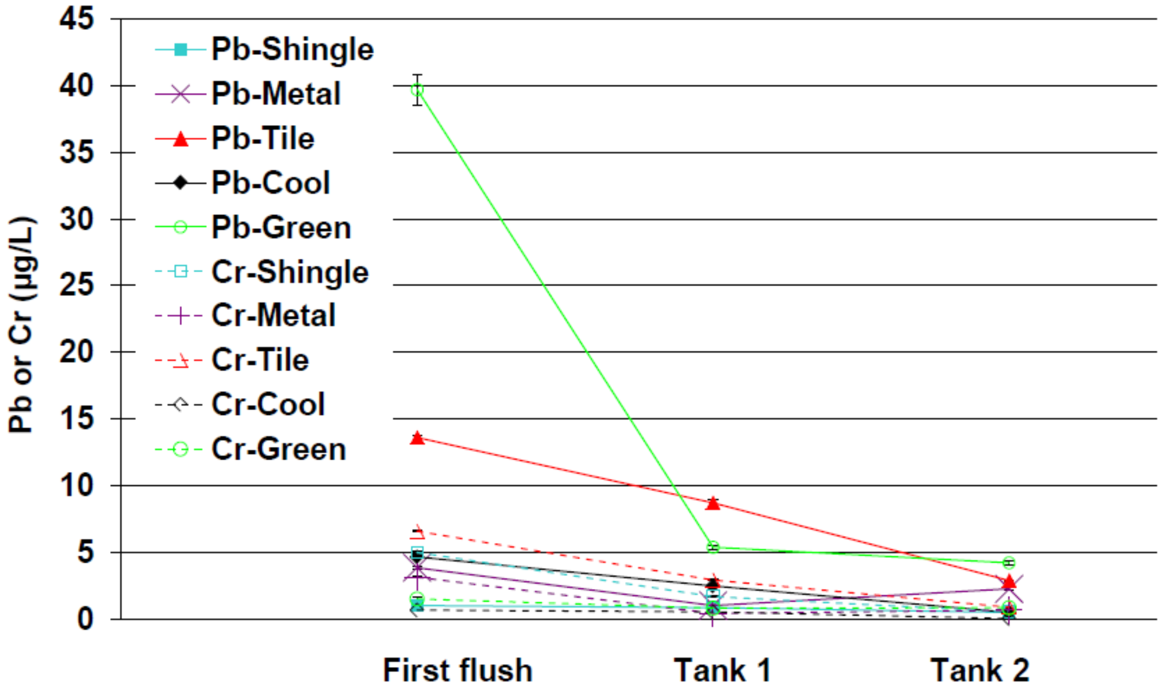

Figure 4-15. **Pb and Cr in harvested rainwater from pilot-scale roofs for April 18, 2009 event. Ambient rainwater had average Pb=0.69 µg/L and Cr=0.059 µg/L. Error bars represent standard deviations from triplicate analyses.**

A total of 18 PAHs and 22 pesticides (Appendix Table 9-3) were analyzed in the ambient rainwater and first flush samples of the fourth rain event (September 11, 2009). Even with very low detection limits (on the order of 10 nanogram per liter [ng/L]), none of these synthetic organics were detected in the harvested rainwater. By comparison, other studies have detected PAHs and pesticides in ambient rainwater samples, at concentrations ranging from 6-165 ng/L (Basheer et al., 2003; Polkowska et al., 2000).

5 Task 3. Full-scale residential roofs

Three full-scale roofs were sampled (in five-foot wide sections): a 12-year-old metal roof (Galvalume®, 22° slope with a 10-foot length) on a single-story residence, a 5-year old asphalt fiberglass shingle roof on a two-story residence (23° slope with 10-foot length, named Shingle 1), and a 5-year-old asphalt fiberglass shingle roof on a one-story residence (18° slope with a 12-foot length and increased overlying rooftop vegetation conditions as compared to the Shingle 1 roof, named Shingle 2). These sites allowed us to investigate the quality of rainwater harvested from aged, full-scale, residential roofs in the Austin, Texas area. Since the full-scale roofs were geographically separated, the quality of harvested rainwater was subject to various factors, including amount of vegetation, local contaminant sources, and rainfall intensity. The sampler gutter insert and the sampler design were similar to those described in Section 4 (Figure 4-2).

Each of the residential roofs was sampled for three rainfall events (February 9, 2009, February 11, 2009, and March 11, 2009). Samples were retrieved immediately after each rain event and analyzed in the laboratory. Between events, each sampling tank was thoroughly washed with Alconox detergent, rinsed thoroughly with deionized water, and autoclaved. The remaining pieces of the field sampler (e.g., PVC piping and funnel) were scrubbed and rinsed with deionized water on site.

For each roof, the following analyses were conducted in triplicate for the three rain events: TSS, TC, FC, total organic carbon (TOC), DOC, selected synthetic organic contaminants, and metals. Nitrate, nitrite, pH, turbidity, and conductivity were measured once for each sample. Analytical, preservation, and storage methods were followed as described in Section 4 (Tables 4-2 and 4-3), except for the synthetic organics. Two hundred synthetic organic compounds (listed in Appendix Table 9-4) were analyzed according to the USEPA method 8260/8270.

As an example rain event, the data from the February 9, 2009 event are shown graphically (Figures 5-1 to 5-8). Since TSS, TOC, DOC, metals, TC, and FC were measured in triplicate, the average of the triplicate measurements (with error bars representing standard deviation or 95% confidence limits) are shown in the plots. Since single measurements were made on each sample for pH, conductivity, turbidity, nitrate, and nitrite, no error bars are shown for those analytes. These average data from each rain event are tabulated (Tables 5-1 to 5-13) such that the minimum, median, and maximum values for the 3 rain events are shown.

Figure 5-1 shows the pH of the harvested rainwater from the February 9, 2009 event, and Table 5-1 summarizes the median, minimum, and maximum pH values for the 3 rain events. For the shingle roofs, the pH of the harvested rainwater increased from the first flush through the first and second tanks; a decreasing trend was seen in the metal roof, which was consistent in all rain events. The pH of rainwater is approximately 5.7 (TWDB, 2005), and our ambient rain samples had pH values from 5.4 to 6.3. In all rain events, the pH of the harvested rainwater was higher than that in ambient samples, ranging from 5.4 to 6.5. Our pH ranges are comparable to other studies including Yaziz et al. (1989), which reported pH values of 5.9 to 6.9 in harvested rainwater, Simmons et al. (2001), which reported pH values of 5.2 to 11.4 in harvested rainwater, and the pilot-scale roofs, which had pH values of 6.0 to 8.2 in the harvested rainwater..

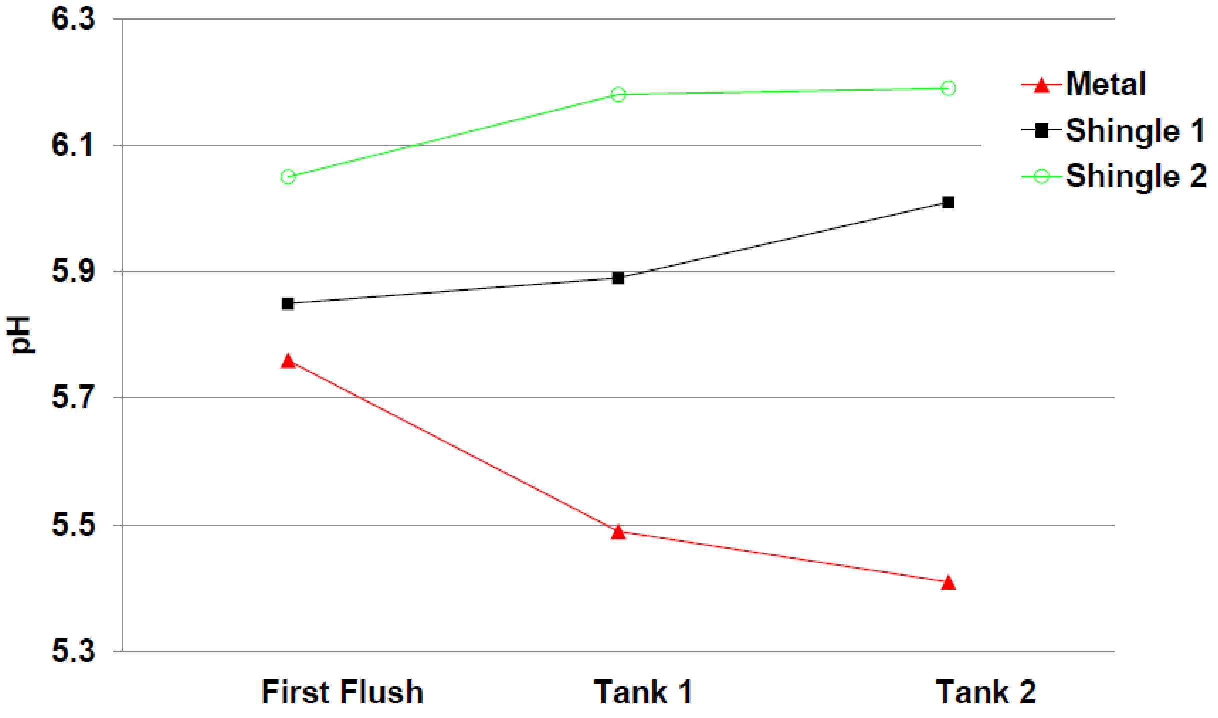

Figure 5-1. **pH in harvested rainwater from full-scale roofs for February 9, 2009 event. Ambient rainwater had pH= 5.4 to 6.3 (a range is reported since different ambient samples were analyzed for each of the three locations).**

Table 5-1. **pH in harvested rainwater from full-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Metal	5.9(5.8-5.9)	5.9(5.5-6.3)	5.8(5.4-6.3)
Shingle 1	5.9(5.8-6.0)	5.9(5.8-6.2)	6.0(5.8-6.2)
Shingle 2	6.1(5.8-6.1)	6.2(5.9-6.5)	6.3(6.2-6.5)
Ambient rain	5.9(5.4-6.3)		

Figure 5-2 shows the conductivity of the harvested rainwater from the February 9, 2009 event, and Table 5-2 summarizes the median, minimum, and maximum conductivity values for the 3 rain events. The conductivity of the harvested rainwater decreased dramatically from the first flush through the first and second tanks, with final conductivities that were similar to those of ambient rain. For all rain events, the rainwater harvested after the first flush had conductivity values ranging from18 µS/cm to 312 µS/cm. Similar to the metal roof in the pilot-scale study, the conductivity for the full-scale metal roof was usually lower than those of the shingle roofs. Conductivity values in our ambient rainwater samples ranged from 22 µS/cm to 142 µS/cm, which are similar to those measured by Yaziz et al. (1989), ranging from 6 µS/cm to 33 µS/cm, and those measured for the pilot-scale roofs, which ranged from 18 µS/cm to 61 µS/cm.

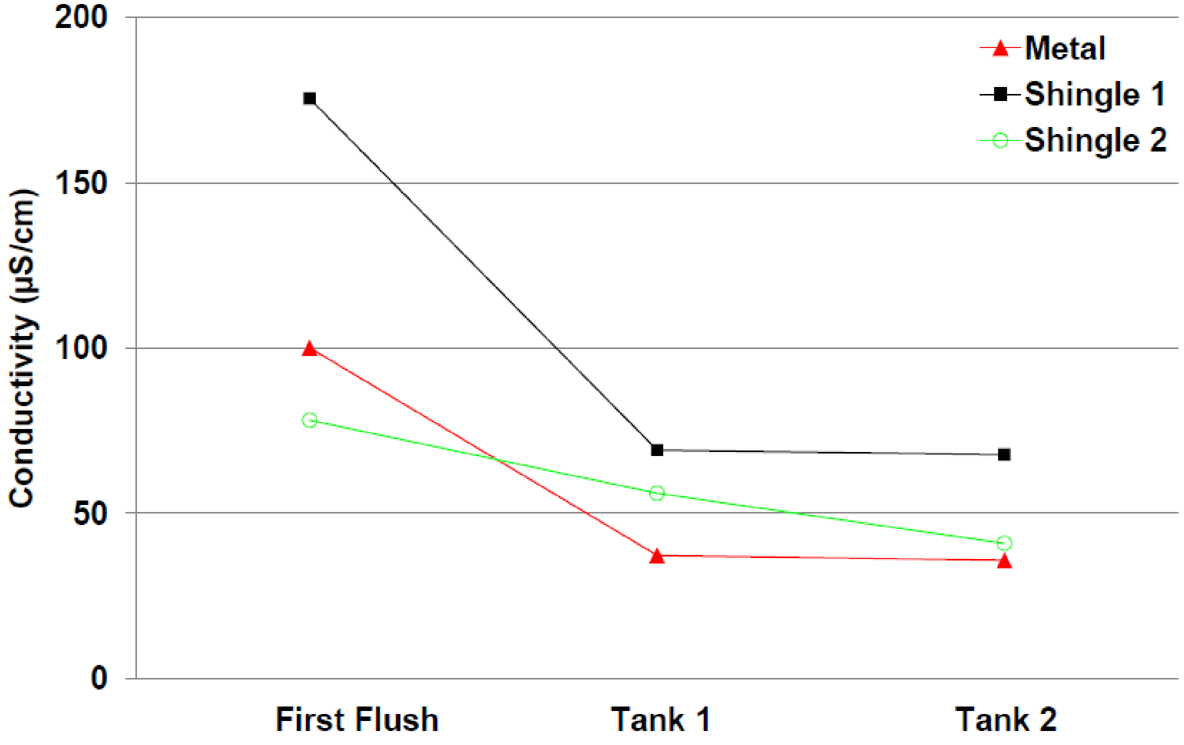

Figure 5-2. Conductivity in harvested rainwater from full-scale roofs for February 9, 2009 event. Ambient rainwater had conductivity=29 to 87 µS/cm (a range is reported since different ambient samples were analyzed for each of the three locations).

Table 5-2. Conductivity (µS/cm) in harvested rainwater from full-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Metal	100(31-171)	37(18-60)	37(36-39)
Shingle 1	176(62-218)	69(26-80)	68(20-86)
Shingle 2	78(33-312)	56(27-97)	71(41-102)
Ambient rain	72(22-142)		

Figures 5-3 and 5-4 show turbidity and TSS of the harvested rainwater from the February 9, 2009 event, and Tables 5-3 and 5-4 summarize the median, minimum, and maximum turbidity and TSS values for the 3 rain events. Turbidity decreased from the first flush through the first and second tanks, with final values of turbidity that were close to those of ambient rain. Turbidity readings in the first flush through the second tank ranged from 5 to 80 NTU for all rain events, which are comparable to the 4 to 94 NTU reported in Yaziz et al. (1989) and the 2 to 105 NTU measured for the pilot scale-roofs. It is important to note that the rainwater harvested after the first flush from the shingle and metal roofs yielded higher turbidity values than the 1 NTU maximum recommended for potable use of harvested rainwater (TWDB, 2006), which is the same as the USEPA's guideline for filtered surface water (USEPA, 2009). In comparison to the turbidity values, similar trends were seen for TSS. Yaziz et al. (1989) reported 53 to 276 mg/L TSS in harvested rainwater and 10 to 64 mg/L TSS in ambient rainwater; the pilot-scale roofs had values ranging from 1 to 260 mg/L TSS in harvested rainwater and 4 to 8 mg/L TSS in ambient rainwater. The values from the full-scale roofs were similar to these, with values of 10 to 760 mg/L TSS in harvested rainwater and 10 to 150 mg/L TSS in ambient rainwater.

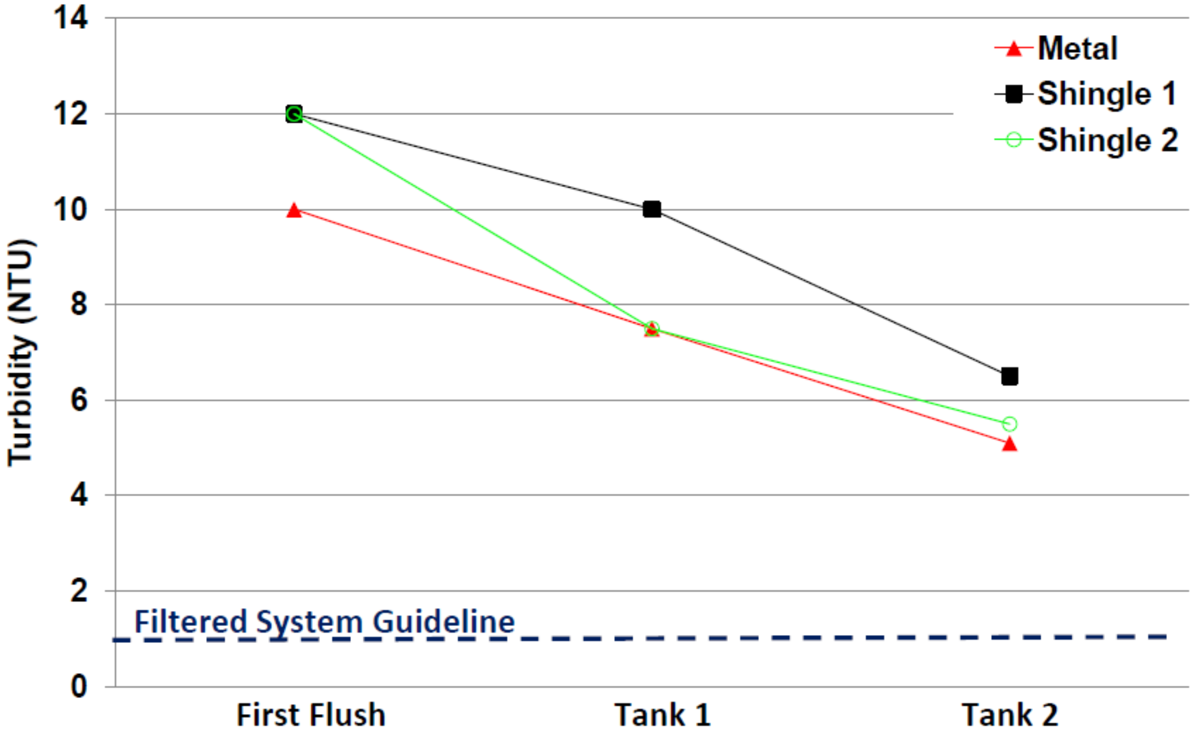

Figure 5-3. **Turbidity in harvested rainwater from full-scale roofs for February 9, 2009 event. Ambient rainwater had turbidity=6 to 17 NTU (a range is reported since different ambient samples were analyzed for each of the three locations). Filtered system guideline adapted from USEPA, 2009.**

Table 5-3. **Turbidity (NTU) in harvested rainwater from full-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Metal	35(10-54)	16(8-24)	9(5-13)
Shingle 1	35(12-80)	17(10-23)	8(7-15)
Shingle 2	15(12-27)	10(8-21)	6(6-6)
Ambient rain	25(6-80)		

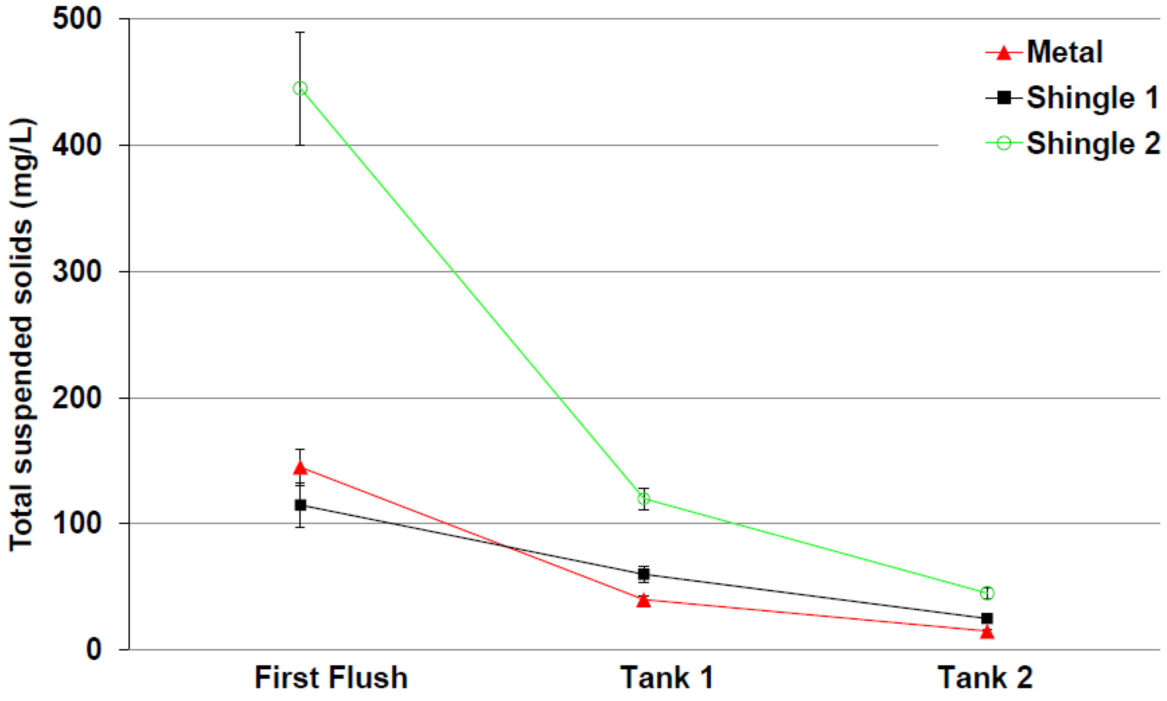

Figure 5-4. TSS in harvested rainwater from full-scale roofs for February 9, 2009 event. Ambient rainwater had TSS=10 to 30 mg/L (a range is reported since different ambient samples were analyzed for each of the three locations). Error bars represent standard deviations from triplicate analyses.

Table 5-4. TSS (mg/L) in harvested rainwater from full-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof Type	First flush	Tank 1	Tank 2
Metal	145(45-245)	40(10-50)	20(15-25)
Shingle 1	115(95-760)	65(60-150)	25(20-85)
Shingle 2	430(150-445)	85(25-120)	32.5(20-45)
Ambient rain	25(10-150)		

Figure 5-5 shows the TC and FC in the harvested rainwater from the February 9, 2009 event, and Tables 5-5 and 5-6 summarize the median, minimum, and maximum TC and FC for the 3 rain events. TC and FC counts decreased dramatically from the first flush through the first and second tanks, with TC concentrations ranging from 64 to 1237 CFU/100mL and FC concentrations ranging from 37 to 810 CFU/100mL. The second tanks had detectable TC and FC, indicating that treatment would be needed prior to potable use. Similar to the pilot-scale roofs, the shingle roof yielded the highest TC and FC in the first flush through the second tank for all rain events. Our data are comparable to other studies, which reported TC concentrations up to 19000 CFU/100mL and FC concentrations up to 840 CFU/100mL in harvested rainwater (Simmons et al., 2001). Ambient rainwater for all rain events contained TC concentrations of 178 to 907 CFU/100mL and FC concentrations of 169 to 473 CFU/100mL, which are generally higher than the ambient rainwater samples in the pilot-scale roofs (TC concentrations of 547 to 648 CFU/100mL and FC concentrations of 3 to 33 CFU/100mL). A possible explanation for the elevated TC and FC concentrations in the ambient samples at the full-scale sites is that these samplers were left open several hours longer than were the ambient samplers at the pilot-scale roof site because of the time it took to travel to the full-scale sites (all 20 miles apart). This might have led to additional deposition of TC and FC.

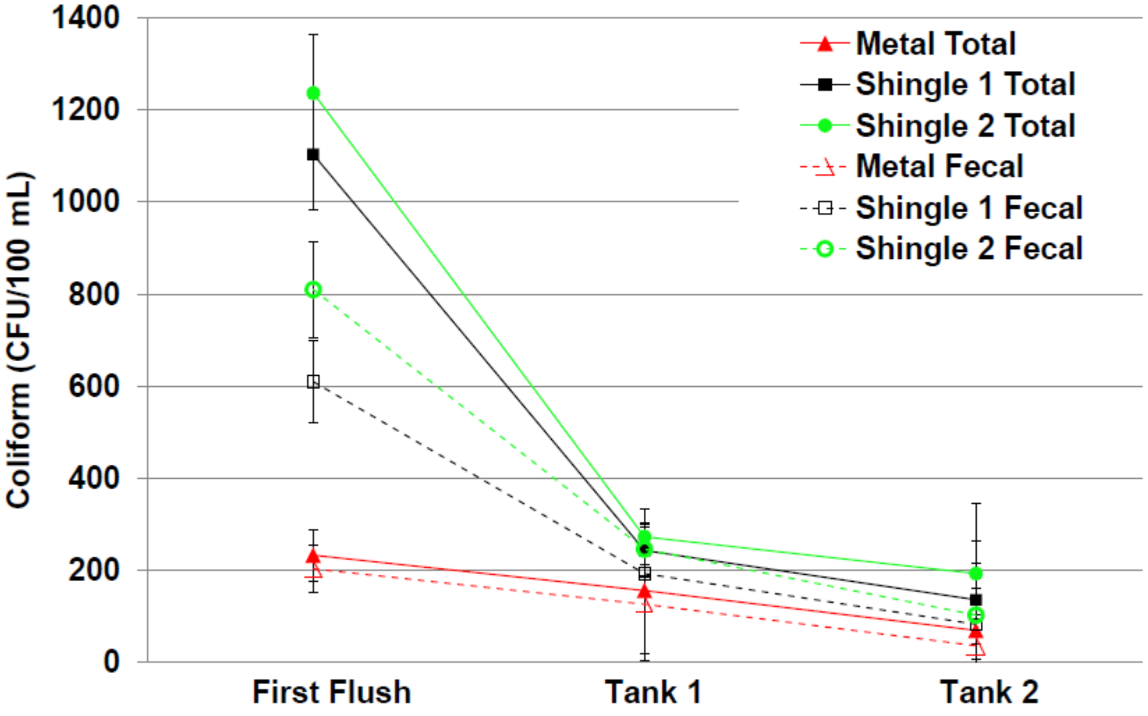

Figure 5-5. **TC and FC in harvested rainwater from full-scale roofs for February 9, 2009 event. Ambient rainwater had TC=640 to 907 CFU/100mL and FC=350 to 473 CFU/100mL (a range is reported since different ambient samples were analyzed for each of the three locations) . Error bars represent 95% confidence intervals from triplicate analyses.**

Table 5-5. **TC (CFU/100mL) in harvested rainwater from full-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Metal	233(91-240)	157(64-173)	83(70-97)
Shingle 1	902(850-1103)	243(213-353)	137(102-317)
Shingle 2	938(817-1237)	220(173-273)	170(147-193)
Ambient rain	647(178-907)		

Table 5-6. **FC (CFU/100mL) in harvested rainwater from full-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Metal	190(91-203)	93(38-127)	38(37-40)
Shingle 1	549(513-610)	207(193-253)	83(73-220)
Shingle 2	680(563-810)	213(184-247)	90(77-103)
Ambient rain	365(169-473)		

Figure 5-6 shows the nitrate and nitrite concentrations in the harvested rainwater from the February 9, 2009 event, and Tables 5-7 and 5-8 summarize the median, minimum, and maximum nitrate and nitrite concentrations for the 3 rain events. Nitrate concentrations decreased from the first flush to the first and second tanks. Nitrate concentrations in rainwater harvested after the first flush are below the USEPA drinking water MCL of 10 mg/L NO_3^--N. Other studies reported higher nitrate concentrations in harvested rainwater, including 420 mg/L NO_3^--N in anthropogenically influenced areas of Florida (Deng, 1998). Similar to nitrate, the nitrite concentrations also showed a decreasing trend from the first flush through the second tank, with nitrite concentrations in the first and second tanks ranging from 0.01 to 0.06 mg/L NO_2^--N.

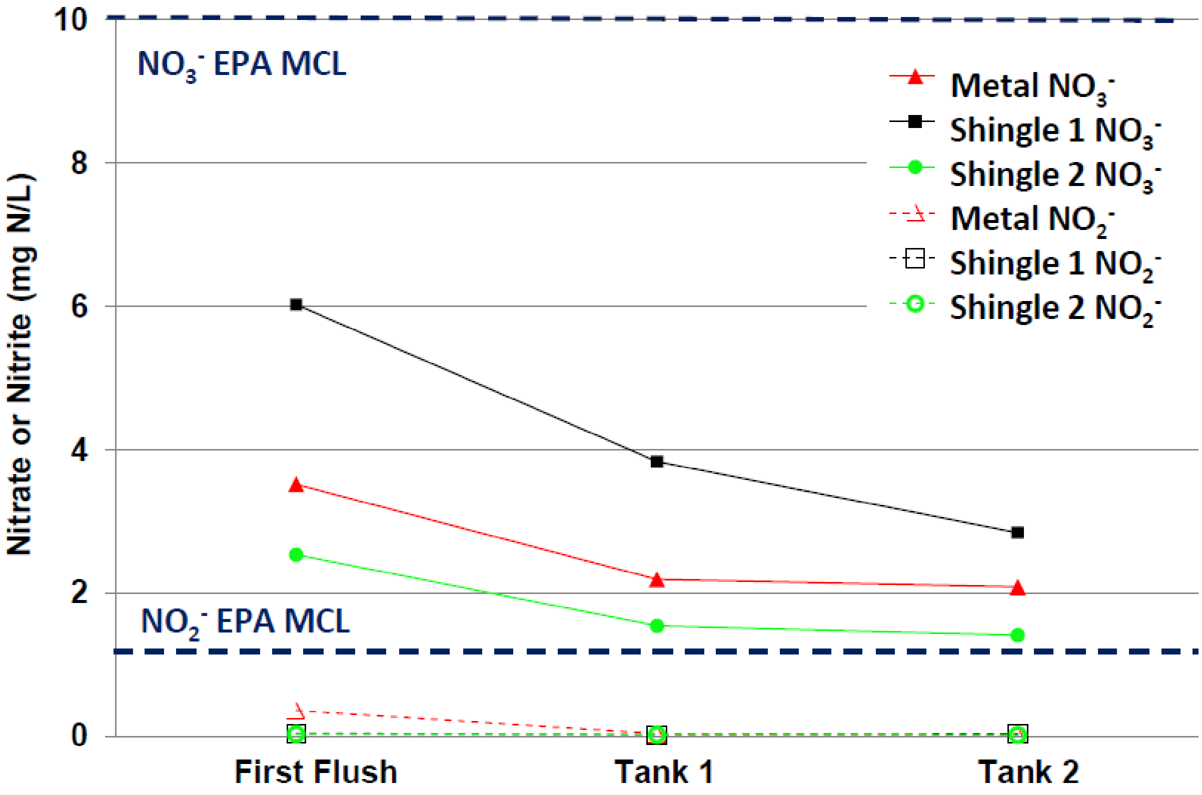

Figure 5-6. **Nitrate and nitrite in harvested rainwater from full-scale roofs for February 9, 2009 event. Ambient rainwater had nitrate=1.52 to 3.17 mg/L NO_3^--N and nitrite=0.001 to 0.087 mg/L NO_2^--N (a range is reported since different ambient samples were analyzed for each of the three locations).**

Table 5-7. **Nitrate (mg/L NO_3^--N) in harvested rainwater from full-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Metal	3.5(1.0-5.0)	2.2(0.4-4.1)	3.0(2.1-3.9)
Shingle 1	6.0(2.3-6.5)	3.8(0.8-4.6)	2.8(0.3-4.7)
Shingle 2	4.2(2.5-8.8)	3.6(1.5-3.6)	2.5(1.4-3.5)
Ambient rain	3.1(1.5-4.6)		

Table 5-8. **Nitrite (mg/L NO_2^--N) in harvested rainwater from full-scale roofs. Median (minimum-maximum) values for the three rain events are shown.**

Roof type	First flush	Tank 1	Tank 2
Metal	0.08(0.05-0.35)	0.03(0.02-0.03)	0.02(0.01-0.02)
Shingle 1	0.04(0.03-0.36)	0.02(0.02-0.06)	0.02(0.02-0.03)
Shingle 2	0.03(0.02-0.03)	0.02(0.01-0.05)	0.01(0.01-0.02)
Ambient rain	0.06(0.01-0.29)		

Figure 5-7 shows the TOC and DOC concentrations of the harvested rainwater from the February 9, 2009 event, and Tables 5-9 and 5-10 summarize the median, minimum, and maximum TOC and DOC concentrations for the 3 rain events. TOC and DOC decreased dramatically from the first flush through the first and second tanks. TOC concentrations in the first and second tanks ranged from 6.6 to 33.8 and DOC concentrations ranged from 0.4 to 31.1 mg/L for all rain events. The rainwater harvested after the first flush for the metal and shingle full-scale roofs had DOC concentrations similar to those observed for the metal and shingle pilot-scale roofs.

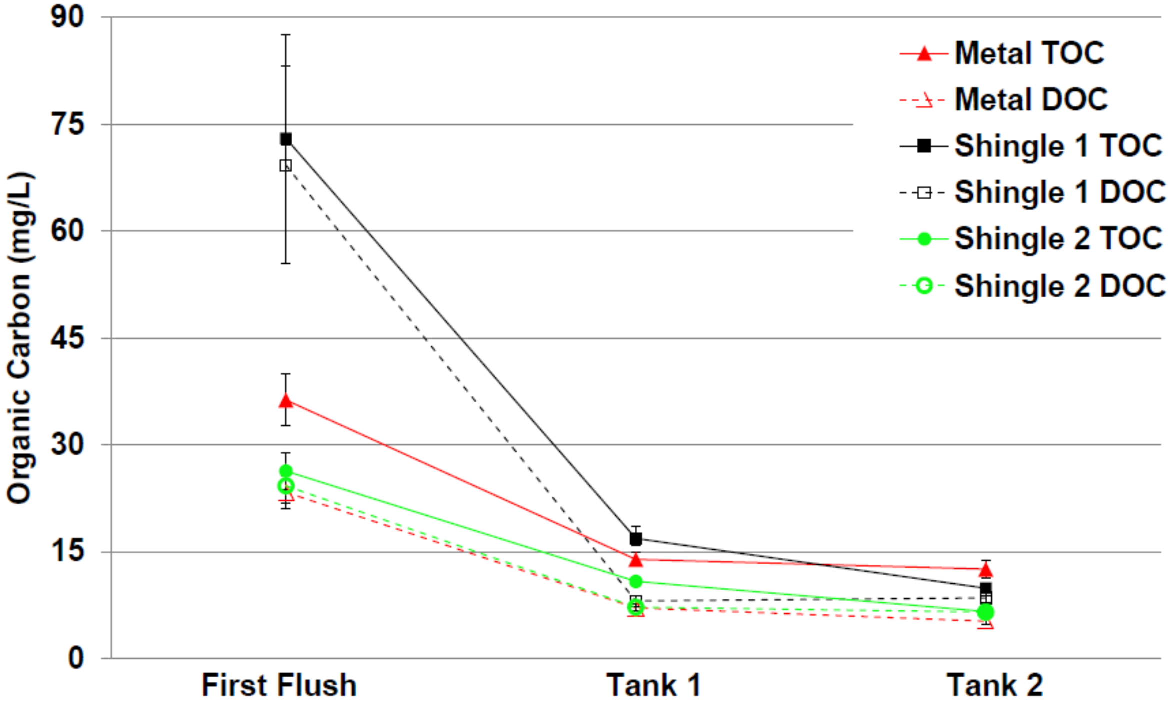

Figure 5-7. **TOC and DOC in harvested rainwater from full-scale roofs for February 9, 2009 event. Ambient rainwater had TOC=8.6 to 25.6 mg/L and DOC=2.3 to 11.9 mg/L (a range is reported since different ambient samples were analyzed for each of the three locations). Error bars represent standard deviations from triplicate analyses.**

Table 5-9. TOC (mg/L) in harvested rainwater from full-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Metal	36.3(22.1-65.8)	13.9(11.2-15.9)	12.3(9.5-12.5)
Shingle 1	73.0(24.3-146.0)	16.8(10.6-25.8)	9.8(8.5-23.4)
Shingle 2	26.3(10.0-33.8)	10.8(6.6-23.5)	10.0(6.6-33.8)
Ambient rain	15.2(5.6-48.9)		

Table 5-10. DOC (mg/L) in harvested rainwater from full-scale roofs. Median (minimum-maximum) values for the three rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Metal	19.1(0.4-23.3)	7.1(0.4-13.0)	8.4(5.2-11.6)
Shingle 1	28.9(2.2-69.3)	8.1(1.3-25.4)	8.5(0.5-19.8)
Shingle 2	24.2(1.5-58.6)	7.2(0.6-26.6)	6.5(6.5-31.1)
Ambient rain	6.7(0.4-23.2)		

A suite of 200 synthetic organic compounds (Appendix Table 9-4) were analyzed on the first flush samples from the February 9, 2009 rain event for the metal and Shingle 1 roofs. The detection limits were on the order of 100 ng/L. Two compounds were detected: benzyl alcohol and 2,4-dinitrophenol, but the concentrations were very low (Table 5-11). Both compounds can originate from a variety of sources such pesticides and oils in plants. In a study of nitrophenols by Förster (1996), 2,4-dinitrophenol was detected at concentrations up to ten times greater in roof runoff as compared to ambient rain. However, the same study also reported a large variation in 2,4-nitrophenol concentrations from within the same roof type and rain intensity, suggesting that the source of the compounds was more likely from dry deposition rather than from roof surface weathering.

Table 5-11. Synthetic organic compounds detected in harvested rainwater first flush from full-scale roofs for February 9, 2009 event.

Contaminant	Roof type	Concentration (µg/L)
2,4-Dinitrophenol	Metal	3.12
2,4-Dinitrophenol	Shingle 1	2.88
Benzyl alcohol	Shingle 1	0.20

For the February 9, 2009 and March 11, 2009 events, Zn and Pb concentrations were measured in the harvested rainwater from the metal and Shingle 1 roofs using atomic adsorption (AA) and following *Standard Methods* (1998). Figure 5-8 shows Zn and Pb concentrations in the harvested rainwater from the February 9, 2009 event, and Tables 5-12 and 5-13 summarize the minimum and maximum Zn and Pb concentrations in the harvested rainwater for the two rain events. The harvested rainwater after the first flush from the full-scale metal roof had 18.3 to 22.5 µg/L Zn, concentrations that were lower than those found in the harvested rainwater after the first flush from the pilot-scale metal roof (77.46 to 362.13 µg/L Zn). The harvested rainwater after the first flush from the full-scale metal roof had 2.1 to 5.8 µg/L Pb, which was comparable to the <0.12

to 2.27 µg/L Pb found in the harvested rainwater after the first flush from the pilot-scale metal roof. The harvested rainwater after the first flush from the full-scale shingle roof had 1.0 to 15.0 µg/L Zn, concentrations that were lower than those found in the harvested rainwater after the first flush from the pilot-scale shingle roof with values of 8.3 to 84.8 µg/L Zn. The harvested rainwater after the first flush from the full-scale shingle roof had 0.7 to 8.6 µg/L Pb, which was comparable to the <0.4 to 1.19 µg/L Pb found in the harvested rainwater after the first flush for the pilot-scale shingle roof. Similar to the pilot-scale roofs, the harvested rainwater from the full-scale roofs had Pb concentrations below the USEPA action level of 15 µg/L and Zn concentrations below the secondary USEPA MCL of 5000 µg/L.

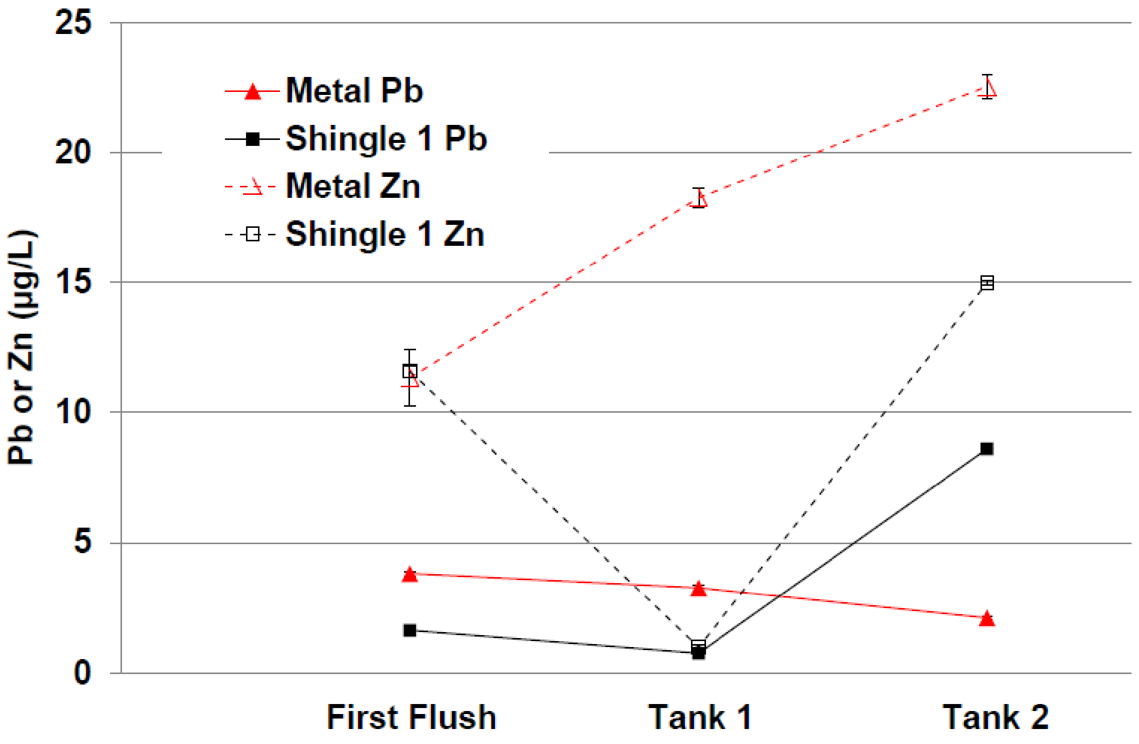

Figure 5-8. **Pb and Zn in harvested rainwater from full-scale roofs for February 9, 2009 event. Ambient rainwater had Pb=3.92 µg/L and Zn=20.52 µg/L. Error bars represent standard deviations from triplicate analyses.**

Table 5-12. Zn (μg/L) in harvested rainwater from full-scale roofs. Minimum-maximum values for the two rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Metal	11.3-23.0	18.3-19.1	21.3-22.5
Shingle 1	11.6-15.5	1.0-3.9	11.0-15.0
Ambient rain	20.5		

Table 5-13. Pb (μg/L) in harvested rainwater from full-scale roofs. Minimum-maximum values for the two rain events are shown.

Roof type	First flush	Tank 1	Tank 2
Metal	3.8-7.5	3.3-4.0	2.1-5.8
Shingle 1	1.6-3.4	0.7-0.9	1.6-8.6
Ambient rain	3.9		

6 Conclusions and recommendations

This study investigated the quality of rainwater harvested from pilot-scale roofs (asphalt fiberglass shingle, Galvalume® metal, concrete tile, cool, and green) and full-scale roofs (asphalt fiberglass shingle and Galvalume® metal). Data from three rain events were collected for the pilot- and full-scale roofs; from these limited data, none of the roofing materials emerged as clearly superior to the others in terms of the quality of the rainwater harvested after the first flush. As discussed below, several conclusions can be drawn and recommendations can be made despite the limited number of rain events sampled.

First, the quality of the rooftop-harvested rainwater generally increased with roof flushing as the rain event progressed, indicating the importance of an effective first-flush diverter. This was observed for both the pilot-scale and full-scale roofs. However, the rainwater harvested after the first flush did contain some contaminants at levels above USEPA drinking water standards (i.e., turbidity, TC, FC, Fe, and Al). This indicates that harvested rainwater must be treated prior to potable use. Thus, we recommend the use of a first-flush diverter and additional treatment prior to potable use.

Second, roofing material is just one factor that affects harvested rainwater quality. The full-scale study showed that the quality of the rooftop-harvested rainwater varied between the two shingle roofs of similar age. In some cases, one of the full-scale shingle roofs showed the highest concentration of a particular contaminant while the other shingle roof showed the lowest concentration of the same contaminant (i.e., as compared to Shingle 1, Shingle 2 consistently showed higher TSS, FC, and TC concentrations), suggesting that geographical location affects harvested rainwater quality.

Third, the metal roofs did not always leach higher concentrations of metals as compared to other roofing materials. For instance, Al and Fe concentrations in rainwater harvested after the first flush were consistently higher from the concrete tile roof as compared to the metal roof.

Fourth, green roofs are not the best candidates for rainwater harvesting for indoor domestic use if the water is disinfected with chlorine. Although the rainwater harvested after the first flush from the green roof consistently had the lowest values of TSS, turbidity, nitrite, Al, Fe, Cu, and Cr, it also had the highest values of DOC. If the harvested rainwater were chlorinated, the high DOC concentrations could lead to high concentrations of disinfection by-products. Thus, we recommend that rainwater harvested from a green roof not be disinfected with chlorine.

Fifth, while metal and tile roofs are commonly recommended for rainwater harvesting in developed countries, our data suggest that asphalt fiberglass shingle and cool roofs also might be considered for this purpose. We recommend additional studies of asphalt fiberglass shingle and cool roofs to provide a robust data set on harvested water quality.

7 Acknowledgements

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9 Appendix

Table 9-1. Summary of contractors.

Ace Roofing Company LLC
All-Tex Roofing Corp.
AmeriWest
Austin Roofing and Siding
Barker Roofing LP
Barr Roofing Co
Beldon Roofing Company
Bentley Sheet Metal & Roofing Co Inc
Billy Parker Roofing LLC
Boyd Inc
Brinkmann Roofing Co
BRM Roofing & Construction Services Inc.
Campos Roofing & Construction
Capco Inc.
Carney Roofing Co. Inc.
Castro Roofing of Texas LP
CBS Roofing Service
Curtis McKinley Roofing and S/M Inc.
D.L. Phillips Construction Co. Inc.

Daniels Roofing Inc
Demarco Exteriors Plus, Inc.
Disk Enterprises
Drury Roofing & Sheet Metal Inc.
Empire Roofing
Empire Roofing Ltd
Energy Waterproofing & Roofing Systems Inc.
Escalante Enterprises
Frazier Roofing & Guttering Co
Frontier/Scholten Roof Service
Fry Roofing Inc
Haeber Roofing Company
Hamilton Roofing Company
Harris Roofing Company
Harrison Roofing Co. Inc.
Hayes Miller Roofing Inc.
HSR Construction Inc.
Hynes Services Inc.
J. J. Flores Roofing & Construction
Jabeau Roofing
Ja-Mar Roofing
Jay-Co Sheet Metal and Roofing Inc.
J-Conn Roofing & Repair Service Inc.
John A. Walker Roofing Inc.
John Bacon Roofing
Johnson Roofing Inc
KENTEX Roofing Systems LLC
Long Horn Remodeling & Roofing
Lydick-Hooks Roofing Co of Lubbock Inc
Lydick-Hooks Roofing Company of Brownwood Texas Inc.
Lydick-Hooks Roofing Company of Wichita Falls Inc.
Marant Construction Inc.
Nations Roof Central
Norton Roofing & Construction
Oliver Roofing Systems
Parsley's S/M & Roofing Co. Inc.
Perry Roofing Company
Raintree Roofing Inc.
Rhynehart Roofing
Robles Roofing, LLC
Roofs by Nicholas Inc.
Sechrist-Hall Company
Signature Exteriors LLC
SLR Roofing Systems Inc
Smith Roofing Co Inc
Smith Roofing Company Inc.
Storm Master Inc and SMI Commercial Roofing
Texas Fifth Wall Roofing Systems Inc
Texas Roof Management Inc
Tower Roofing LLC
Vega Roofing Co.
Wilson Roofing Co. Inc.

Highlighted contractors participated in survey.

Table 9-2. Summary of survey questions and answers. [a]

1. What residential roofing materials do you most commonly use (i.e., shingles, tiles, metal)?
-Residential roofers: asphalt fiberglass shingles.
-Commercial roofers did not answer this question, did not have expertise in residential roofing.

2. In your experience, what residential roofing materials are most commonly used in Texas?
-Commercial and residential roofers: asphalt fiberglass shingles.

3. Who manufactures these roofing materials? This information will be useful in case we want to purchase these materials for our pilot roofs.
-Commercial and residential roofers: Johns Manville, Tamko, GAF/ELK, Owens Corning, USS, Dofasco, Capitol Roofing Company, Kemko, MonierLifetile, Roofing Supply Group, Bradco Supply.

4. Is there a regional record of what roofing materials are used? (online database or written manual)
Commercial and residential roofers: information is not available; contact manufacturers or roofing associations: National Roofing Contractors Association, Roofing Contractors Association of Texas, Western States Roofing Contractors Association, Tile Roofing Institute.

6. If you know that the roof will be used for rainwater harvesting, what roofing materials are used?
-Commercial and residential roofers: anything besides asphalt based (shingles) and coal tar pitch products.

7. Is there a roofing material or adhesive that you think SHOULD NOT be used in rainwater harvesting because of its toxic nature?
-Commercial and residential roofers: asphalt-based (shingles) and coal tar pitch products should not be used.

8. What roofing system would you recommend for rainwater harvesting because of its limited toxic materials?
-Commercial and residential roofers: more than 80% recommended metals; others said tiles or PVC.

[a] 32 out of 71 contractors participated: 23 residential and 9 commercial roofing contractors

Table 9-3. PAHs and pesticides tested in harvested rainwater from pilot-scale roofs.

1-Methylnaphthalene
2-Methylnaphthalene
Acenaphthene
Acenaphthylene
Anthracene
Benzo[a]anthracene
Benzo[a]pyrene
Benzo[b]fluoranthene
Benzo[g,h,i]perylene
Benzo[k]fluoranthene
Chrysene
Dibenz[a,h]anthracene
Fluoranthene
Fluorene
Indeno[1,2,3-cd]pyrene
Naphthalene
Phenanthrene
Pyrene
4,4´-DDD

4,4´-DDE
4,4´-DDT
Aldrin
alpha-BHC
alpha-Chlordane
beta-BHC
Chlordane
delta-BHC
Dieldrin
Endosulfan I
Endosulfan II
Endosulfan sulfate
Endrin
Endrin aldehyde
Endrin ketone
gamma-BHC
gamma-Chlordane
Heptachlor
Heptachlor epoxide
Methoxychlor
Toxaphene

Table 9-4. Synthetic organic compounds tested in harvested rainwater from full-scale roofs.

1,2,4-Trichlorobenzene
1,2-Dichlorobenzene
1,3-Dichlorobenzene
1,4-Dichlorobenzene
2,4,5-Trichlorophenol
2,4,6-Trichlorophenol
2,4-Dichlorophenol
2,4-Dimethylphenol
2,4-Dinitrophenol
2,4-Dinitrotoluene
2,6-Dichlorophenol
2,6-Dinitrotoluene
2-Chloronaphthalene
2-Chlorophenol
2-Methylnaphthalene
2-Methylphenol
2-Nitroaniline
2-Nitrophenol
3,3´-Dichlorobenzidine
3-Nitroaniline
4,6-Dinitro-2-methylphenol
4-Bromophenyl phenyl ether
4-Chloro-3-methylphenol
4-Chloroaniline
4-Chlorophenyl phenyl ether
4-Methylphenol
4-Nitroaniline
4-Nitrophenol
Acenaphthene

Acenaphthylene
Aniline
Anthracene
Benzo[a]anthracene
Benzo[a]pyrene
Benzo[b]fluoranthene
Benzo[g,h,i]perylene
Benzo[k]fluoranthene
Benzyl alcohol
Bis(2-chloroethoxy)methane
Bis(2-chloroethyl)ether
Bis(2-chloroisopropyl)ether
Bis(2-ethylhexyl)phthalate
Butyl benzyl phthalate
Carbazole
Chrysene
Di-n-butyl phthalate
Di-n-octyl phthalate
Dibenz[a,h]anthracene
Dibenzofuran
Diethyl phthalate
Dimethyl phthalate
Fluoranthene
Fluorene
Hexachlorobenzene
Hexachlorobutadiene
Hexachlorocyclopentadiene
Hexachloroethane
Indeno[1,2,3-cd]pyrene
Isophorone
N-Nitrosodi-n-propylamine
N-Nitrosodiethylamine
N-Nitrosodiphenylamine
Naphthalene
Nitrobenzene
Pentachlorophenol
Phenanthrene
Phenol
Pyrene
Surr: 2,4,6-Tribromophenol
Surr: 2-Fluorobiphenyl
Surr: 2-Fluorophenol
Surr: 4-Terphenyl-d14
Surr: Nitrobenzene-d5
Surr: Phenol-d6 21.5 0 20 -
TIC: 2,2-Dimethyl-6-cyclohexanepropanol,
TIC: Ethyl cyclopropanecarboxylate,
1,1,1,2-Tetrachloroethane
1,1,1-Trichloroethane
1,1,2,2-Tetrachloroethane
1,1,2-Trichloroethane
1,1-Dichloroethane
1,1-Dichloroethene
1,1-Dichloropropene
1,2,3-Trichlorobenzene
1,2,3-Trichloropropane

1,2,4-Trichlorobenzene
1,2,4-Trimethylbenzene
1,2-Dibromo-3-chloropropane
1,2-Dibromoethane
1,2-Dichlorobenzene
1,2-Dichloroethane
1,2-Dichloropropane
1,3,5-Trimethylbenzene
1,3-Dichlorobenzene
1,3-Dichloropropane
1,4-Dichlorobenzene
2,2-Dichloropropane
2-Chlorotoluene
4-Chlorotoluene
Benzene
Bromobenzene
Bromochloromethane
Bromodichloromethane
Bromoform
Bromomethane
Carbon tetrachloride
Chlorobenzene
Chloroethane
Chloroform
Chloromethane
cis-1,2-Dichloroethene
cis-1,3-Dichloropropene
Dibromochloromethane
Dibromomethane
Dichlorodifluoromethane
Ethylbenzene
Hexachlorobutadiene
Isopropylbenzene
m,p-Xylene
Methylene chloride
n-Butylbenzene
n-Propylbenzene
Naphthalene o-Xylene
p-Isopropyltoluene
sec-Butylbenzene Styrene
tert-Butylbenzene
Tetrachloroethene
Toluene
trans-1,2-Dichloroethene
trans-1,3-Dichloropropene
Trichloroethene
Trichlorofluoromethane
Vinyl chloride
Surr: 1,2-Dichloroethane-d4
Surr: 4-Bromofluorobenzene
Surr: Dibromofluoromethane
Surr: Toluene-d8

Table 9-5. Responses to review comments.

Please consider spelling out all the units of measurements used in the report, at first use. While most have been spelled out (for example, NTU and MSDS), others (for example, mg/L and µg/L) have not.
The report was revised to define all abbreviations.

Page 2, paragraph 2, lines 9 and 12. Please consider changing “twelve of twenty-four” and “one-hundred and twenty-five” to “12 of 24” and “125”, respectively.
The sentences were revised accordingly.

Pages 3 and 4. Survey information on products commonly used to fix roofing materials was not presented in the report. Please explain or justify its omission.
This information was contained in the report, but we revised the report to state our findings more clearly. We found that self-adherent asphalt fiberglass shingles, Galvalume, and concrete tiles are fastened with nails.

Page 3, paragraph 2, lines 4 and 5. The percentages of different materials in the Tamko asphalt fiberglass shingle total more than 100 percent. Please correct or explain.
A footnote has been added to explain this. “Note that amount of each material listed is shown as “less than” a threshold value. Thus, these threshold values do not add up to 100%.”

Page 4, paragraph 1, lines 13 and 14. Please consider adding a sentence or two stating that although environmental conditions may have been the same at all test roof sites, the cool and green roofs were not sloping, and that slope may or may not (your opinion here) have had an effect on the results.
The sentences were revised accordingly. “All of the pilot-scale roofs were exposed to the same natural environment and were therefore subject to the same atmospheric deposition, ultraviolet radiation, temperature changes, and rainfall intensity. Although all five roofs were exposed to the same environment, the lack of a slope on the green roof and the cool roof could have affected the quality of harvested rainwater because slope has previously been shown to affect harvested rainwater quality (TCEQ, 2007; Kingett Mitchell, 2003).”

Page 5, paragraph 2, lines 5 and 11. Please consider spelling out “2-L” and “10-L” or show the abbreviation for liter at first use in the report.
The report was revised to include all abbreviations.

Page 6, Figure 4-2. Please consider labeling the collection system and the sampling containers (First flush, Tank 1, and Tank 2) shown in the figure.
Figure 4-2 was revised to include the suggested labels.

Pages 6 and 7. Please consider adding a sentence or two describing where the samples were analyzed: in the field or in the laboratory.
A sentence was added to explain this. “Samples were retrieved immediately after each rain event and analyzed in the laboratory.”

Page 8, Figure 4-4, and very figure thereafter through Figure 5-7. The value of data used in the plots does not appear to be consistent. In some plots, the data used are the median values, in others they are the maximum values, and in some extreme cases, a single plot uses both median and maximum values for different parameters. Please correct and consider adding an explanation for the choice of value in the plots.

An explanation was added in the text. "As an example rain event, the data from the April 18, 2009 event are shown graphically (Figures 4-4 through 4-15). Since pH, conductivity, turbidity, TSS, DOC, metals, TC, and FC were measured in triplicate, the average of the triplicate measurements (with error bars representing standard deviation or 95% confidence limits) are shown in the plots. Since single measurements were made on each sample for nitrate and nitrite, no error bars are shown for those analytes. These average data from each rain event are tabulated (Tables 4-4 through 4-21) such that the minimum, median, and maximum values for the 3 rain events are shown."

Thus, each plot shows the data from just one rain event, while each table shows data compiled from all three rain events. As an example, the following is a summary of the pH values for the shingle roof (Table 4-4). Median pH values (with minimum-maximum pH values in parentheses) are presented in bold with their respective dates labeled in red. Therefore, for the 4/18/09 event, the pH in the first flush tank was the median value of the 3 rain events; the pH in tank 1 was the median value of the 3 rain events; the pH in tank 2 was the maximum of the 3 rain events.

Roof type	**First flush**	**Tank 1**	**Tank 2**
Shingle	**6.6** 4/18/09 (**6.4** 5/11/09-**7.1** 7/23/09)	**6.7** 4/18/09 (**6.7** 5/11/09-**6.9** 7/23/09)	**6.7** 5/11/09 (**6.7** 7/23/09-**6.9** 4/18/09)

Page 25, paragraph 1, line 1. Please consider changing "a twelve-year-old metal roof" to "a 12-year old metal roof".
The sentence was revised accordingly.

Page 29, Figure 5-3. Please remove the second "had" in the caption. Also, cite the source of the filtered system guideline value (dashed line) used in the figure.
The caption was revised accordingly.

As stated in the scope-of-work, please consider adding a recommendations section to the report. If you determined that the exiting "Conclusions" section contains recommendations, please consider renaming the section as "Conclusions and Recommendations".
Since the section includes both conclusions and recommendations, the title was changed to "Conclusions and recommendations".

Please double-check all references listed in the section to make sure that they have been used in the report. For example, based on the cursory search of the document in print format, we could not locate the Berndtsson et al. (2006) and TWDB (2002) references in the report.
The report has been revised accordingly.