Harvested rainwater quality: the importance of building design

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Abstract This paper summarises the physicochemical and microbiological quality of water from a rainwater harvesting (RWH) system in a UK-based office building. 7 microbiological and 34 physicochemical parameters were analysed during an 8 month period. Physicochemically, harvested rainwater quality posed little health risk; most parameters showed concentrations below widely used guideline levels for *drinking* water. However, RWH system components (e.g. fittings and down pipes) appear to be affected soft water corrosion, resulting in high concentrations of some metals (copper, zinc and aluminium). This suggests the material selection of such fittings should be considered keeping in view the hardness of rainwater of an area. Microbiologically, *Cryptosporidium*, *Salmonella* and *Legionella* were not present in the samples analysed. However, faecal coliform counts were high at the beginning of the study, but did decrease over time in weak correlation with increasing pH. *Enterococcus faecalis* displayed counts consistently above UK rainwater harvesting standards. Poor building and roof design and material selection appear to be responsible for the reduced microbial quality, as they promoted contributions from avian sources and inhibited cleaning activities. Building design is therefore critical in establishing and maintaining good harvested rainwater quality, to prevent both the development of contaminated sediments and health impacts.
Keywords Harvested rainwater; water demand management; water quality

INTRODUCTION

Rainwater harvesting (RWH) is being increasingly promoted as a supplementary water source to mains water within the UK, for non-potable applications such as toilet flushing (BSI, 2009). Förster (1999) emphasised the importance of investigating the variability of pollution in roof runoff. Other researchers have reinforced this by asserting that it is necessary to evaluate the quality of rainwater, even for non-potable applications, to ensure that it will not be a hazard to users' health in relation to its intended use (May and Prado, 2006).

There exists a large body of research on the quality of water available through RWH systems worldwide (Lye, 2002 and Meera and Ahammed, 2006). With respect to developed countries, the majority of contemporary studies have originated from Australia (Evans *et al*. 2006, Magyar *et al*. 2007, Ahmed *et al*. 2008), where RWH is accepted as a potable and non-potable supply source. In contrast, there is very little UK-based research. Both Birks *et al*. (2004) and Fewtrell and Kay (2007) highlight the need for small scale monitoring studies to investigate RWH system water quality and potential health impacts.

There has been very limited research into the physicochemical characteristics of harvested rainwater supplies in the UK. This may be due to the fact that physical and chemical characteristics do not generally pose a significant *health* risk when using harvested rainwater for non-potable applications. However, elevated concentrations of such parameters can have implications for RWH *system operation*. For example, Förster (1999) identified that tar roofs exhibit higher polycyclic aromatic hydrocarbon (PAH) concentrations, which can influence the effectiveness of pollution reducing devices such as filters (PAHs are also carcinogenic).

Additionally, Förster (1999) found zinc and copper concentrations in runoff from roofs made of these materials exceeded threshold values causing aquatic toxicity and affecting the disposal or utilisation of sewage sludge and soil. Furthermore, Magyar *et al.* (2007) identified that levels of heavy metals within sediments of RWH system storage tanks exceeded Australian and New Zealand's recreational and irrigation guideline levels, as well as Victorian EPA guidelines for the disposal of waste. This could have implications for non-sanitary use of rainwater (such as garden watering) and for the disposal of sediments after routine storage tank cleaning. Such studies demonstrate the importance of roof and building material selection during the design and construction phases.

In order to help fill the knowledge gap identified above, this paper presents the results of a long term (8 month) study into the physicochemical and microbiological characteristics of harvested rainwater within a RWH system located within a UK-based office building.

MATERIALS AND METHODS
Site characteristics
The Innovation Centre (IC) on the University of Exeter's Streatham campus is a new-build office building. A RWH system is located within the building and used to flush toilets in order to reduce mains water consumption. The system of RWH and distribution consists of a south-facing bitumastic-felt-membrane roof catchment (1500m²), rainwater goods (aluminium guttering and pipes), a glass-reinforced plastic (GRP) underground storage tank ($25m^3$), a control system, two GRP header tanks ($0.8m^3$ each) and associated medium-density-polyethylene (MDPE) and copper pipework.

Although there are no trees or vegetation directly overhanging the building, there are large numbers of trees in close proximity (the campus is a registered botanical gardens). These provide perches for over-flying birds. In addition, the site is in close proximity to several car parks, approximately 1km from a large railway station (to the west), less than 6km from a wastewater treatment plant (WWTP) to the south, 10km from Dartmoor National Park (to the north west) and 18km from the south coast. Weather data were recorded during the study by the Centre for Water System's weather station, located approximately 0.5km from the IC. Temperature, precipitation levels and wind speed and direction were recorded at 15 minute intervals and then averaged to daily or weekly figures, as required.

Sampling and analysis (August 2008 to April 2009)
The layout of the RWH system is illustrated in Figure 1. Samples were obtained via a sampling point (6) installed on the copper pipe outlet from the RWH system control panel (5) in the central plant room of the building. This is located between the main storage tank (2) and the header tanks (7). Samples were obtained before the header tanks to rule out the possibility of dilution with mains water from the top-up system.

Due to budgetary constraints, the number and type of parameters to be examined were restricted and two sampling regimes were followed:

(i)   Weekly collection of rainwater samples – 15 parameters (Table 1);
(ii)   Three-monthly collection of rainwater samples – 41 parameters (Table 2).

Overall, samples were analysed for 7 microbiological and 34 physicochemical parameters.

Standard water quality sampling procedure is to flush a sampling point for a period proportional to the diameter and length of pipe prior to sampling (APHA, 2000). Due to the location of the tap (inside a building) this was not possible. Instead, one litre of rainwater was drawn off immediately before samples were obtained. This procedure is inline with that used by Ahmed *et al.* (2008). Samples were kept in cool and dark conditions during transit and were processed by a commercial laboratory using standard methods (APHA, 2000).
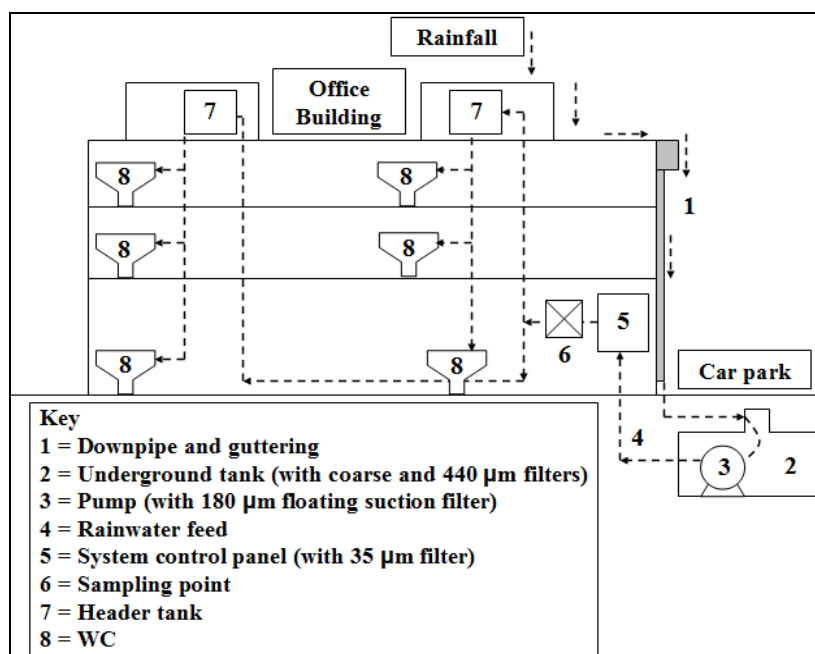

Figure 1. Schematic of the RWH system, including sampling point location (6).

RESULTS AND DISCUSSION
Results for each parameter examined in the study are summarised in Table 1 and Table 2.

Physicochemical
Organic chemistry. Oil and grease and PAHs showed concentrations below the laboratory detection limits (Table 1 and Table 2). This would indicate that airborne particulate deposition from possible nearby sources (car parks, railway) is negligible. This also indicates that the bitumastic-felt-membrane roof covering is, at present, not being significantly leached during runoff processes. Such levels represent a low risk to both health and RWH system operation. However, as the building is less than two years old, the contribution made by the roof covering may change over time.

General chemical analysis. Conductivity ranged from 43 to 261 µS/cm and turbidity levels throughout the study never exceeded 3 NTU, well within the recommended level of 10 NTU. This corroborated visual inspections, which observed that the harvested rainwater was '*visually clear and free from floating debris*' and therefore compliant with UK RWH standards (BSI, 2009). Total dissolved solids (TDS) ranged from 30 to 183 mg/l, which is well below the recommended acceptable *aesthetic* criteria for *drinking* water (600 mg/l; WHO, 2006). Biochemical oxygen demand (BOD) remained below 3 mg/l throughout the study and chemical oxygen demand (COD) below 12 mg/l. These results indicate that the health hazard from physicochemical parameters is low. However, pH values for approximately 41% of samples exceeded the recommended pH band of between 5 and 9, which could have potential implications for system operation (BSI, 2009).

Table 1. Quality of rainwater samples collected weekly.

Category	Subcategory	Parameter	Range measured	Guideline
Microbiology	Bacteriology	Total coliforms (no/100ml)	0-2600	1000[a]
		Faecal coliforms (no/100ml)	0-1500	2000[b]
		Enterococcus faecalis (no/100ml)	0-1460	100[a]
		TVC 22°@ 3 days (no/ml)	300-2020000	NI
		TVC 37°@ 2 days (no/ml)	5-28000	NI
Inorganic Chemistry	General Chemical Analysis	pH	7.6-10.4	5-9[a]
		Conductivity at 20°C (μS/cm)	43.5-261	NI
		Total Dissolved Solids (mg/l)	30.4-183	600[c]
	Nutrients & other Anions	Turbidity (NTU)	0.3-2.8	10[a]
		Nitrogen as NO_3 (mg/l)	1.36-17.76	NI
		Ammonium as NH_4 (mg/l)	<0.01-0.59	NI
		Nitrate as NO_3 (mg/l)	1.32-17.74	50[c]
		Nitrite as NO_2 (mg/l)	<0.01-0.22	3[c]
		Chloride as Cl (mg/l)	3-28	2[a]
		Silicate as SiO_2 (mg/l)	0.35-4	NI

TVC – Total Viable Count

Table 2. Quality of samples collected every three months.

Category	Subcategory	Parameter	Range measured	Guideline
Microbiology	Bacteriology	*Salmonella* spp (no/100ml)	0	0[b]
	Protozoa	*Cryptosporidium* oocyst (no/l)	0	1/1600 [c]
Inorganic Chemistry	Nutrients & other Anions Metals	Phosphorus as P (μg/l)	15-50	NI
		Sulphate as SO_4 (mg/l)	<2.5-5.3	NI
		Calcium as Ca (mg/l)	5.7-10	NI
		Magnesium as Mg (mg/l)	0.36-0.58	NI
		Potassium as K (mg/l)	1-2.4	NI
		Sodium as Na (mg/l)	2.8-4.3	NI
		Aluminum as Al (μg/l)	80.2-108	NI
		Iron as Fe (μg/l)	9-27.4	NI
		Manganese as Mn (μg/l)	<2-3.18	400[c]
		Copper as Cu (μg/l)	218-290	2000[c]
		Zinc as Zn (μg/l)	193-480	NI
		Lead as Pb (μg/l)	25.5-64.4	10[c]
		Cadmium as Cd (μg/l)	<0.4	3[c]
		Chromium as Cr (μg/l)	<0.5	50[c]
		Nickel as Ni (μg/l)	<1.5-1.68	70[c]
Organic Chemistry	General Chemical Analysis	BOD 5 day (mg/l)	<3	NI
		COD (mg/l)	10-12	NI
	Miscellaneous	Oil and Grease (mg/l)	<1	<0.3[a]
	Polycyclic Aromatic Hydrocarbons (PAHs)	Benzo[a]Pyrene (ng/l)	<1	700[c]
		Benzo[b]Fluoranthene (μg/l)	<0.001	NI
		Benzo[ghi]Perylene (μg/l)	<0.002	NI
		Benzo[k]Fluoranthene (μg/l)	<0.001	NI
		Indeno[1 2 3-cd]Pyrene (μg/l)	<0.003	NI
		PAHs (Total) (μg/l)	0	NI

a = BSI (2009); b = EC Bathing Water Directive (1975) (MTP, 2007); c = WHO (2006) for *drinking* water; NI = None Identified

Nutrients and other anions. Nitrogen, nitrate, nitrite and ammonium levels were generally low, although two peaks did occur in early December 2008 and late March 2009. pH, conductivity, TDS and silicate also peaked on these occasions. Phosphorous levels never exceeded 50 µg/l and sulphate 5.3 mg/l. Chloride on the other hand, increased during winter months and was consistently in excess of the recommended level of 2 mg/l (Figure 2). Evans *et al.* (2006) compared weather data and ionic concentrations of sodium and chloride and identified that both dry and wet deposition of chloride from sea salt was a dominant source of chloride in harvested rainwater. Förster (1999) also observed that the application of de-icing salts to roads in winter resulted in airborne salt spray leading to high chloride concentrations from roof runoff. Examination of weather data collected during the present study identified that prevailing winds were from the south (coastal) and north-westerly direction (Figure 3). The winter months (December to February) of 2008/09 saw below average temperatures throughout most of the UK. As a consequence de-icing salt spreading on icy roads was more prevalent during this time, especially on treacherous country roads, such as those found on Dartmoor (to the north-west). It is therefore likely that both coastal and de-icing salt sources contributed to chloride concentrations, with de-icing salt perhaps dominating in winter. A further peak in levels at the end of March 2009 maybe attributed to low rainwater levels and maintenance activities causing re-suspension of sediments on the tank bottom.
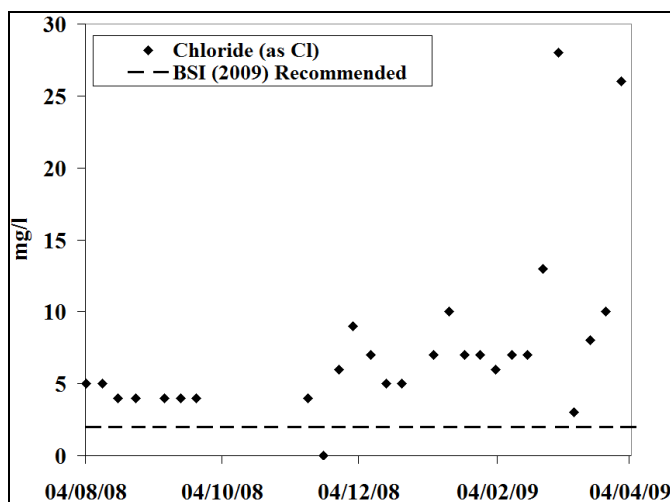

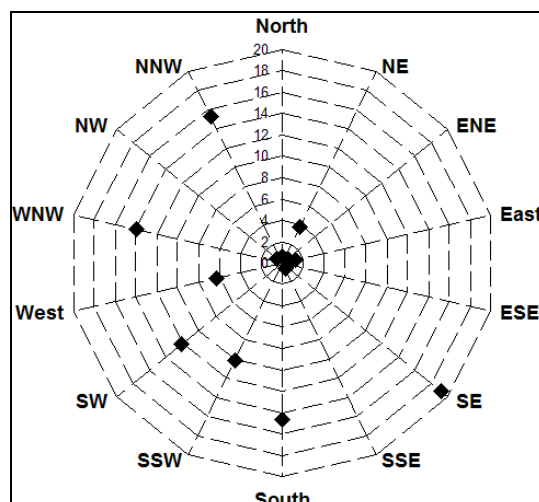**Figure 2.** Chloride concentrations in harvested rainwater from the Innovation Centre.

Figure 3. Prevailing wind directions for the Innovation Centre (% of total number of incidences).

Metals. Metal concentrations are summarised in Table 2. There are currently no guidelines in relation to metal concentrations in harvested rainwater; guideline values (where they exist) for *drinking* water are given in Table 2, merely to place the results in context. Concentrations of cadmium, chromium, magnesium, manganese, nickel, potassium and sodium were observed to be of little significance and iron concentrations were below levels known to promote the staining of plumbing fixtures (300 µg/l; WHO, 2006).

Calcium concentrations were very low (10 mg/l or less) and therefore should not cause scaling problems. Conversely, such low concentrations have implications for system operation – concentrations less than 60 mg/litre can be very corrosive to copper pipework (WHO, 2006). This effect may not be as pronounced for the investigated RWH system, since it is usually associated with pHs below 6.5. However, copper concentrations were

above levels observed to cause staining of sanitary-ware (1mg/l; WHO, 2006). Currently, no such staining has been observed in the IC, but this may require temporal monitoring. Relatively high zinc levels were observed and although a source of zinc could not be confirmed, such levels may result from soft water corrosion of brass fittings. Lead levels were in excess of drinking water guidelines, but due to the high pH of the harvested rainwater, levels were below those expected if plumbosolvency of any lead fittings were occurring (100 µg/l; WHO, 2006). Aluminium concentrations were between 80 and 108 µg/l. These are on the boundary for the deposition of aluminium hydroxide floc (100-200 µg/l; WHO, 2006), posing a potential source of contamination to storage tank sediments. The main source of aluminium is likely to be the aluminium downpipes. These are coated with a protective powder on the exterior but not on the interior; therefore runoff comes into direct contact with and potentially dissolves the uncoated aluminium. Had the likelihood of the presence of soft water been assessed during the building design phase, a different material may have been selected, or the coating also applied to the interior.

Microbiological
No incidences of the protozoa *Cryptosporidium* or the bacteria *Salmonella* were recorded during the study. During the study an independent environmental services company also conducted a spot check for the bacteria *Legionella*; no presence was detected. In terms of indicator organisms, however, results were very different. Faecal coliform (FC) counts never exceeded the recommended guideline and total coliform (TC) counts rarely exceeded the recommended guideline. In contrast counts for *Enterococcus faecalis* (previously known as *Streptococcus faecalis*; faecal strep) regularly exceeded the guideline level of 100/100ml, with counts as high as 1460/100ml and the average being 213.5/100ml. Regression analysis revealed a weak inverse correlation between pH and both TC and FC counts (r = -0.59 and r = -0.62, respectively), but no correlation with *E. faecalis* counts (r = -0.40), (Figure 4).

The WHO (2006) summarise that faecal enterococci tend to survive longer in water environments than FC and are relatively tolerant of sodium chloride and alkaline pH levels. Therefore it is likely that the high chloride and pH levels measured are responsible for low FC counts, but are less detrimental to *E. faecalis*. Evans *et al.* (2006) highlight the contribution of airborne micro-organisms to harvested rainwater quality. As previously identified, one of the dominant wind directions was from the south. Airborne bacteria from a WWTP located to the south could be a potential source. However, further research is required in this area.

Faecal enterococci are entirely related to the intestinal tract of humans and other animals (WHO, 2006). As such, a more probable source of *E. faecalis* was identified as being bird faeces deposited on the roof catchment area. On conducting a building inspection (summarised in Figure 5), it was discovered that runoff passes over two roof surfaces. Initially it lands on a raised, sloped area that is open underneath (A), from where it is diverted via a downpipe to a second, flatter roof area, which has a covering of algae (B). The algal growth is exacerbated by the use of bitumastic-felt, as it is difficult to clean thoroughly. A flock of birds had set up roost in the open area resulting in the runoff flowing through and stagnating by a large area of avian faeces (Ai). It was also observed that the flat area was being used for the storage of items, such as wooden crates and PVC pipes. Additionally, some debris screens were covered with organic matter, including leaves, feathers and relocated faeces (C). Furthermore, downpipe hoppers were not covered (D), allowing debris to collect and birds to perch. Some downpipes feeding into drains connected to the RWH system were also identified as being open to ground-level (path) catchment areas (E). Ground level catchments

were not accounted for in the design of the RWH system and therefore no devices are included to manage pollution from such sources.

All the features identified had the potential to compromise the quality of the harvested rainwater and offer an additional explanation for the high *E. faecalis* counts. Upon identification of the above issues, action was taken to limit impacts to harvested rainwater quality by extending the building maintenance schedule to include periodic cleaning of the roof, debris screens and hoppers. Additionally, options to limit microbial counts were considered, which included installing netting to the open roof area to prevent the entry of birds or the installation of a UV disinfection device. The extra cost of implementing and maintaining such measures could have been avoided if the building's roof design had been considered with respect to the RWH system and harvested rainwater quality.
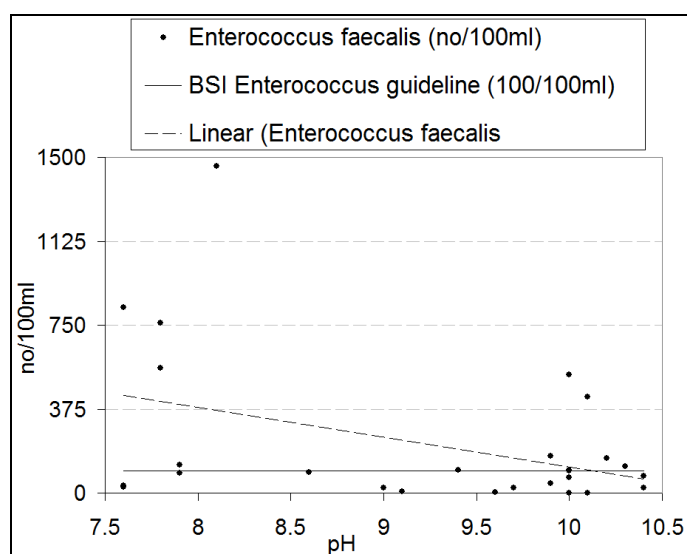

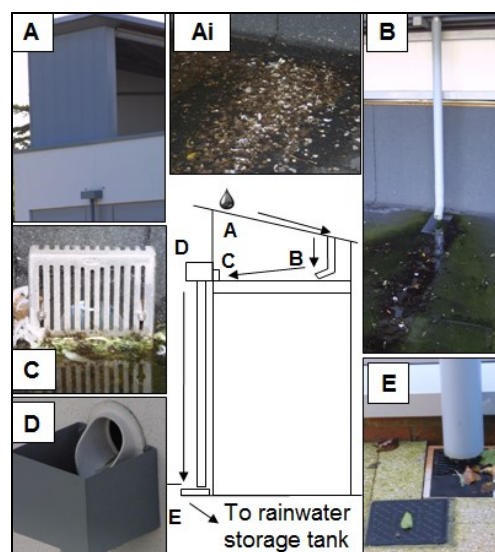**Figure 4.** *E. faecalis* counts in harvested rainwater from the Innovation Centre.

Figure 5. Schematic of the poor roof design of the Innovation Centre (see main text for explanation).

CONCLUSIONS

This study has identified that the variability of harvested rainwater quality was influence by local factors. This included the possible contribution of airborne deposition of chloride and bacteria from local sources. The most significant local factor influencing quality, however, was the design and construction of the building and roof, within which the RWH system is situated. Physicochemically, parameters presented little health hazard. However, internal fittings and external rainwater goods were subject to soft water corrosion, resulting in high concentrations of some metals (copper, zinc and aluminium). This suggests the material selection of such fittings should be considered keeping in view the hardness of rainwater of the area in which a system is to be located. Microbiologically, *Cryptosporidium*, *Salmonella* and *Legionella* were not present in the samples analysed. However, *E. faecalis* counts were consistently above guideline levels, suggesting a potential infectious hazard. Poor building and roof design and material selection were responsible for the reduced microbial quality, as they promoted contributions from avian sources and inhibited cleaning activities. Building design is therefore critical in establishing and maintaining good harvested rainwater quality and preventing both the development of contaminated sediments and health impacts.

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