Demographics, practices and water quality from domestic potable rainwater harvesting systems

Bonnie Stump, Matthew McBroom and Ray Darville

ABSTRACT

In semi-arid regions experiencing rapid population growth, rainwater harvesting is becoming increasingly important. Roof-collected rainwater is the exclusive water source for many households worldwide. Improper collection, storage or treatment of rainwater can result in adverse health effects. This study surveys rainwater harvesting practices and examines water quality from these systems. At 36 households, stored 'pre-filtration' rainwater and 'post-filtration' water from the kitchen faucet used for drinking and cooking were sampled. Rainwater harvesters desire to conserve water and believe that rainwater is more healthful than surface or groundwater. Almost 95% of homeowners use filtration and purification devices, but 64% have never tested their water. Coliform bacteria were not found in any post-filtration water, but some pre-filtration water samples were high in total heterotrophic bacteria. Lead levels exceeded the United States Environmental Protection Agency (USEPA) standard of 15 $\mu g\ L^{--1}$ in 25% of pre-filtration samples and 6% of post-filtration samples. First-flush diversion devices significantly decreased the likelihood of pre-filtration lead levels above 15 $\mu g\ L^{-1}$. Aluminium, copper and iron exceeded USEPA recommended levels in a small percentage of homes. Although water from roof-collected rainwater harvesting systems was generally within drinking water standards, regular testing should be encouraged to avoid potential health problems.

Key words | bacteria, heavy metals, lead, potable rainwater, rainwater harvesting, roof-collected rainwater

Bonnie Stump
University of Texas Health Science Center at Tyler,
Tyler,
TX 75708,
USA

Matthew McBroom (corresponding author)
Ray Darville
Stephen F. Austin State University,
Box 6109 SFA Station,
Nacogdoches,
TX 75962,
USA
E-mail: *mcbroommatth@sfasu.edu*

'Make you every man a cistern in his house…'

King Mesha of Moab, 850 BC (Lars 1995)

INTRODUCTION

After decades of limited interest, rooftop rainwater harvesting is making a comeback in Texas, USA, as in other arid and semi-arid regions of North America. The Texas Water Development Board predicts that even as population doubles between the years 2000 and 2060 in Texas, existing water supplies will actually decrease about 18% due to accumulation of sediments in lakes and the depletion of aquifers (TWDB 2007). The drought of 2009 forced many cities to impose strict water use restrictions as reservoirs and aquifers reached alarmingly low levels. In response to water shortages, rural residents are discovering that rooftop rainwater harvesting can provide abundant, high-quality water for household use for less than the cost of a new well, especially as new wells are required to go ever deeper due to dropping water tables. Users often prefer the taste and softness of rainwater to the limestone-saturated or high total dissolved solids (TDS) sometimes found in well water (TWDB 2005).

A typical potable rainwater system in central Texas requires adequate roof area, extensive guttering and a large storage tank, usually greater than 18,927 L, to take advantage of infrequent heavy rains and to provide adequate water supply for dry spells that can last three to four months (TWDB 2005). Mean annual rainfall for Austin, Texas, is 84 cm with an annual average of 84 days with precipitation (TWDB 2007). Metal is the most common roofing material, with either aluminium or vinyl gutters. The

doi: 10.2166/aqua.2012.007

majority of systems include appliances for filtration (sand and/or carbon filters) and disinfection (ultraviolet light or chlorination) of water entering the house.

In addition to contaminants that may be present in rainfall, the process of collection and storage offers multiple opportunities for contamination. Previous studies in international locations have demonstrated that roof-collected rainwater may become microbiologically contaminated with pathogens such as *Salmonella*, *Campylobacter*, *Pseudomonas*, *Clostridium botulinum*, *Echinococcus granulosus*, *Giardia lamblia* and *Cryptosporidium parvum* (Yaziz *et al.* 1989; Lye 1992, 2002; Meera & Ahammed 2006). These pathogens are thought to enter the rainwater as it passes over the roof and through the gutters, picking up bird and other animal feces (Meera & Ahammed 2006). Ozonation and ultraviolet light are the purification technologies most commonly used by Texas rainwater harvesters (TWDB 2005). Chlorination is unpopular among rainwater harvesters, primarily because of objections to the taste and smell of chlorine in drinking water in addition to concerns about potential health effects of disinfection byproducts such as trihalomethanes. Chlorination is also ineffective against cysts of *Cryptosporidium* and *Giardia* (Fayer *et al.* 1997).

Another potential contaminant of roof-collected rainwater is lead, which can leach from lead flashings surrounding chimneys and vent pipes or from plumbing within the house. Atmospheric deposition can also be a source of lead on rooftops. Elevated levels of lead in drinking water are of serious concern because lead is known to cause neurocognitive impairment of developing children, even at very low concentrations (Mushak *et al.* 1989; Canfield *et al.* 2003; Lidsky & Schneider 2003). Lead intoxication is also associated with reproductive failure in women of child-bearing age (Hertz-Picciotto 2000; Lamadrid-Figueroa *et al.* 2007) and at high levels can cause abdominal pain, hypertension, decreased renal function and impaired fertility in adults (ATSDR 2007).

A study from Australia found that 33% of 49 urban residential rainwater tanks sampled had lead concentrations exceeding the Australia Drinking Water Guidelines (ADWG) limit of 10 μg L^{-1} with a maximum concentration of 350 μg L^{-1} (Magyar *et al.* 2008). In that study, roof materials included glazed tile, pre-painted steel and aluminium-zinc coated steel, both with and without lead flashing material. Magyar *et al.* (2008) found that lead flashings contributed the majority of the lead content in the collected water. Another Australian study of 26 residential tanks found that 14.2% exceeded the ADWG of 10 μg L^{-1} (Huston *et al.* 2009). This study included measurements of bulk deposition of lead on the roofing material and concluded that atmospheric deposition was not the major source of lead in the collected water. Kus *et al.* (2010a) sampled 10 domestic rainwater tanks in the Sydney, Australia, area and found that six exceeded ADWG standards at least some of the time, with some values reaching 67 μg L^{-1}. A related study by the same authors analyzed the effect of first-flush devices on lead content of rainwater. First-flush devices divert the first few millimetres of rainfall, and the majority of rooftop debris, away from the storage tank. They found that it was necessary to divert 5 mm of rainfall to meet ADWG standards for lead content; diverting only 2 mm of rainfall was not adequate (Kus *et al.* 2010b). This finding would imply that atmospheric deposition of lead may indeed play a role in lead contamination.

A larger study of 125 potable rainwater collection systems in Auckland, New Zealand, demonstrated that over 14% of sampled households had lead levels above 10 μg L^{-1} at the kitchen cold water faucet (Simmons *et al.* 2001). These investigators found that systems with a pH <6.5 were 3.95 times more likely to have elevated lead levels than those in which the pH was ≥ 6.5, consistent with the relationship between lower pH values and higher metal solubility.

A study of 32 experimental roofs in Nacogdoches, Texas, found lead levels from roof runoff during 31 storm events up to 700 μg L^{-1}, even though median lead levels were below the detection limit of 25 μg L^{-1} (Chang *et al.* 2004). The highest lead levels were collected off a wood shingle roof, but all roof materials (composition shingles, aluminium and galvanized iron) occasionally produced lead levels from 134 to 255 μg L^{-1}, well above the USEPA maximum contaminant level of 15 μg L^{-1}. Even rainwater not exposed to roofing material produced one sample containing 116 μg L^{-1}. Similar results were reported by Chang & Crowley (1993). A German study of five rooftops discovered lead levels up to a maximum of 310 μg L^{-1} (Forster 1999). Studies in France and Switzerland have also found that rainwater occasionally contains lead levels above the USEPA maximum contaminant level of 15 μg L^{-1} (Meera & Ahammed 2006).

Other metals like copper, zinc, arsenic and aluminium can be associated with significant health risks as well. Chang *et al.* (2004) found that rainwater concentrations of copper and zinc can violate water quality standards in eastern Texas, with no significant differences between rainwater and roof runoff concentrations. Furthermore, new roofs often have significantly higher concentrations than older ones (Chang *et al.* 2004).

The purpose of this study is to survey demographics, attitudes and actual practices regarding water collection and purification among Texas rainwater harvesters, and to sample the water quality in these systems, both before and after treatment. Special attention is paid to the presence of lead contamination with comparisons to EPA drinking water standards.

MATERIALS AND METHODS

Survey of demographics and practices

Thirty-six study households were recruited from the Texas Rainwater Catchment Association and their associates to participate in this study (Figure 1). This number of households and their geographic distribution provided a reasonable representation of rainwater catchment systems in this region. Participants were required to have a rainwater collection system that was intended for the production of potable water for indoor household use. The owner of each system filled out a short questionnaire about the number of people in the household (including the number of women of reproductive age and children, the most vulnerable population for lead toxicity), the age of the system, the composition of roofing material, gutters and tanks, the method of purification used and the reasons for using rainwater rather than some other source of water. Participants were also queried about how often they maintained their water purification devices and how frequently their water was tested by a laboratory.

Water quality testing

After completion of the survey, a 'pre-filtration' water sample was collected either directly from the rainwater storage tank, or from a faucet located between the tank and the purification system. A 'post-filtration' sample was taken from the kitchen cold water faucet that the family used for cooking and drinking water.

All samples were tested for alkalinity, hardness, total and free chlorine, nitrates and nitrites using Hach 5-in-1 Water Quality Test Strips. Conductivity and TDS were determined by a Hach Sension 156 Multiparameter meter, and pH was determined by an EcoTester pH2. Qualitative bacteriological testing was also done. Each sample was inoculated onto a Hach paddle tester for total bacteria and total coliforms and incubated at 35 °C for 24 hours. A 500 mL aliquot of each sample, preserved with 1 mL of nitric acid at time of collection, was analyzed for lead, zinc, copper, iron, arsenic and aluminium at the Soil, Plant, and Water Analysis Laboratory at Stephen F. Austin University in Nacogdoches, Texas, using approved analytical methods (APHA 2005). Lead and arsenic concentrations were determined using atomic absorption spectroscopy on a Perkin Elmer Analyst Model 700 with graphite furnace. Copper, iron, zinc and aluminium were analyzed by inductively coupled plasma emission spectroscopy on a Thermo XSP Intrepid. Water samples analyzed for metals were sampled within 30 days to meet established hold time requirements.

Water quality testing is not required in the state of Texas for individual domestic water wells or rainwater collection systems. Survey results were strictly confidential. All participants were informed of their own results.

Data analysis

Survey results were tallied and percentages were calculated for each question. Water quality and heavy metal result distributions were analyzed for normality by one-sample Kolmogorov-Smirnov test, SPSS statistical software, version PASW Statistics 18. Filtration effectiveness for each variable was evaluated by comparing pre- and post-filtration values using the non-parametric related pairs Wilcoxon signed ranks test. Normally distributed water quality results were tested for relationship to various system components (roof type, first flush, etc.) by independent samples *T*-test. Non-parametric distributions were tested by independent samples Mann-Whitney *U* test.

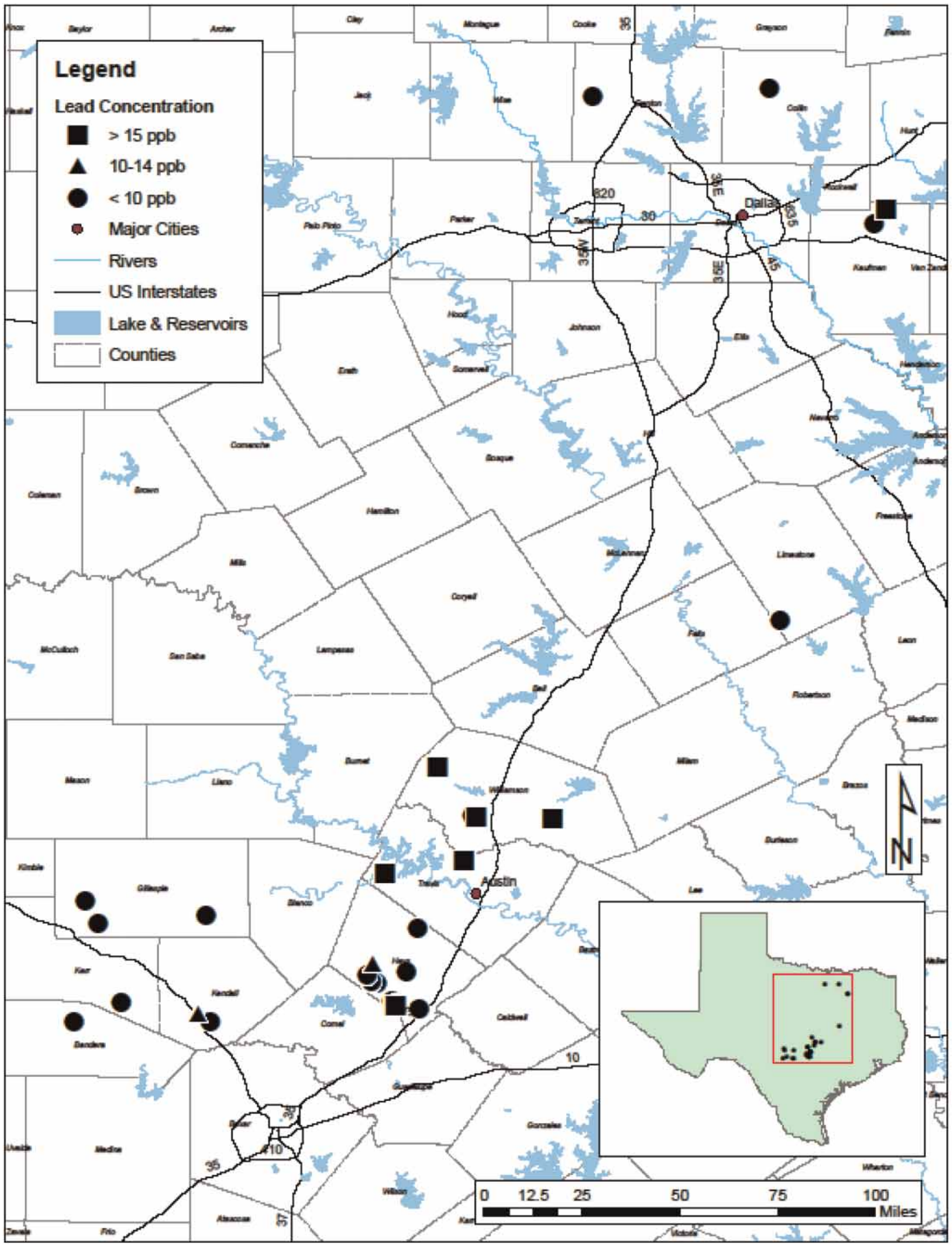

Figure 1 | Map of locations where household roof rainwater catchment systems were sampled and lead concentrations (ppb) in central Texas, USA.

RESULTS

Survey of demographics and practices

Participants in this study were found to be highly motivated conservationists, with 89% agreeing or strongly agreeing with the statement that their decision to install a potable rainwater system was influenced by their concern for water resources. Seventy-five percent believed that rainwater is healthier than either well water or municipal water supplies. Forty-four percent of households stated that one factor in the decision to purchase a rainwater system was that rainwater collection was the least expensive way to get potable water into the home.

In terms of demographics, the majority of the households had only one or two members and no children present in the home (75%) (Figure 2). Only nine households (25%) included children under the age of 17. Twenty-two percent of households included at least one female aged 15–45. These numbers are fairly consistent with overall Texas demographics, with an average household size of 2.74 people per residence and 27% of the population being below the age of 18 (US Census Bureau 2011).

When collection systems were analyzed, it was found that 29 of the 36 surveyed homes (81%) had been specifically designed and built to include a potable rainwater system. Systems tended to be relatively new, with eight systems that were less than 2 years old and 22 installed between 2000 and 2007. Only six systems were installed prior to the year 2000. Metal was the dominant roofing material, with 32 homes having metal roofs (of which 18 were Galvalume, a 55% aluminium-zinc alloy coated sheet steel (Galvalume 2010)); three had composite shingles and one was clay tile (Figure 3). Storage tanks were of various types, primarily fibreglass, polypropylene, steel and ferrocement (a cement structure built over a mesh skeleton of steel). Wood, steel and concrete tanks were lined with food grade liners. Only one tank was underground. Storage capacity ranged from 9,463 to 189,270 L with a median capacity of 75,708 L. For 20 of the surveyed households (56%), the rainwater system was the only source of water for the household. Fifteen homes also had a well on the property as a secondary source of water. Only two homes had municipal water available to their location but neither had elected to use it. Twenty-one systems (58%) had some sort of first-flush device to allow the first, and presumably dirtiest, water off the roof during a rain event to be diverted away from the storage tank. Some of these first-flush devices diverted less than the recommended volume of 76 L per 93 m^2 of roof area (TWDB 2005).

In terms of water purification, 30 systems (83%) purified the water with an ultraviolet light appliance preceded by a series of filters. There was much variation in the kind of filters used, but most began at approximately 25 microns and decreased to a mesh of 3–5 microns. Four homes used an ozone generator in the storage tank followed by filtration at the point of entry to the house. Only two systems had no method of purification. The owner of one system without purification was planning to install an ultraviolet light and was not yet actually drinking his water, and the other was content to use water from the tank without any formal method of purification. Eighty-one percent of households

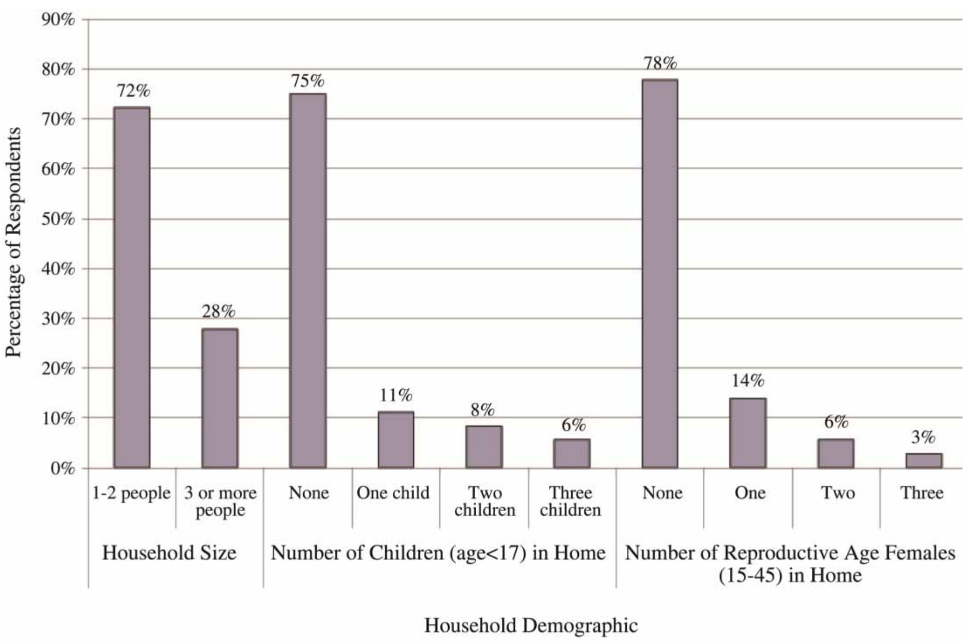

Figure 2 | Household demographics for survey respondents from roof rainwater catchment survey and water quality analysis in central Texas, USA survey.

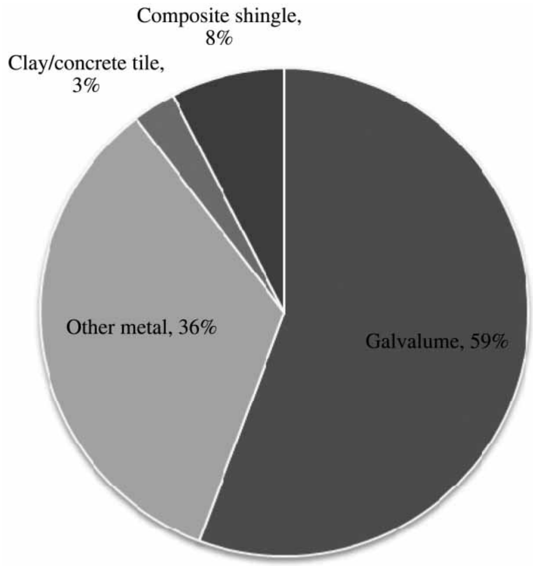

Figure 3 | Type of roofing materials (%) used in roof rainwater catchment systems in central Texas, USA survey.

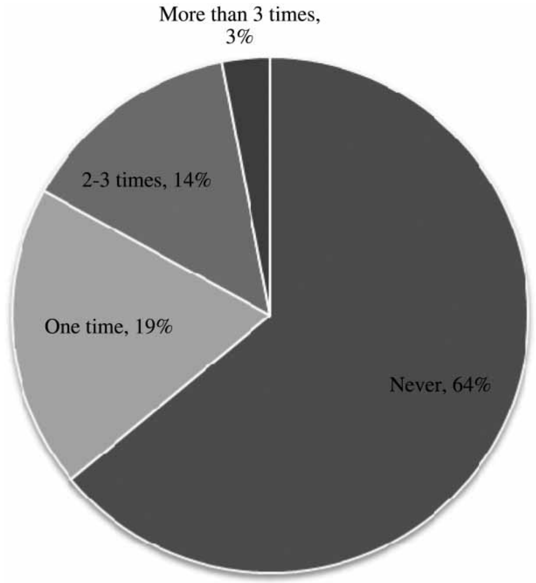

Figure 4 | Percentage of survey respondents that have conducted water quality test from household roof rainwater catchment systems in central Texas, USA survey.

replaced, repaired or otherwise maintained their filters at least every 6 months, but 19% only did so every 6–12 months, or even less often than every year.

One finding that would cause concern was that drinking water from a majority (64%) of households had never been tested for any contaminants, even though state and federal environmental agencies and the American Rainwater Catchment Systems Association all recommend periodic testing for coliform bacteria as a minimum level of surveillance (TWDB 2005; Figure 4). Water from only six homes had been tested more than once.

Water quality

No chlorine was detected in any water sample. No household exceeded recommended levels of nitrates or nitrites. Low alkalinity, hardness and conductivity were consistent with expected values for rainwater in almost all cases (Table 1). In the few instances in which the water was found to be unexpectedly high in solutes, an explanation was usually discovered. One household occasionally ran well water into the house if they expected excessive use of water, and another added sodium bicarbonate to deliberately raise the pH to prevent corrosion of copper plumbing. TDS in pre-filtration water was decreased by the presence of a first-flush diversion device ($p < 0.01$ on independent samples *T*-test).

Bacteriological water quality

No household with a functioning purification system had any growth of total coliforms on the post-filtration sample. In fact, 92% of households had no growth of total coliforms even from the pre-filtration sample. Total bacteria, also known as heterotrophic plate count (HPC), in the pre-filtration samples ranged from no growth to exceedingly heavy growth on the cultures used in this survey. Seven homes exceeded the USEPA recommendation for bacterial content in drinking water of 500 colonies/mL in the tank water. There was no significant relationship between the presence or absence of a first-flush device with the quantity of bacteria in the collection tank. Roof type was also unrelated to bacteria in the tank. Filtration/purification significantly decreased bacterial content compared to pre-filtration samples by related samples Wilcoxon signed ranks test ($p < 0.0005$). No home exceeded an HPC of 500 colonies/mL in the post-filtration water.

Table 1 | Descriptive statistics from pre- and post-filtration water quality parameters from roof rainwater collection systems in Texas

Parameter	Filtration	Mean	Median	Maximum	Number (%) of samples >EPA standard	EPA recommended
pH	Pre	6.7	6.7	7.7	0 (0%)	6.5–8.5
	Post	6.9	6.9	9.0	1 (2.9%)	
Alkalinity ($CaCO_3$) mg L^{-1}	Pre	23.9	20.0	120.0	NA	NA
	Post	43.7	20.0	240.0	NA	
Hardness ($CaCO_3$) mg L^{-1}	Pre	19.3	0.0	120.0	NA	NA
	Post	21.7	0.0	120.0	NA	
Total chlorine mg L^{-1}	Pre	0	0.0	0.0	0 (0%)	4 mg L^{--1}
	Post	0	0.0	0.0	0 (0%)	
Nitrates mg L^{-1}	Pre	0.2	0.0	0.5	0 (0%)	10 mg L^{--1}
	Post	0.3	0.0	5.0	0 (0%)	
Nitrites mg L^{-1}	Pre	0	0.0	0.0	0 (0%)	1 mg L^{--1}
	Post	0	0.0	0.0	0 (0%)	
[a]Conductivity μSiemens/cm	Pre	42.4	29.2	212.0	NA	
	Post	**110.4**	44.6	1329.0	NA	
[a]Total dissolved solids mg L^{-1}	Pre	19.8	13.4	101.0	0 (0%)	<500 mg L^{-1}
	Post	**53.1**	20.8	657.0	1 (2.9%)	

NA = not applicable.
[a]Mean values bold and underlined were significantly higher post-filtration at $\alpha = 0.05$ using the related samples Wilcoxon signed ranks test.

Lead concentrations

Lead levels in pre-filtration water samples ranged from undetected (<0.5 μg L^{-1}) to 181.8 μg L^{-1} with a median of 1.35 μg L^{--1} (Table 2). Nine households (25%) exceeded the USEPA maximum contaminant level of 15 μg L^{-1} on the pre-filtration sample and two additional homes exceeding the stricter World Health Organization (WHO) guideline of 10 μg L^{-1}. Post-filtration values ranged from undetected (<0.26 μg L^{-1}) to 20.7 μg L^{-1}, with two households (6%) exceeding 15 μg L^{-1}. While the median post-filtration level (2.1 μg L^{-1}) was slightly higher than the pre-filtration median, the Wilcoxon signed ranks test for related samples revealed that there were no statistically

Table 2 | Descriptive statistics from pre- and post-filtration heavy metal concentrations (μg L^{-1}) from roof rainwater collection systems in Texas

Element	Filtration	Mean	Maximum	Number (%) of samples >EPA standard	EPA standard	Limit of detection
Lead	Pre	16.10	181.80	9 (25%)	15	0.26
	Post	3.79	20.69	2 (6%)		
[a]Copper	Pre	48.30	637.10	0 (0%)	1,000	5.70
	Post	**261.60**	2,842.00	2 (6%)		
Zinc	Pre	441.90	1,980.00	0 (0%)	5,000	0.60
	Post	381.00	1,726.00	0 (0%)		
[a]Aluminium	Pre	**56.40**	797.40	2 (6%)	200	16.20
	Post	17.00	136.70	0 (0%)		
Arsenic	Pre	0.70	298.70	0 (0%)	10	0.43
	Post	0.65	683.30	0 (0%)		
[a]Iron	Pre	**96.00**	1,135.00	2 (6%)	300	3.00
	Post	48.30	922.90	2 (6%)		

[a]Mean values bold and underlined were significantly greater for pre- versus post-filtration at $\alpha = 0.05$ using the related samples Wilcoxon signed ranks test.

significant differences between pre- and post-filtration lead concentrations. However, the pre-filtration samples were more likely to violate the USEPA drinking water standard for lead. Furthermore, the use of a first-flush diversion device was associated with significantly lower concentrations, with pre-filtration lead being more frequently below the USEPA recommended limit of 15 μg L^{-1} by Fisher's exact test ($p < 0.001$). There was no statistical relationship between roof or gutter composition (or even the presence of lead flashings) and lead content of the water.

Copper concentrations

No household in this study exceeded the USEPA drinking water standard of 1,000 μg L^{-1} copper in pre-filtration samples; however, two households exceeded that level in post-filtration samples (Table 2). The highest copper concentration measured was 2,840 μg L^{-1}. The median copper level was much higher post-filtration (39.8 μg L^{-1}) than it was pre-filtration (not detected, <5.7 μg L^{-1}). Wilcoxon Signed Rank test for related samples confirmed that copper levels were higher post-filtration ($p < 0.01$). Although this increase in copper levels might be due to copper plumbing within the house, the survey did not include a question about copper plumbing.

Concentrations of other metals

No sample obtained in this study exceeded the USEPA secondary maximum contaminant level for zinc of 5,000 mg L^{-1}. In fact the highest zinc level in any sample was 1,980 μg L^{-1}. Median zinc level was 310 μg L^{-1} pre-filtration and 270 μg L^{-1} post-filtration and mean values were not significantly different (Table 2).

All arsenic levels were also below the USEPA maximum contaminant level of 10 μg L^{-1}. The highest arsenic level was 6.8 μg L^{-1} on a post-filtration sample. Arsenic was undetectable (<0.43 μg L^{-1}) in 69 and 74% of pre- and post-filtration samples, respectively. Pre- and post-filtration levels were not significantly different (Table 2).

Median levels of aluminium were also very low. Fifty-three percent of pre-filtration samples had undetectable levels (<5.7 μg L^{-1}) of aluminium, as did 86% of post-filtration samples (Table 2). The USEPA gives aluminium a secondary maximum contaminant level of 50–200 μg L^{-1}. Two systems exceeded 200 μg L^{-1} on pre-filtration samples and none on post-filtration samples. The highest aluminium level was 797 μg L^{-1} on a pre-filtration sample. Aluminium levels were significantly lower post-filtration than pre-filtration ($p < 0.008$).

The USEPA recommends that iron content of drinking water be less than 300 μg L^{-1}, but this recommendation is based on taste and appearance rather than any particular health effect. One home exceeded 300 μg L^{-1} on both pre- and post-filtration samples, another home on the pre-filtration sample only and a third home on the post-filtration sample (Table 2). All three had metal roofs. Mean iron concentrations were significantly lower post-filtration ($p < 0.01$).

DISCUSSION

Rainwater harvesting from residential roofs can be an effective water conservation strategy (TWDB 2005). Not only is it a wise use of an increasingly scarce resource, but in 41% of surveyed households it was the least costly water source available. Rainwater harvesting for lawn and garden irrigation is fairly uncomplicated with fewer potential health risks than with direct human consumption. Rainwater harvesting for potable use requires better filtration and disinfection. Rainwater can become contaminated with pathogens or toxins if collected and stored without this attention to detail. Water collected from potable systems in this study was generally free of bacteria. However, extremely high growth of total bacteria (HPC) did exist in a few tanks. Although there are no adverse health effects directly associated with a high HPC per se, the USEPA recommends no more than 500 colonies per millilitre in drinking water. To illustrate the range of HPC that humans routinely consume, the US Department of Health allows pasteurized milk to have up to 20,000 colonies per millilitre (USFDA 2009). The USEPA describes the HPC as measuring 'a range of bacteria that are naturally present in the environment' and states that the 'lower the concentration of bacteria in drinking water, the better maintained the water system is' (USEPA 2009).

As rainwater harvesting gains in popularity, systems could be purchased by consumers who may not be as well informed of potential hazards and may be installed with less attention to detail. The American Rainwater Catchment Systems Association recommends that, prior to placing a system into service, water should be tested for *E. coli*, total coliform and HPC at a minimum. They also recommend subsequent, periodic testing (Boulware 2009). From a practical standpoint, more extensive bacteriological testing will also be required by the Texas Commission for Environmental Quality (TCEQ) if potable rainwater systems are to expand from individual homes to public buildings.

Lead contamination is also a potential hazard with roof-collected rainwater. This study demonstrates that lead levels greater than USEPA standards are possible even in homes that were specifically designed for rainwater harvesting and that attempted to avoid the inclusion of lead-containing fixtures. The source of the lead contamination could not be determined by this study design. Of the three participants who had known lead flashings on the roof, only one had an elevated lead level in pre-filtration water, and none of the three had an elevated level after filtration. The association of first-flush devices with lowered pre-filtration lead concentrations is an interesting finding. If diverting the first water from the roof during a rain event decreases the lead content in the collected water, atmospheric deposition is implied as the possible source of the lead. There were four homes that could be considered outliers for pre-filtration lead. These homes had lead levels ranging from 44 to 182 $\mu g\ L^{-1}$ in pre-filtration water, and none of these four had first-flush devices. It is possible that this skewing of pre-filtration lead levels skewed statistical analyses. Since the presence or absence of a first flush device was the only variable that had a statistically significant association to pre-filtration lead levels, additional studies should be able to identify increased lead in the diverted water if atmospheric deposition is indeed the source.

Brass plumbing fixtures are allowed to contain up to 8% lead, and are allowed to leach up to 11 $\mu g\ L^{-1}$ even under NSF/ANSI standard 61 (NSF 2010), so brass fixtures might be responsible for some of the elevated lead levels. The use of brass fixtures inside the houses might explain the increase of the median lead level after filtration. The participant in this study who had the highest level of lead (181.8 $\mu g\ L^{-1}$ pre-filtration and 20.7 $\mu g\ L^{-1}$ post-filtration) had no known lead on the roof. Additional rainwater samples from two gutter downspouts obtained during a rain event were submitted to a separate laboratory and were negative for lead, as was water drawn directly from both storage tanks. Water obtained from a PEX pipe running underground from the storage tank to the pump house (where the purification system was housed) contained 59 $\mu g\ L^{-1}$ lead. This finding would imply that the source of lead contamination is somewhere in that pipe, but the owner knows of no lead-containing fixtures in that part of the plumbing. Possibly there is a small leaded fitting or some non-code solder in that length of pipe. Plumbing fixtures that might not leach lead under normal circumstances could leach higher quantities under the low pH, low hardness conditions that exist in a rainwater system, as was noted by Simmons *et al.* (2001). This leaching effect is another potential area of further research.

An important question needing further research is whether a lead level of 15–20 $\mu g\ L^{-1}$ has any significant health effects in the long term. Although municipal water departments are required to keep lead levels below 15 $\mu g\ L^{-1}$ as water leaves the treatment plant, the USEPA estimates that 20% of the American population is currently using drinking water that contains greater than 20 $\mu g\ L^{-1}$, because of leaching from lead service pipes and household plumbing fixtures (Landrigan 1990). An intake of 5 μg lead per kilogram of body weight per day has been demonstrated to cause accumulation of lead in a child (Shannon 1998). A 4 kg child drinking 1 L of formula made with rainwater containing 20 $\mu g\ L^{-1}$ would achieve this intake, but an adult would have to drink more than 12 L daily to accumulate lead from rainwater at this low concentration. Although lead concentrations slightly above the established water quality standard observed in post-filtration water in this study would be unlikely to harm adults, they could potentially be harmful to young children. Other metals like copper, zinc, aluminium and arsenic were generally within drinking water standards.

CONCLUSIONS

Current practices of rainwater harvesting and purification appear to produce potable water generally within the range of USEPA drinking water standards. All systems surveyed in this study met recommended criteria for bacteriological purity, even though surveillance practices were sometimes less than optimal. Lead contamination is a potential hazard, and further studies are indicated to elucidate the source of contamination and devise methods to assure that lead content remains below recommended guidelines. The current methods of filtration do not appear to be consistently effective at removing sufficient lead to meet current USEPA drinking water standards at the tap.

In this study the presence of first-flush diverters did not have an effect on bacterial content in the tank, which is one of the presumed purposes of roof washing. Although first flush did appear to have an effect on pre-filtration lead levels, this finding should be confirmed in a larger sample before recommending first flush as an effective remedy for lead contamination. Additional research on the effect of first-flush devices is needed. Leaching of copper and lead from plumbing fixtures within the house by low pH rainwater may be a potential problem that also merits further investigation. Additional studies on the effect of alkalinization of collected water on metal content are indicated.

Regular testing of household potable rainwater is recommended, but is only being performed by a minority of rainwater harvesters. The general belief that rainwater is healthy and pure, and a lack of appreciation for the variety of potential contaminants, may contribute to the infrequency of water quality testing. It would be beneficial to the rainwater harvesting community to investigate barriers to testing, and to promote user-friendly testing procedures in order to safeguard rainwater's reputation as a healthy alternative water source.

ACKNOWLEDGEMENTS

The authors would like to thank Leon Young, PhD, and Wayne Weatherford, MS, of the Waters of East Texas (WET) Center, Division of Environmental Sciences, Stephen F. Austin University for processing the heavy metal samples. We also sincerely appreciate the cooperation of the members of the Texas Rainwater Catchment Association. Funding was graciously provided by the Occupational and Environmental Medicine residency program at UTHSCT and TIOSH, Texas Institute of Occupational Safety and Health and the SFASU WET Center.

REFERENCES

Agency for Toxic Substances and Disease Registry (ATSDR) 2007 *Toxicological Profile for Lead*. US Department of Health and Human Services, Public Health Service, Washington, DC, pp. 582.

American Public Health Association (APHA) 2005 *Standard Methods for the Examination of Water and Wastewater*, 21st edition, American Public Health Association, Washington, DC.

Boulware, E. W. B. 2009 *Rainwater Catchment Design and Installation Standards*. American Rainwater Catchment Systems Association and American Society of Professional Engineers, Austin, TX, 40 pp.

Canfield, R. L., Henderson, C. R., Cory-Sclechta, D. A., Cox, C., Jusko, T. A. & Lanphear, B. P. 2003 Intellectual impairment in children with blood lead concentrations below 10 μg per deciliter. *New Eng. J. Med.* **348**, 1517–1526.

Chang, M. & Crowley, C. M. 1993 Preliminary observations on water quality of storm runoff from four selected residential roofs. *Water Resour. Bull.* **29**, 777–783.

Chang, M., McBroom, M. W. & Beasley, R. S. 2004 Roofing as a source of nonpoint water pollution. *J. Environ. Manage.* **73**, 307–315.

Fayer, R., Speer, C. A. & Dubey, J. P. 1997 The general biology of *Cryptosporidium*. In: *Cryptosporidium and Cryptosporidiosis* (R. Fayer, ed.). CRC Press, Boca Raton, Florida, p. 41.

Forster, J. 1999 Variability of roof runoff quality. *Water Sci. Technol.* **39**, 137–144.

Galvalume 2010 Website of Product Information for Galvalume®. Available from: www.galvalume.com (accessed 20 February 2010).

Hertz-Picciotto, I. 2000 The evidence that lead increases the risk for spontaneous abortion. *Am. J. Ind. Med.* **38** (3), 300–309.

Huston, R., Chan, Y. C., Gardner, T., Shaw, G. & Chapman, H. 2009 Characterisation of atmospheric deposition as a source of contaminants in urban rainwater tanks. *Water Res.* **43** (6), 1630–1640.

Kus, B., Kandasamy, J., Vigneswaren, S. & Shon, H. K. 2010a Analysis of first flush to improve the water quality in rainwater tanks. *Water Sci. Technol.* **61** (2), 421–428.

Kus, B., Kandasamy, J., Vigneswaren, S. & Shon, H. K. 2010b Water quality characterization of rainwater in tanks at different times and locations. *Water Sci. Technol.* **61** (2), 429–439.

Lamadrid-Figueroa, H., Tellez-Rojo, M. M., Hernandez-Avila, M., Trejo-Valdivia, B., Solano-Gonzalez, M., Mercado-Garcia, A., Smith, D., Hu, H. & Wright, R. O. 2007 Association between the plasma/whole blood lead ratio and history of spontaneous abortion: a nested cross-sectional study. *BMC Pregnancy Childbirth* **27** (7), 22.

Landrigan, P. 1990 Current issues in the epidemiology and toxicology of occupational exposure to lead. *Environ. Health Perspect.* **89**, 61–66.

Lars, W. 1995 The family cistern: 3,000 years of household water collection in Jordan. In: *Ethnic Encounter and Culture Change, Papers from the Third Nordic Conference on Middle Eastern Studies* (M. Sabour & K. S. Vikor, eds). Joensuu, Finland, pp. 19–22, June 1995.

Lidsky, T. I. & Schneider, J. S. 2003 Lead neurotoxicity in children: basic mechanisms and clinical correlates. *Brain* **126**, 5–19.

Lye, D. 1992 Microbiology of rainwater cistern systems: a review. *J. Environ. Sci. Health* **A27** (8), 2141.

Lye, D. 2002 Health risks associated with consumption of untreated water from household roof catchment systems. *J. AWRA* **38** (5), 1301–1306.

Magyar, M. I., Mitchell, V. G., Ladson, A. R. & Diaper, C. 2008 Lead and other heavy metals: Common contaminants of rainwater tanks in Melbourne. In: *Water Down Under 2008 Conference*, Adelaide, Australia, pp. 14–17, April 2008.

Meera, V. & Ahammed, M. 2006 Water quality of rooftop rainwater harvesting systems: a review. *J. Water Supply: Res. Technol. – AQUA* **55** (4), 257–268.

Mushak, P., Davis, J. M., Crocetti, A. F. & Grant, L. D. 1989 Prenatal and postnatal effects of low-level lead exposure: integrated summary of a report to the U.S. Congress on childhood lead poisoning. *Environ. Res.* **50** (1), 11–36.

National Science Foundation (NSF)/American National Standards Institute (ANSI) 2010. *Drinking Water System Components – Health Effects*. NSF International, Ann Arbor, MI, 194 pp.

Shannon, M. 1998 Lead poisoning from an unexpected source in a 4 month old infant. *Environ. Health Perspect.* **106** (6), 313–316.

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.

Texas Water Development Board (TWDB) 2005 *Texas Manual on Rainwater Harvesting*, 3rd edition. Texas Water Development Board, Austin, TX, 88 pp.

Texas Water Development Board (TWDB) 2007 *Water for Texas, 2007*. Texas Water Development Board Document No. GP-8-1, Austin, TX.

United States Census Bureau 2011 2010 *Census Redistricting Data (Public Law (P.L.)* 94–171 Summary File – [Texas].

US Department of Health and Human Services/Food and Drug Administration (USFDA) 2009 *Revision, Grade "A" Pasteurized Milk Ordinance*, Washington, DC, 389 pp.

United States Environmental Protection Agency (USEPA) 2009 *Drinking Water Contaminants*, USEPA EPA 816-F-09–004, May 2009, Washington, DC.

Yaziz, M. I., Gunting, H., Sapari, N. & Ghazali, A. W. 1989 Variations in rainwater quality from roof catchments. *Water Res.* **23** (6), 761–765.

First received 11 February 2011; accepted in revised form 12 July 2012