Assessment of rainwater quality from rainwater harvesting systems in Ontario, Canada

Christopher Despins, Khosrow Farahbakhsh and Chantelle Leidl

ABSTRACT

Rainwater samples were collected from rainwater harvesting (RWH) systems at seven sites located in a 30 km radius around the City of Guelph in Ontario, Canada. From October 2006 to October 2007, a total of 360 samples were collected from two sampling locations—the rainwater cistern and at the point of use—and analysed for pH, turbidity, colour, total and fecal coliforms, total organic carbon, total nitrogen and UV absorbance (254 nm). Additional parameters, including polycyclic aromatic hydrocarbons, total metals, *Campylobacter* and *Legionella* were examined in selected samples. Following data collection, statistical analysis was performed to investigate the factors that influenced rainwater quality. The results of the quality assessment programme were largely consistent with those reported by several other researchers, with the exception of improved microbiological quality during periods of cold weather. Total and fecal coliforms were detected in 31% and 13% of the rainwater samples, respectively, while neither *Campylobacter* nor *Legionella* were detected above 1 CFU/100 ml detection limits. The results indicate that, while quality can be expected to vary with environmental conditions, the rainwater from a RWH system can be of consistently high quality through the selection of appropriate catchment and storage materials and the application of post-cistern treatment.

Key words | cistern, point-of-use, rainwater harvesting, water quality

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INTRODUCTION

Rainwater harvesting (RWH) is the ancient practice of capturing rain runoff from roofs and other surfaces and storing it for a later purpose. Issues such as urban growth, limited water supplies, ageing stormwater infrastructure and environmental sustainability have prompted a renewed interest in the practice, which has become common in countries such as Germany and Australia. One of the primary areas of concern regarding the use of rainwater, for either non-potable or potable applications, is quality. The quality of water collected in a RWH system is affected by many factors, including:

1. Environmental conditions such as proximity to heavy industry or major roads, the presence of birds or rodents (Förster 1998; Taylor *et al.* 2000).
2. Meteorological conditions such as temperature, antecedent dry periods, and rainfall patterns (Evans *et al.* 2006).
3. Contact with a catchment material and the dirt and debris that are deposited upon it between rainfall events (Simmons *et al.* 2001; Van Metre & Mahler 2003).
4. Treatment by pre-cistern treatment devices such as filtration or first-flush diversion (Yaziz *et al.* 1989; Martinson & Thomas 2005).
5. Natural treatment processes taking place within the rainwater cistern (Scott & Waller 1987; Spinks *et al.* 2003*a*).
6. Treatment by post-cistern treatment devices such as particle filtration, ultraviolet disinfection, chlorination,

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slow sand filtration or hot water systems (Coombes *et al.* 2000; Kim *et al.* 2005; Ahammed & Meera 2006; Sazakli *et al.* 2007).

As part of a research and development project aimed at encouraging rainwater harvesting in Ontario, a one-year rainwater quality assessment programme was initiated with the objectives to: (i) assess the quality of rainwater from RWH systems located in the Southern Ontario region of Canada; and (ii) investigate the impact of factors such as contact with a catchment surface, storage in a rainwater cistern, weather (temperature and rainfall patterns), seasonal variation, post-cistern treatment and site environment on the quality of harvested rainwater. The findings are used to comment on the suitability of using harvested rainwater for non-potable purposes.

BACKGROUND

Environmental conditions such as the presence of atmospheric pollutants, overhanging foliage and bird debris can contribute to the contamination of rainwater; however, these factors are site specific and independent of the design of the RWH system itself. While such factors are difficult to control, several features of the RWH system also affect water quality. Catchment material, storage material and treatment are three design considerations that can be optimized to maximize water quality.

Catchment material

Contamination from roof surfaces can come from two main sources. Particles can accumulate on the roof surface either from direct atmospheric deposition, or from overhanging foliage or bird and rodent debris. Alternatively, the roof material itself continuously degrades and can contribute both particulate matter and dissolved chemicals to runoff water. While the former is largely site specific, the impact of different roof materials is fairly consistent regardless of location.

Metal roofs are often associated with the leaching of trace elements, detected in the dissolved form in the runoff itself and adhered to the particulate matter washed from the roof. Förster (1996) reports a threefold increase in the concentration of dissolved and particulate copper from copper flashings, compared with both pure rainwater and runoff collected from clay or concrete tiles. A similar trend is shown for zinc concentration in runoff from a zinc sheet roof and, to a lesser degree, from zinc gutters. Van Metre & Mahler (2003) compared galvanized metal roofs with asphalt roofs and also found metal roofs to be a greater source of both zinc and cadmium contamination, while asphalt was associated with higher levels of lead and possibly mercury. In contrast, Hart & White (2006) found no significant difference between concentrations of lead, zinc or copper in runoff from asphalt roofs and metal roofs, indicating a wide variation in results among similar roof-based studies.

Apart from metals, the leaching of polycyclic aromatic hydrocarbons (PAHs) from bitumen is another concern associated with asphalt shingles. While this has been observed under artificial and highly exaggerated laboratory conditions (Brant & de Groot 2001), one study of runoff from existing buildings has shown no evidence that asphalt roofs are a source of PAHs (Van Metre & Mahler 2003). Other studies suggest that flat tar felt roofs, however, may be a more significant source due to the more prolonged contact with the tar (Förster 1999). In cases where the concentration of PAHs was higher in the roof runoff than in the precipitation itself, it has been suggested that, rather than leaching from the roofing material, the presence of adsorption sites on the roof surface sorbs PAHs from the air during dry periods (Förster 1999; Polkowska *et al.* 2002).

Of the above studies, those based on asphalt shingles and flat tar roofs are most relevant to the Ontario context as these materials are the most common in the residential and industrial sectors, respectively.

Storage material

While roof surfaces are often viewed as a potential source of contamination for rainwater, cisterns can be seen as a means of treatment, offering a series of beneficial processes. For example, as rainwater is often slightly acidic, the increase in pH caused by contact with a concrete tank is beneficial for the protection of the distribution system and the chemical quality of the water by minimizing the potential for leaching metals. In a study evaluating the quality of stored water in a concrete cistern, Scott & Waller (1987) report a rise in pH from 5.0 on the roof surface, to 9.4 in the tank and 10.3 from the tap. A similar trend was observed for alkalinity, calcium and potassium concentrations. Their study also suggests that a higher pH can inhibit coliform growth. During sampling over a two year period, coliform bacteria were only detected during periods of low pH.

Sedimentation also plays a primary role in reducing the contaminant load of stored rainwater. Spinks *et al.* (2005) observed that the concentrations of aerobic HPC (heterotrophic plate count) bacteria were 50–100 times higher in the sediment than in the water column. For lead, Spinks *et al.* (2005) found that this magnification of the concentration in the sediment was as high as 340,000 in some tanks. Scott & Waller (1987) expressed concerns regarding this sediment layer because of the potential for re-suspension by means of low cistern levels, thermal mixing or the turbulent influx of rainwater during a rainfall event. Others have found that the re-suspension of sludge was minimal, and easily mitigated with proper RWH system design (Spinks *et al.* 2005).

While storage in cisterns is generally considered to enhance the quality of the rainwater, there is some concern over the potential for chemical leaching. Leaching of zinc from metal tanks was found to be significant in one study, but concrete or plastic tanks did not have any notable impact on the concentration of zinc, lead or copper (Hart & White 2006). The leaching of organic compounds is a concern with plastic tanks; however many American and Canadian regulations now require that any materials used for potable water applications must comply with the NSF/ANSI 61 Standard (NSF 2007). While this certification does not guarantee the absence of leached compounds, it ensures the material adheres to minimum established health effects requirements for any chemical contaminants or impurities that are imparted to the water (EPA 2002).

Treatment

To improve the quality of rainwater, a variety of treatment technologies have been developed to mitigate the contamination which takes place following contact with a catchment surface. One treatment technique popularized in Australia is the first-flush device, which is used to divert the first 0.8–3.5 mm of rainfall from storage in the rainwater cistern (Martinson & Thomas 2005; TWDB 2005). The rationale for these devices is the first-flush phenomenon reported in the literature, whereby the concentration of contaminants decreases exponentially during the first few millimetres of rainfall. This trend has been observed for a range of contaminants including suspended solids, PAHs, organic compounds and trace metals (Yaziz *et al.* 1989; Förster 1996; Shu & Hirner 1998; Förster 1999; Li *et al.* 2007).

Following storage in a rainwater cistern, particle filtration and UV disinfection are other means by which rainwater can be treated. A study by Kim *et al.* (2005) examined the performance of 5 μm and 1 μm metal membrane filters (comparable to polymeric membrane filters) and UV disinfection on roof-harvested rainwater. The Korean study observed a 50% reduction in the number of total coliforms for rainwater samples treated using a UV lamp, even at the low intensity of $I_{UVA} = 5.4\,W\,m^{-2}$ (Kim *et al.* 2005). Filtration was also found to reduce the number of total coliforms by rejecting them at the membrane surface. A removal efficiency of 78% and >98% was achieved with 5 μm and 1 μm metal membrane filters, respectively. In addition to the rejection of biological organisms, 80% and 95% of the particles present in the rainwater were removed by the 5 μm and 1 μm metal membrane filters, respectively (Kim *et al.* 2005).

Slow sand filtration is another method shown to be effective at improving the quality of rainwater. Ahammed & Meera (2006) compared two slow sand filters, one with iron hydroxide-coated sand and one with an uncoated sand medium. The uncoated sand filter was shown to achieve a bacterial removal of <21%, whereas the iron hydroxide-coated sand reduced total and fecal coliforms by 97–99%. Both turbidity and the concentration of the heavy metals zinc and lead showed improvement following slow sand filtration. The turbidity of rainwater collected from a concrete catchment surface was reduced from 8.2 to 0.5–2.4 NTU following slow sand filtration. Zinc levels dropped from 3.6 to $0.1\,mg\,l^{-1}$ and lead was reduced by 90% to $0.01\,mg\,l^{-1}$ on samples collected from a galvanized iron roofing material (Ahammed & Meera 2006).

Storing rainwater at temperatures typical inside a residential hot water tank (50–70°C) has also been shown to reduce biological contamination. A study of 27 rainwater systems at Figtree Place in Australia found that all coliform bacteria were removed after storage in the hot water tank in the 23 samples collected. This removal efficiency was achieved with rainwater of fairly poor quality. The average number of total coliforms throughout the study was 166 CFU/100 ml, with 20 CFU/100 ml fecal coliforms (Coombes *et al.* 2000). Another study showed a similar inactivation for *Escherichia coli* at sub-boiling temperatures. Spinks *et al.* (2003*b*) observed an almost 5 log reduction in *E. coli* concentrations when the water was maintained at 60°C for a period of 5 minutes in a laboratory setting.

METHOD

Description of study area and rainfall patterns

The rainwater quality assessment programme comprised seven households with RWH systems (sites) located in a 30 km radius around the City of Guelph. Guelph is located in the southern region of Ontario, Canada, and is approximately 100 km west of Toronto (shown in Figure 1). The one-year programme took place from October 2006 to October 2007, during which time cistern-stored (CS) rainwater samples and point-of-use (POU) samples were collected at each site concurrently on 30 occasions (with the exception of Site 5 and Site 7, where only POU samples could be collected). In total, 360 individual samples were collected and analysed.

The mean annual precipitation for the City of Guelph is 930 mm; 650 mm of this is in the form of rainfall from April to November, and the remainder from snowfall which takes place in December to March. The temperature ranges from a daily mean of 17°C in the summer months to −5°C in the winter (Environment Canada 2004).

Rainfall data for the City of Guelph was recorded on a daily basis by a rain gauge maintained as part of this quality assessment programme, and daily temperature records were obtained from Environment Canada's (2007) *Canadian Climate Database*. As shown in Figure 2, the average monthly temperatures recorded throughout the programme were roughly the same as the 1971–2000 climate normals for the City of Guelph; however rainfall differed in some months (Environment Canada 2007).

Monthly rainfall accumulations for the City of Guelph were roughly 40% higher than average during the period

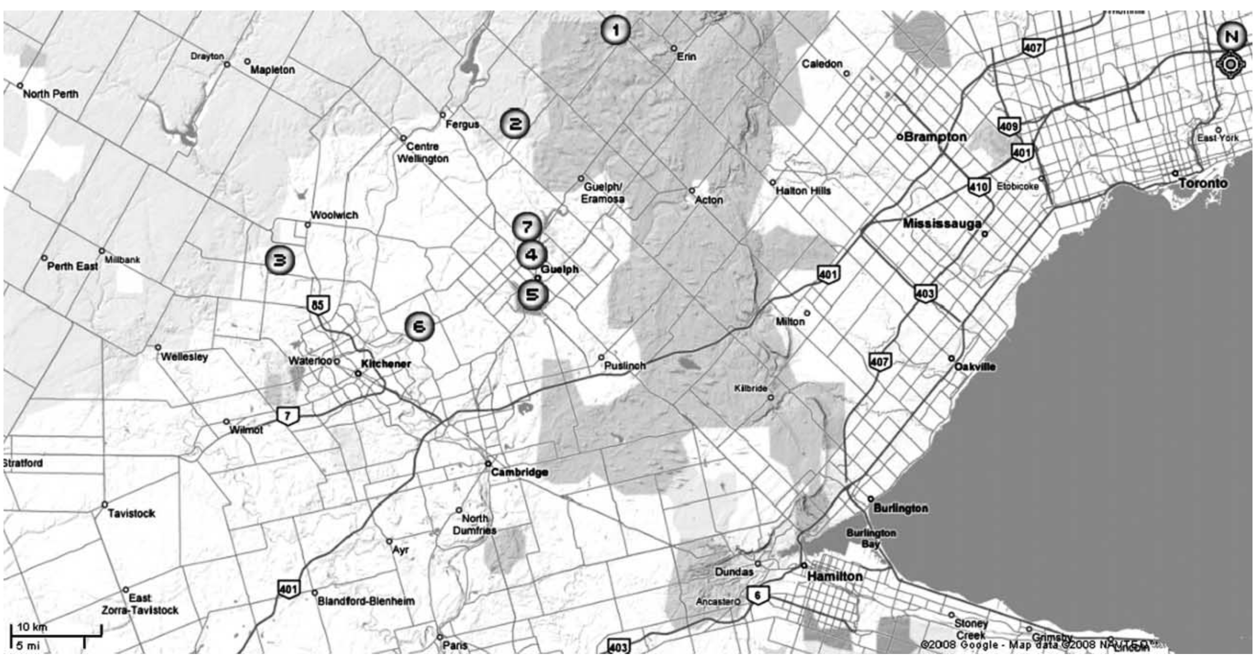

Figure 1 | Location of the seven sites participating in the quality assessment programme.

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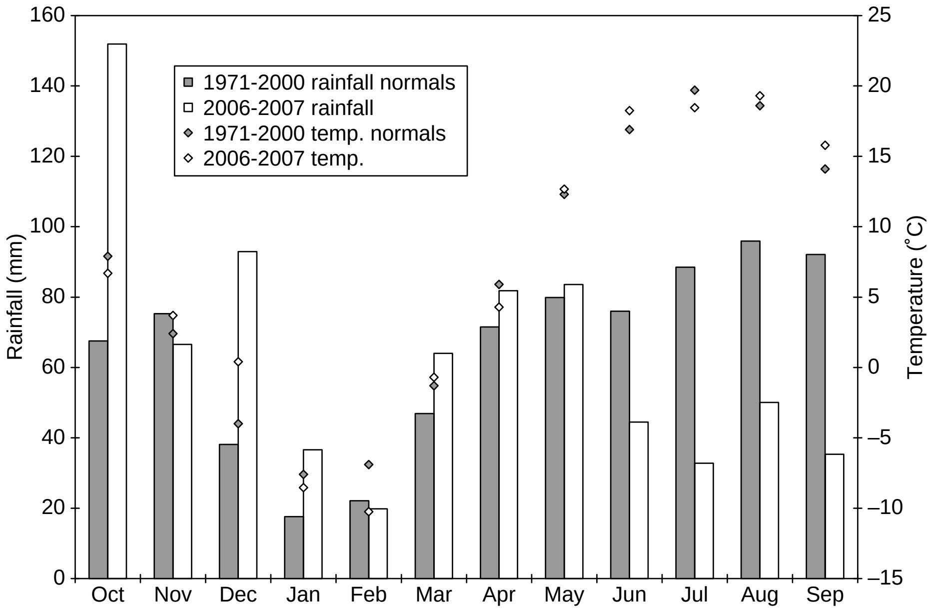

Figure 2 | Climate normals, monthly rainfall accumulations and mean monthly temperatures for the City of Guelph during the quality assessment programme.

October–January 2006, and were slightly above average from March–May 2007 The months of June and July had the greatest deviation from average rainfall figures, when the monthly rainfall was 60% below the 30-year norms, as drought-like conditions were present throughout much of southern Ontario.

Site characteristics

While each of the sites that participated in the quality assessment programme was unique in some respects, surveys conducted at each site revealed that several characteristics were shared among sites (summarized in Table 1). Only two types of storage material were utilized, concrete and plastic, while steel and asphalt shingle were the two predominant catchment materials. There is also an even distribution between urban and rural sites. The RWH systems at these sites were between one and three years old, with the exception of Site 3, which had been in use for approximately eight years.

Table 1 also lists the applications for which rainwater was used at each site. The majority of the sites used rainwater to service, at minimum, toilet flushing and outdoor use, with two sites (Site 1 and Site 3) meeting nearly all household water demand with rainwater. In general, the degree of treatment increased in proportion to the number of rainwater applications; the combination of particle filtration and UV disinfection was the most prevalent method of post-cistern treatment in the sites studied.

Sample collection and laboratory analysis

Two sampling mediums were used to collect the rainwater samples. A 1-l polypropylene Nalgene® bottle was used to collect rainwater for analysing pH, turbidity, colour, total and fecal coliforms; and a 250-ml amber glass bottle was used for total organic carbon (TOC), total nitrogen (TN) and UV-absorbance measurements. Prior to sampling, the Nalgene® bottles were rinsed with Milli-Q water and sterilized in an autoclave at 121°C at 15psig for 30 minutes. All glassware was acid washed with a 1:1 solution of sulphuric acid and Milli-Q water and baked in a 100°C oven for a minimum of 12 hours.

The cistern-stored rainwater samples were collected by lowering each bottle to the approximate centre of the cistern to produce a composite of the top half of the cistern's water column. During periods of low water levels in the tank, samples were collected at a greater depth to ensure that a composite sample was obtained. This range

Table 1 | Site characteristics

Site	Location	Site environment	Catchment material	Storage material	Treatment	Rainwater applications
1	Town of Erin	Rural	Steel	Plastic	Slow sand filter	Drinking & cooking
		Mature trees on property			Granulated activated carbon	Hot water service
					UV lamp	Bathing
					On-demand hot water heater	
2	Guelph-Eramosa	Rural Mature trees on property	Steel	Concrete cinder block with NSF polymer coating	20 μm particle filter UV lamp	Dishwasher Laundry
						Toilet flushing
						Outdoor use
3	St Jacobs	Rural	Asphalt shingle	Concrete cinder block	Hot water tank	Hot water service
		Mature trees on property				Bathing
						Toilet flushing Outdoor use
4	Guelph	Urban	Asphalt shingle	Precast concrete	20 μm particle filter	Laundry
		Mature trees overhanging the catchment surface			UV lamp	Toilet flushing Outdoor use
5	Guelph	Urban	Asphalt shingle	Precast concrete	First-flush device	Laundry
		Mature trees on property				Toilet flushing Outdoor use
6	Breslau	Industrial	Flat membrane	Precast concrete	Inline vortex pre-filter	Toilet flushing Outdoor use
		Immature trees on property			Fine mesh pump inlet filter	
7	Guelph	Urban	Steel	Precast concrete	No treatment	Toilet flushing Outdoor use
		Immature trees on property				

over which samples were collected inside the cisterns is illustrated in Figure 3.

Also identified in Figure 3 is the location where the point-of-use (POU) samples were collected. These samples were collected from a hose bib or other suitable location downstream of the post-cistern treatment units employed at each site. To minimize time variability between samples, samples from all locations were collected on the same day and transported to the laboratory by car during a 6–8 hour sampling period.

The following parameters were analysed throughout the quality assessment programme: pH, turbidity, colour, total coliforms, fecal coliforms, total organic carbon (TOC), total nitrogen (TN) and UV absorption (254 nm). The analytical procedures outlined in *Standard Methods for the Examination of Water and Wastewater* (1995) were used for measuring pH, turbidity, total and fecal coliforms. TN was determined using a Shimadzu TOC-V_{CSH} with a TNM-1 total nitrogen measuring unit, and colour was measured with a LaMotte SMARTSpecctro Spectrophotometer utilizing a platinum cobalt method wavelength calibration curve. Total organic carbon and UV absorption were analysed following EPA Method 415.3 (EPA 2005).

The pH, turbidity, colour, TOC, TN and UV-absorption were measured in duplicate from individual sub-samples of the collected rainwater, and total coliform and fecal coliform were plated in triplicate to minimize experimental error. TOC samples were acidified with sulphuric acid to $pH \leq 2$, and analysed within one week of sample collection. Analysis of all the remaining water quality parameters was completed within a maximum of 24 hours following sample collection.

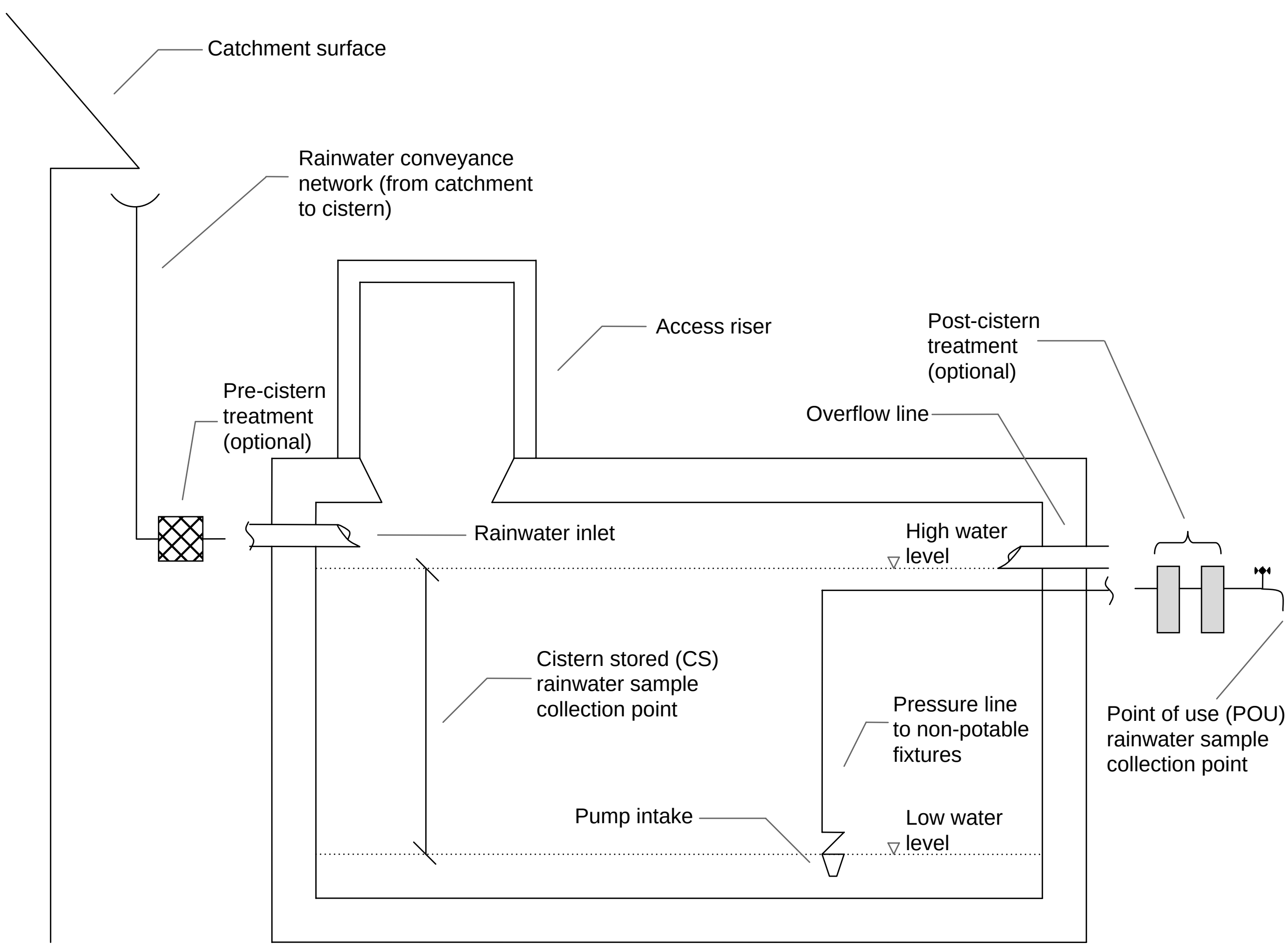

Figure 3 | Representative schematic of interior of rainwater cistern (section view).

In addition to the in-house testing programme detailed above, polycyclic aromatic hydrocarbons (PAHs), total metals, *Campylobacter* and *Legionella* were examined by an external testing facility for selected sites sampled on 6 November 2006 and 31 May 2007. For these water quality parameters, sample collection and analysis was performed in accordance with SW486 8270, EPA 200.8 and SW846 7470A, Health Canada MFLP-46, and ISO 11731, respectively.

Statistical analysis

Statistical analysis of the rainwater quality data was performed using SAS® Ver. 9.1. Since none of the water quality parameters met the assumption of normality, a logarithmic transformation and the removal of a maximum of eight outliers from each parameter was sufficient to achieve normality in all but three cases. Total and fecal coliforms, which were highly skewed towards < 1 CFU/100 ml, as well as UV absorbance, failed to meet the assumption of normality.

For the parameters that were normally distributed, a mixed statistical model was used to determine whether the independent variables of site environment and post-cistern treatment had a statistically significant impact on rainwater quality. The effect of site environment was assessed by comparing the quality of cistern-stored rainwater between sites, whereas the treatment effect was detected by comparing the quality of the point-of-use samples with the quality of the cistern-stored samples. To determine whether cistern-stored rainwater quality varied over time (seasonal variation), the SAS® repeated function was utilized.

The influence of weather on cistern-stored rainwater quality was assessed utilizing site-specific temperature and rainfall data collected as part of this study and from Environment Canada (2007). Three weather-based parameters were placed into the SAS® mixed model statement as covariates: average temperature in the week prior to sample collection, total rainfall in the week prior to sample collection, and the total number of dry days before sample collection (the antecedent dry period).

To determine the effect of catchment material and storage material, sites were grouped by material in SAS® using contrast statements. Contrasts were used to compare the quality of rainwater stored in concrete cisterns with that of plastic cisterns, and the quality of cistern-stored rainwater collected from asphalt shingle roofs compared with steel roofs. To further investigate the effect of site environment, contrasts were also performed comparing the quality of rainwater in urban locations with that of rural locations.

A bivariate linear logistic regression model was used for total and fecal coliforms to analyse these parameters based on the presence or absence of coliforms. Similar to the mixed model, site, treatment, weather and the contrasts were included in the analysis. The level of statistical significance for all tests was set at $\alpha = 0.05$.

RESULTS AND DISCUSSION

The physicochemical and microbiological rainwater quality data are reported in Tables 2 and 3, respectively.

From the data presented in Tables 2 and 3, a number of trends are evident. The mean turbidity of rainwater samples collected from the cisterns ranged from a low of 0.9 ± 0.5 NTU at Site 6 to a high of 2.6 ± 3.1 NTU at Site 4. The mean pH of the cistern-stored rainwater across all sites was neutral at 7.3, with a standard deviation of 1.0. Total nitrogen was detected in relatively small concentrations in the cisterns at the seven sites, ranging from $1.5 \pm 0.4\,\text{mg}\,\text{l}^{-1}$ at Sites 2 and 4 to $2.0 \pm 0.6\,\text{mg}\,\text{l}^{-1}$ at Site 3.

High variability in the quality data was observed with TOC, colour and UV absorption. With TOC, this variability can be observed at Sites 3 and 4, which had TOC concentrations of $6.3 \pm 4.5\,\text{mg}\,\text{l}^{-1}$ and $8.5 \pm 8.3\,\text{mg}\,\text{l}^{-1}$, respectively. At the point-of-use, Site 4 had a mean colour of 24.9 CU, but during the assessment programme, rainwater colour at this site ranged from a minimum of 4 to a maximum 64.5 CU. At Site 3, a slight difference in mean UV absorption is observed from the cistern (0.169 ± 0.114) to the point-of-use (0.191 ± 0.139); however, the implications of this difference are difficult to assess because of the large standard deviations of the data.

Total coliforms were detected above 1 CFU/100 ml in 114 of the 360 cistern-stored (30%) and point of use rainwater samples collected throughout the quality

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Table 2 | Physicochemical properties of rainwater observed for cistern-stored (CS) and point of use (POU) samples (values: mean ± standard deviation)

Sample location	pH	Turbidity (NTU)	TOC ($mg\,l^{-1}$)	TN ($mg\,l^{-1}$)	Colour (CU)	UV-ABS (254 nm)
Site 1 CS	7.1 ± 0.6	1.1 ± 1.6	3.1 ± 1.9	1.8 ± 0.7	11.1 ± 7.8	0.023 ± 0.026
Site 1 POU	7.2 ± 0.4	0.3 ± 0.1	2.3 ± 2.1	1.6 ± 0.6	7.1 ± 6.4	0.027 ± 0.092
Site 2 CS	5.8 ± 0.9	1.0 ± 0.5	1.8 ± 1.0	1.5 ± 0.4	11.6 ± 10.6	0.031 ± 0.064
Site 2 POU	5.9 ± 1.1	0.8 ± 0.3	2.7 ± 2.1	1.3 ± 0.6	15.2 ± 17.3	0.027 ± 0.040
Site 3 CS	7.2 ± 0.4	1.5 ± 0.7	6.3 ± 4.5	2.0 ± 0.6	25.5 ± 17.0	0.169 ± 0.114
Site 3 POU	7.3 ± 0.3	1.5 ± 0.8	6.9 ± 4.9	2.3 ± 1.5	27.4 ± 19.8	0.191 ± 0.139
Site 4 CS	7.5 ± 0.7	2.6 ± 3.1	8.5 ± 8.3	1.5 ± 0.5	32.8 ± 28.7	0.193 ± 0.177
Site 4 POU	7.0 ± 1.2	1.2 ± 0.5	6.4 ± 5.2	1.5 ± 0.6	24.9 ± 19.4	0.142 ± 0.113
Site 5 POU	8.1 ± 0.7	1.4 ± 0.6	7.4 ± 5.5	1.5 ± 0.5	23.4 ± 10.1	0.188 ± 0.170
Site 6 CS	8.2 ± 0.9	0.9 ± 0.5	2.9 ± 1.7	1.8 ± 0.9	13.1 ± 8.0	0.032 ± 0.056
Site 6 POU	8.2 ± 0.8	0.9 ± 0.3	3.2 ± 1.6	1.7 ± 0.7	13.8 ± 8.1	0.029 ± 0.034
Site 7 POU	7.5 ± 0.4	1.3 ± 0.7	2.4 ± 1.1	1.5 ± 0.3	14.9 ± 8.2	0.041 ± 0.061

assessment programme. The incidence rate for the detection of fecal coliforms was lower at 14%; 52 out of 360 samples had greater than 1 CFU/100 ml. The portion of samples with coliforms present (≥1 CFU/100 ml) on a site-by-site basis is presented in Table 3. As seen in the table, total and fecal coliforms ranged from <1 (below detection limits) to 400 CFU/100 ml. Despite this range, the geometric mean of the total and fecal coliforms was <1 CFU/100 ml at each site, with the exception of Site 4, which had a geometric mean of 1 CFU/100 ml total coliforms.

The statistical analysis revealed several important trends, the first of which was the overall sensitivity of the water quality parameters to both the design aspects of RWH systems and environmental conditions. The influence of each factor on rainwater quality is discussed below. Due to the failure of UV absorption to meet the criteria for normality, this parameter is not specifically addressed; however, since a statistically significant correlation was found between UV absorption and TOC (Spearman's $r = 0.51$), the trends observed for TOC are generally applicable to UV absorption as well.

Table 3 | Microbiological properties of rainwater observed for cistern-stored (CS) and point of use (POU) samples

Sample location	Total coliform (CFU/100 ml)			Fecal coliform (CFU/100 ml)		
	Geometric mean	Range	Portion of samples ≥1 CFU/100 ml (%)	Geometric mean	Range	Portion of samples ≥1 CFU/100 ml (%)
Site 1 CS	<1	<1–128	76	<1	<1–14	31
Site 1 POU	<1	<1– <1	4	<1	<1– <1	0
Site 2 CS	<1	<1–86	60	<1	<1–4	11
Site 2 POU	<1	<1– <1	0	<1	<1– <1	0
Site 3 CS	<1	<1–255	46	<1	<1–234	36
Site 3 POU	<1	<1– <1	0	<1	<1– <1	0
Site 4 CS	1	<1–398	89	<1	<1–400	54
Site 4 POU	<1	<1–12	14	<1	<1– <1	0
Site 5 POU	<1	<1–112	42	<1	<1–54	25
Site 6 CS	<1	<1–51	17	<1	<1–10	7
Site 6 POU	<1	<1–40	10	<1	<1–6	7
Site 7 POU	<1	<1–24	28	<1	<1–5	3

Catchment material

Nearly all water quality parameters (pH, turbidity, total organic carbon, total nitrogen and colour) were found to vary significantly based on the type of catchment material, either asphalt shingle or steel. In general, poorer quality was observed at sites utilizing asphalt shingle roofs for rainwater collection. This trend is shown using box-and-whisker plots for turbidity in Figure 4. Each box in the figure represents the bounds of the first and third quartile, the median is marked by the horizontal line inside the box, and the ends of the 'whiskers' represent the minimum and maximum.

The three sites that utilized asphalt shingles as a catchment surface (Sites 3, 4 and 5) had cistern-stored rainwater with a mean turbidity of 1.6 NTU, whereas at the sites with steel roofs (Sites 1, 2 and 7) the mean turbidity was about 40% lower, at 1.0 NTU. Similar trends were observed with TOC and colour: sites with asphalt shingles had means of 5.8 mg l^{-1} TOC and 23 CU, and the sites with steel roofs had lower values of 2.5 mg l^{-1} TOC and 13 CU in the samples collected from the rainwater cisterns.

The influence of catchment material on rainwater quality, particularly turbidity, has been reported in other studies. In a study examining different catchment materials in northern China, Zhu et al. (2004) found that cistern-stored rainwater turbidity ranged from 2.0 to 3.5 NTU when collected from mortar roofs, whereas the turbidity of rainwater collected from cement-paved courtyards was higher at 3.0–6.5 NTU. Another study, by Yaziz et al. (1989), examined the direct roof runoff from galvanized iron and concrete tile roofs. Although comparisons between this study and Yaziz et al. (1989) are difficult because of the different sampling locations, a similar trend was observed: the runoff turbidity ranged from 10 to 22 NTU from the galvanized iron roof, while concrete tile roofs had substantially higher values of 24–56 NTU.

These findings indicate that the design characteristics of RWH systems, such as the selection of a catchment material, can have a significant impact on rainwater quality. Yaziz et al. (1989) and Shu & Hirner (1998) have proposed that this trend may be attributed to the material properties of different catchment surfaces, as some may provide a greater surface area for the adsorption of atmospheric debris between rainfall events. This hypothesis was supported by this study, as poorer quality was observed at sites with textured surface of the asphalt shingles, as opposed to the relatively flat surface of the steel roofs.

Storage material

Storage material had a statistically significant ($p < 0.05$) effect on fewer quality parameters (pH, turbidity, total organic carbon and colour) than catchment material. Of these parameters, pH was the most sensitive to the type of storage material. The variation in pH between sites with concrete cisterns and those with plastic cisterns is presented in Figure 5.

The pH of rainwater stored in plastic cisterns tended to be slightly acidic. The minimum pH was 4.8 at Site 2, although the mean of all sites was higher at 6.5. Conversely, the rainwater at sites with concrete cisterns was more basic, with a mean of 7.7 and a maximum of 10.2 at Site 6.

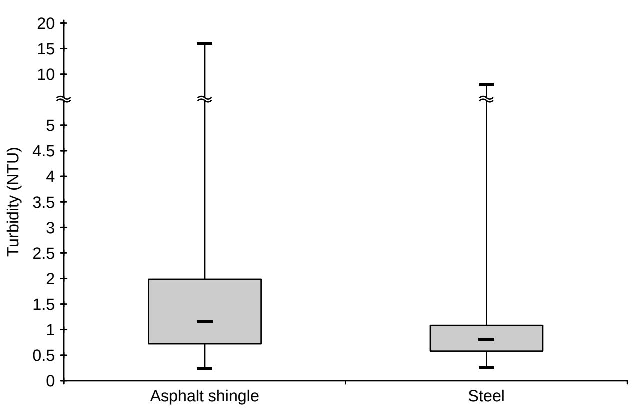

Figure 4 | Box-and-whisker plots of the cistern-stored (CS) turbidity among sites with asphalt shingle and steel catchment materials.

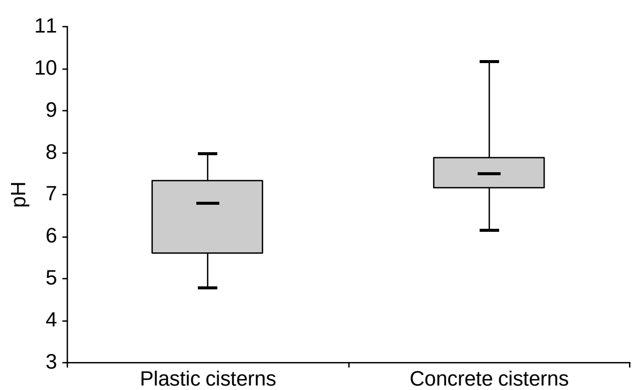

Figure 5 | Comparison of the cistern-stored (CS) pH among sites with plastic and concrete cisterns.

Similar patterns were observed with the other water quality parameters. For instance, the mean colour of rainwater stored in concrete cisterns was 21.8 CU, whereas for plastic cisterns colour was only 11.1 CU. Turbidity and TOC of rainwater stored in plastic cisterns had means of 0.8 NTU and 2.5 mg l^{-1} TOC, while 5.4 mg l^{-1} TOC and 1.4 NTU were detected in rainwater sampled from the concrete cisterns.

Comparing these results with those presented in the literature, Sazakli *et al.* (2007) reported a similar range of pH values, 7.6–8.8, for rainwater stored in concrete cisterns in Greece. In a study of 125 household RWH systems in New Zealand, Simmons *et al.* (2001) also found a statistically significant difference between concrete and non-concrete cisterns (plastic, wood, fibreglass or galvanized iron) which had median pH values of 7.5 and 5.9, respectively. Scott & Waller (1987) and Zhu *et al.* (2004) attribute the increased pH in concrete cisterns to the leaching of calcium carbonate from the cistern walls; however, it is unclear what factors led to the heightened levels of TOC and turbidity at the sites with concrete cisterns. It is possible that site environment or the type of catchment material may be confounding these findings, making it difficult to determine what factors have affected these water quality parameters.

Weather

The three weather-based criteria (temperature, rainfall and the antecedent dry period) were found to have little effect on the majority of the water quality parameters. Colour was affected by the amount of rainfall ($p < 0.05$) and the antecedent dry period ($p < 0.05$), while turbidity and TN also varied with the length of the dry period.

In general, the colour, turbidity and TN concentration of the cistern-stored rainwater tended to increase during dry periods, indicating that some aspects of rainwater quality, especially the colour, are more sensitive to rainfall or drought conditions than other water quality parameters, and will thus naturally vary to a great extent depending on climatic conditions.

A significant relationship between temperature and the number of total and fecal coliforms was also discovered. Since changes in temperature followed a seasonal trend, the effect of temperature on coliform counts shall be discussed within this context.

Seasonal variation

Differences of a statistically significant level were observed with all water quality parameters with respect to time (seasonal variation effect). Rainwater quality tended to improve following the summer months, with the highest quality rainwater detected during the winter. This trend was most evident with total and fecal coliforms, shown in Figure 6.

During the summer months, 50% of the total coliform samples and 30% of the fecal coliform samples tested positive for the presence of coliforms (≥1 CFU/100 ml). In contrast, during the winter, total and fecal coliforms were present in only 22% and 2% of samples, respectively. This decline in microbiological activity throughout the winter months could be attributed to a number of factors. One possibility is that the colder air temperatures between December 2006 and April 2007 (ranging from −19.2 to 14.4°C) inhibited the growth of bacteria within the cistern itself, thereby reducing the number of samples with coliforms present. Another potential contributor to the smaller number of samples with coliforms in the winter and spring months is the decreased activity of animals and birds. The decreased fecal contamination of the catchment surface by birds and animals during these months would be likely to reduce the influx of fecally contaminated rainwater into the cistern.

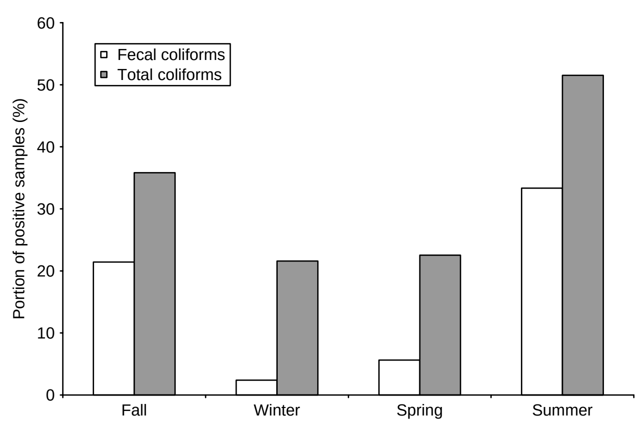

Figure 6 | Seasonal variation in the portion of samples positive for the presence of total and fecal coliforms (CS & POU combined).

Statistical analysis of the rainwater data provides some indication that the former of the above scenarios is most likely. Temperature had a highly significant effect ($p < 0.0001$) on both total and fecal coliforms. While this finding on its own is inconclusive (i.e. was it from temperature, or from decreased animal activity in response to temperature?) when combined with the results from two additional statistical tests, temperature, rather than animal activity, seems to be the most important contributor to decreased coliform counts in the winter.

The first of these test results is the weak positive correlation between temperature and both total and fecal coliforms, estimated at 0.101 ± 0.020 and 0.120 ± 0.023, respectively. This correlation suggests that as the temperature increased, the presence of total and fecal coliforms at the sites tended to increase as well. The second set of supporting data is the failure to find a significant impact from the number of consecutive dry days, or the volume of rainfall in the week prior to sample collection, on the biological parameters. If bird or animal activity was the primary contributor to the presence of total and fecal coliforms, one would expect to see a significant correlation for either the antecedent dry period (during which time fecal deposits would accumulate) or the rainfall in the week prior to sample collection (an indicator of whether fecal material had been transferred to the cistern following a rainfall event). Since neither of these tests was statistically significant, it suggests that temperature inside the cistern has a greater impact on the presence of total and fecal coliforms than did an external source such as bird or rodent debris.

This premise has some support from the research findings of Simmons *et al.* (2001) and Sazakli *et al.* (2007). Simmons *et al.* (2001) found statistically significant seasonal variations in total coliforms ($p = 0.086$) and fecal coliforms ($p = 0.031$), while Sazakli *et al.* (2007) reported a nearly identical seasonal trend in the presence of total coliforms. The Sazakli *et al.* (2007) study detected the lowest ratio of positive samples in the winter months, which gradually increased in the spring and summer, with autumn having the highest number of positives detected. Although it was the summer, and not autumn, that had the highest number of positive samples in the quality assessment programme, the similarities between these studies shows that seasonal variation (specifically the difference in temperature between seasons) may influence the level of microbiological activity inside rainwater cisterns.

A statistically significant seasonal effect was also detected with the physicochemical parameters; however, unlike total and fecal coliforms, temperature was not the source of this variation, as this factor lacked significance. The physicochemical parameters tended to follow the same trend as the total and fecal coliforms, with poorer quality rainwater observed during the summer and fall. This trend is presented in Figure 7 for the TOC concentration in cistern-stored rainwater.

As seen in Figure 7, the TOC concentration was especially poor during the summer, during which time the TOC varied from a low of 2.1 mg l^{-1} at Site 6 to a high of 33.9 mg l^{-1} at Site 4. Reports of a seasonal trend in rainwater quality have come from Germany with respect to the PAH benzo[b]fluoranthene and Greece with respect to conductivity (Förster 1999; Sazakli *et al.* 2007). However, in both cases an opposite trend was observed as quality tended to improve in the summer months. A possible explanation for this discrepancy is that in this study lower levels of atmospheric pollutants may have been present during the winter months. Cold climate conditions, including the presence of snow on the ground and decreased animal and plant activity, may have reduced the transfer of particulate matter and organics on to the catchment surface.

Treatment effect

The use of post-cistern treatment devices was found to have a significant impact on three water quality parameters:

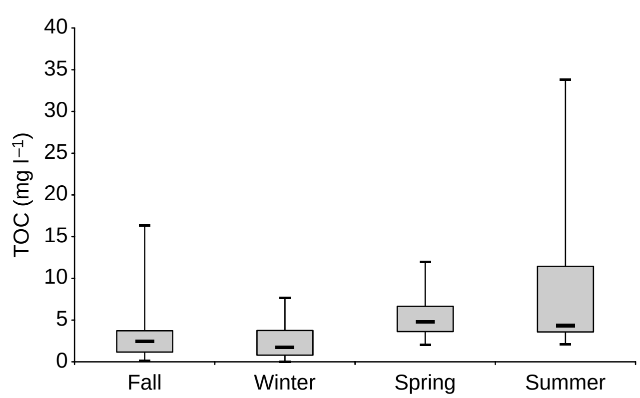

Figure 7 | Seasonal variation in TOC concentration in cistern-stored (CS) rainwater samples.

turbidity, total and fecal coliforms. This treatment effect is demonstrated by observing the decrease in both the mean and the range of rainwater turbidity and coliform counts in the point-of-use samples compared with the pre-treated rainwater from the cistern. The effect of treatment on turbidity is illustrated in Figure 8.

As seen in Figure 8, turbidity decreased by roughly 20% at Site 2, 60% at Site 4, and 75% at Site 1 from the rainwater cistern to the point-of-use. These observations can be attributed to the use of particle filtration at each of these three sites. Site 2 and Site 4 both employed a 20 μm particle filter, whereas the higher removal efficiency at Site 1 was from the use of a slow sand filter. Site 3 and Site 6 also showed a decrease in turbidity, even though there was not the same degree of filtration used as the other sites. In the case of Site 3, the reduction in turbidity is most likely due to particle settling within the cistern itself. Particle settling probably improved turbidity at Site 6 as well, as did the use of a German-designed fine mesh filter installed on the pump inlet.

The reduction in the number of total and fecal coliforms following post-cistern treatment is shown in Figures 9 and 10. Of the samples that tested positive for the presence of total coliforms in the rainwater cistern, 96% had <1 CFU/100 ml following treatment. Similarly, 97% of the cistern-stored rainwater samples positive for fecal coliforms had <1 CFU/100 ml at the point-of-use. Of note is that the reduction in the number of total and fecal coliforms took place regardless of the post-cistern treatment technique applied: UV lamp, slow sand filter or hot water tank.

The treatment effect of the hot water tank, in particular, is of interest, and was observed at the only site employing rainwater hot water service (Site 3). Total coliforms and fecal coliforms decreased to <1 CFU/100 ml following storage in a typical residential hot water tank, at approximately 60°C. This level of treatment was achieved with 100% effectiveness ($n = 30$), even when as many as 60 CFU/100 ml total coliforms were present in the cistern-stored rainwater. This treatment effect is consistent with the work by Coombes *et al.* (2000) and Spinks *et al.* (2003*b*) demonstrating the bacteriological inactivation properties of temperatures present in hot water tanks.

Site environment

A statistically significant difference was detected in all of the water quality parameters between sites. This difference in

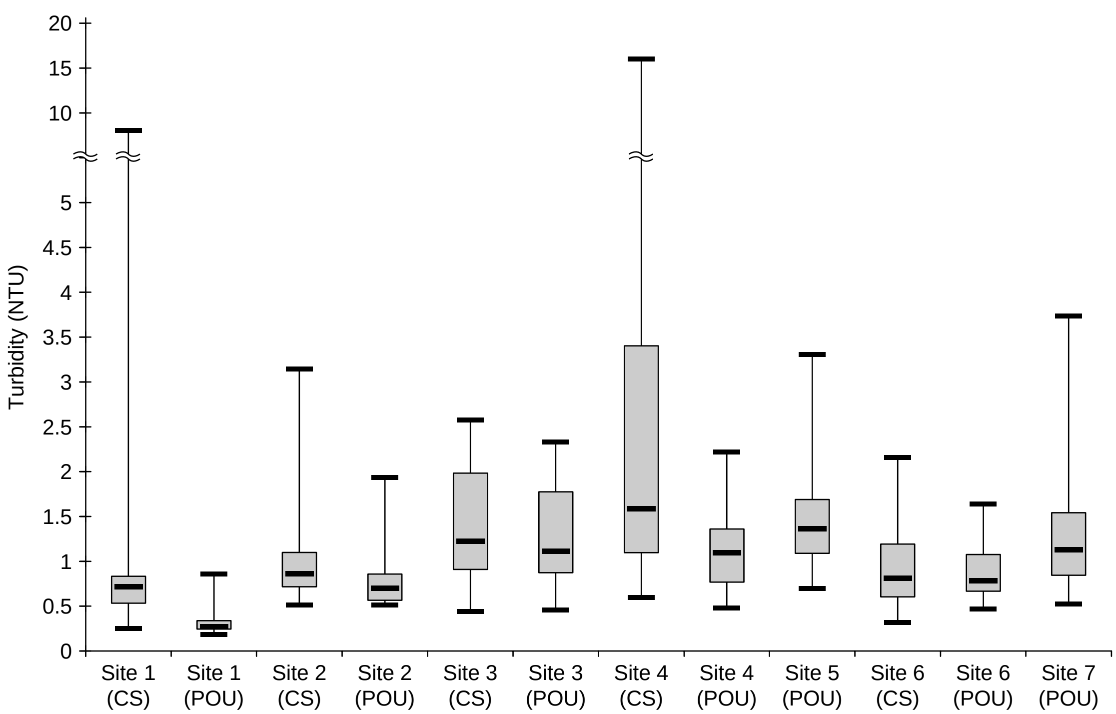

Figure 8 | Comparison of turbidity in cistern-stored (CS) and point of use (POU) rainwater samples.

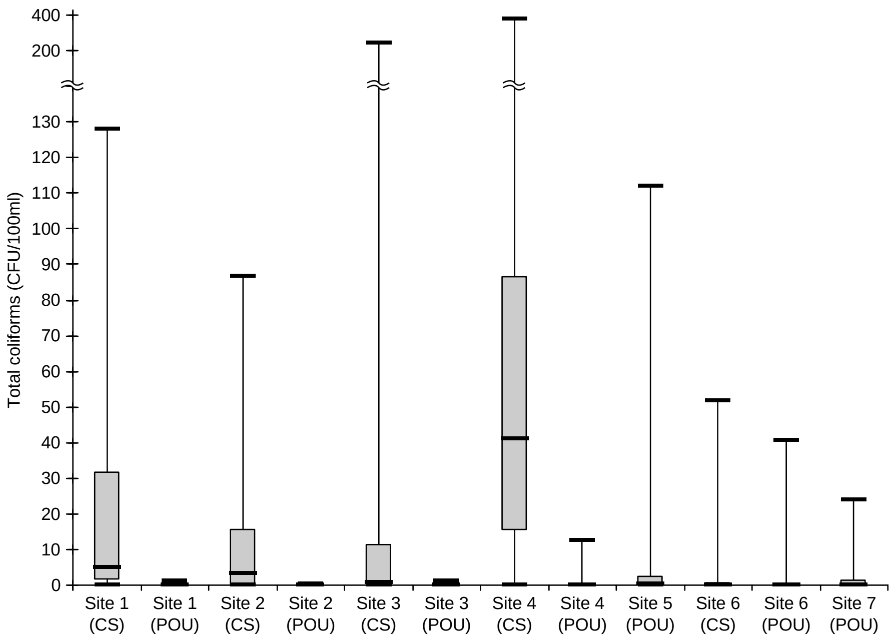

Figure 9 | Comparison of the total coliforms in cistern-stored (CS) and point of use (POU) rainwater samples.

cistern-stored rainwater quality is most evident with Site 4, which consistently had the poorest quality of all the sites throughout the course of the study. The characteristics of Site 4 were quite similar to several of the other sites, particularly Sites 3 and 5; however, these sites did not exhibit the poor quality of Site 4. Thus, it is likely that at Site 4, environmental conditions (a site environment effect) had a far more detrimental effect on rainwater quality than at the other sites.

Evidence of a site environment effect is provided by comparing the total and fecal coliforms at Sites 3, 4 and 5. Site 4 had the same catchment and storage materials as Sites 3 and 5, and was located at a distance of only 7 km from Site 5, yet it had a much higher number of coliforms than these sites. One could argue that the higher microbiological loading at Site 4 was the result of a lack of a first-flush device or other type of pre-cistern treatment. Although Site 5 had many of the same characteristics of Site 4, it employed a first-flush device to divert the first millimetre of roof runoff from entering the cistern. Excluding this first millimetre of rainfall, and with it, the easily mobilized dirt and debris deposited on the roof surface between rainfall events, may have contributed to the lower number of total and fecal coliforms detected at this location. The data from Site 3, which did not use a pre-cistern treatment device, indicates that pre-cistern treatment alone is not the only factor influencing the number of total and fecal coliforms. The number of total and fecal coliforms in the cistern at Site 3 was consistently lower than that at Site 4, despite the lack of pre-treatment.

Site conditions have been identified as a source of potential contamination by Förster (1998) and Van Metre & Mahler (2003); however, given the proximity of Sites 4 and 5, it is thought that, rather than different rates of atmospheric deposition on the catchment surface, conditions specific to Site 4 contributed to its poor overall quality. For instance, the quality of the cistern-stored rainwater may have been affected by the presence of several mature trees overhanging the roof. This site had the greatest number of trees of all of the sites monitored, and was the only site with trees directly overhanging the roof surface. The deposition of plant matter onto the catchment surface from the overhanging trees may have adversely affected the quality of runoff stored in the rainwater cistern.

A statistically significant site environment effect was also observed when sites from urban settings (Sites 4, 5, and 7) were compared with rural sites (Sites 1, 2 and 3).

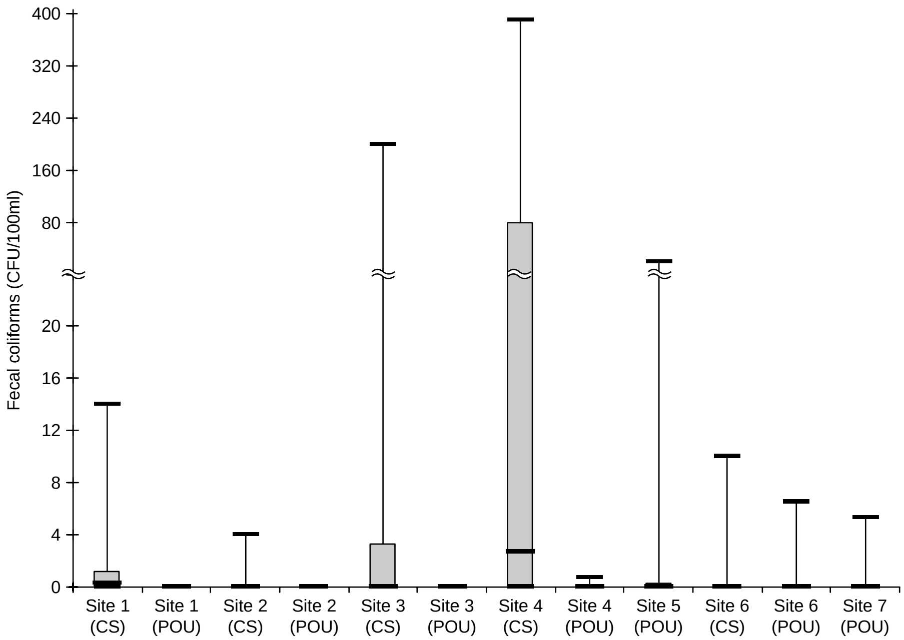

Figure 10 | Comparison of the fecal coliforms in cistern-stored (CS) and point of use (POU) rainwater samples.

The trend was detected with all water quality parameters, except total and fecal coliforms. In general, the quality of rainwater in rural locations was better than that harvested in urban settings, with the exception of TN. The mean concentration of TN in the cistern-stored rainwater from rural sites was $1.7\,mg\,l^{-1}$, whereas in the urban cisterns the concentration was $1.5\,mg\,l^{-1}$. This exception may be due to the increased use of nitrogen-containing agricultural inputs in rural settings. Some of the aerosolized agricultural inputs may have collected on the catchment surface during dry periods and subsequently been transferred into the cistern following a rainfall event.

PAHs

The PAHs benzo[a]pyrene, benzo[b]fluoranthene, benzo[j]-fluoranthene, benzo[k]fluoranthene and indeno[1,2,3-cd]pyrene, classified as 'probably carcinogenic to humans' by the Government of Canada (Government of Canada, Environment Canada, Health Canada 1994), and 15 other PAHs recognized by the Canadian Council of Ministers for the Environment (CCME), were analysed on samples collected from the rainwater cisterns at Sites 1, 2, 4, 5 and 6 in November 2006 and May 2007. Detection limits of the PAHs ranged from $0.005\,\mu g\,l^{-1}$ for benzo[a]pyrene to $4\,\mu g\,l^{-1}$ for acridine, while the remaining PAHs were detected at a concentration above $0.02\,\mu g\,l^{-1}$ in the rainwater samples. Despite the sensitivity of the detection limits, none of the 20 CCME PAHs was found above the detection limits from the rainwater samples collected at the five sites in November 2006 and May 2007.

Förster (1996, 1998) has reported that PAH concentrations in roof runoff can vary between different roof surfaces during the same rainfall event, and also vary with the proximity of roofs to other sources of PAHs (such as roads). Another study, by Van Metre & Mahler (2003), reported spatial variations in the PAHs pyrene, fluoranthene and phenanthrene in rainwater samples, but found no difference between roofing materials. This study's identical findings between sites and across different sampling periods prevent conclusions such as those presented by Förster or Van Metre & Mahler.

Metals

Analysis of the metals present in the cistern-stored rainwater revealed that only calcium ($0.8-12.2\,mg\,l^{-1}$)

and strontium ($0.001-0.12\,mg\,l^{-1}$) were present above detection limits at all of the sites tested. Aluminium, arsenic, copper, magnesium, manganese, silicon, sodium, tin and zinc were also detected in low concentrations at some of the sites. Although arsenic was detected at Sites 1 and 2, the average concentration of $0.001\,mg\,l^{-1}$ at these sites was well below the maximum acceptable concentration (MAC) in drinking water ($0.01\,mg\,l^{-1}$) set by Health Canada (Health Canada 2007). Other metals of concern, such as cadmium ($MAC \leq 0.005\,mg\,l^{-1}$), lead ($MAC \leq 0.01\,mg\,l^{-1}$) and mercury ($MAC \leq 0.001\,mg\,l^{-1}$) were also below these levels in the cistern-stored rainwater (Health Canada 2007).

The results of the metals analysis reveal some similarities between the sites in this study and trends discussed in the literature. Van Metre & Mahler (2003) have reported elevated concentrations of zinc and cadmium from metal rooftops. Higher levels of zinc and lead have also been detected in rainwater collected from galvanized iron roofs and zinc sheet roofs (Yaziz *et al.* 1989; Förster 1996; Simmons *et al.* 2001). Although this trend was not detected for cadmium or lead in this study, as both heavy metals were below detection limits, it was observed for zinc. The median zinc concentration from steel roofs in this study was $0.28\,mg\,l^{-1}$, roughly 23 times higher than the zinc concentration from the asphalt shingle roofs.

Similar concerns regarding the leaching of metals from asphalt shingle roofs have been raised by Van Metre & Mahler (2003), who observed a potential correlation between asphalt shingles and the leaching of mercury. This relationship, however, was not found in this study. Mercury was not detected above the $0.0001\,mg\,l^{-1}$ detection limit at any of the sites employing asphalt shingles, or from the sites with steel roof surfaces.

Thus, although zinc levels from steel roofs were elevated compared with asphalt shingle roofs, the rainwater collected from both catchment surfaces had zinc concentrations well below Health Canada's (2007) $5.0\,mg\,l^{-1}$ aesthetic objectives (AO). The absence of any other significant degree of metal contamination, from either roof material, suggests that both asphalt shingle and steel roofing (with respect to metals) are suitable for the collection of rainwater for non-potable use.

Legionella and *Campylobacter*

The results of the *Legionella* and *Campylobacter* analysis showed that neither pathogen was detected in the rainwater. Additional samples from Site 4 and Site 5 were sent for further *Campylobacter* analysis in July 2007. These two sites were selected because of the large number of fecal coliforms detected in the pre-treated rainwater at the sites in the previous sampling period (79 CFU/100 ml at Site 4, and 54 CFU/100 ml at Site 5). Despite the heightened coliform loading in the rainwater systems at these sites, *Campylobacter* was not detected.

Studies reviewed by Lye (2002) have reported the presence of *Campylobacter* in rainwater harvesting systems in New Zealand, and have documented an outbreak of legionnaires' disease in the US Virgin Islands attributed to rainwater contaminated by *Legionella pneumophila*. Albrechtsen (2002) detected *Campylobacter* in 2 out of 17 samples, but failed to find *Legionella pneumophila* in 14 samples from rainwater cisterns in Denmark.

The absence of *Legionella* and *Campylobacter* in the rainwater cisterns in this study (even with large numbers of fecal coliforms present) and the infrequent detection of these pathogens in the literature suggest that *Legionella* and *Campylobacter* are not predominant within RWH systems. Further study is advised, however, due to the limited number of samples analysed in this study.

CONCLUSIONS

The physicochemical properties of rainwater were most influenced by the catchment and storage materials and site environment. Catchment surfaces employing steel roofs provided rainwater runoff of higher quality than did asphalt shingle roofs. The material properties of asphalt shingles may have contributed to poorer quality runoff, owing to the adsorption of atmospheric particulates deposited on the catchment surface between rainfall events. The pH of rainwater stored in plastic cisterns tended to be slightly acidic, whereas rainwater pH was slightly basic when stored in concrete. The quality of harvested rainwater appears to depend, in part, on the location in which RWH systems are operated. In some cases, site environment may have a detrimental impact on rainwater quality, as was observed at Site 4.

Season, temperature and extent of treatment had the greatest impact on the microbiological quality of the rainwater. During the summer and fall seasons total and fecal coliforms were detected in a greater proportion of samples, and were also detected in greater numbers. Post-cistern treatment, by means of a 20 μm particle filter and UV disinfection, was shown to be effective at reducing the number of total and fecal coliforms and turbidity prior to use. Following post-cistern treatment, the number of samples with detectable levels of total and fecal coliforms was reduced, on average, by 96% and 97%, respectively. The average reduction in turbidity was 42%.

The absence of heavy metals, CCME PAHs, *Legionella*, or *Campylobater* in any of the cistern-stored rainwater samples indicates that there is minimal risk associated with the non-potable use of harvested rainwater. While quality can be expected to vary with environmental conditions, the rainwater from a RWH system can be of consistently high quality through the selection of appropriate catchment and storage materials and the application of pre- and post-cistern treatment.

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