

## Water quality of rooftop rainwater harvesting systems: a review

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### ABSTRACT

There has been a growing interest, especially in developing countries, in rooftop rainwater harvesting as an alternative source of drinking water. This paper reviews the available information on the water quality of rooftop rainwater harvesting systems. Various factors that affect the physico-chemical and microbiological quality of harvested water are discussed. Different contaminants including heavy metals and trace organic pollutants in the roof runoff reported from different parts of the world are compared. The review shows that the quality of harvested water from roof catchments often does not meet the drinking-water guideline values. Most of the studies reveal that harvested water is heavily contaminated microbiologically by a variety of indicator and pathogenic organisms unless special care is taken during collection and storage of rainwater. Heavy metals and trace organics could also pose problems in some cases. The review thus indicates that the purity of rainwater harvested from rooftops should not be taken for granted, and analysis of the harvested water especially for microbiological contamination should be undertaken. Appropriate treatment of collected rainwater would be necessary to make the harvested rainwater fit for drinking. The review also shows the need for further research on proper design and maintenance strategies to minimise contamination of roof-collected rainwater supplies.

**Key words** | rainwater harvesting, rainwater quality, roof catchments, roof runoff, water quality

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### INTRODUCTION

A large proportion of the world's population does not have access to safe sources of water. WHO/UNICEF has estimated that 1.1 billion people do not have access to "improved drinking-water sources" (WHO/UNICEF 2000). Despite major efforts to deliver safe, piped, community water to the world's population, the reality is that water supplies delivering safe water will not be available to all people in the near future. The Millennium Declaration by the WHO established a goal of halving the proportion of the global population without access to safe water by 2015. It is clear that all possible approaches must be tried to mitigate the problem of drinking water, maximising the control of households with regard to their own water security.

In this context, rainwater harvesting is receiving increased attention worldwide as an alternative source of

drinking water. While rainwater may be harvested in a number of ways, this paper focuses only on the collection and storage of rainwater from individual household roof catchments. Traditionally this was the major option to people in water-scarce regions in rural areas of developing countries where people had to manage to fulfil drinking water and household water needs by rainwater harvesting. Due to ubiquitous contamination of surface and ground-water resources by microbial and chemical contaminants, rainwater harvesting has become more relevant now even in areas which enjoy high rainfall.

Governmental agencies across the world are now introducing policies to promote increased use of rainwater. In India, for example, several state governments have introduced legislation that make it obligatory to incorporate

rooftop rainwater harvesting systems in newly constructed buildings in urban areas. Governments are also providing subsidies to promote the use of rainwater harvesting systems. Even in developed countries such as Germany, Denmark, Australia and New Zealand, rainwater utilisation by means of pipe-bound systems in private households, public buildings and industry is being introduced with a view to saving the valuable drinking water, and not to use it for flushing the toilets, but to substitute it with collected roof runoff (Hermann & Schmida 1999; Mikkelsen *et al.* 1999).

While rooftop rainwater harvesting is being promoted, little attention has been paid to the quality of collected rainwater until recently. In developing countries, where harvested water is used as a source of drinking water, the quality of harvested rainwater is of great importance. Recently, attempts have been made by several researchers across the world to estimate the quality of roof runoff. Most of these studies, however, are reported from the urban areas of developed countries with a view to determining the role of roof runoff in urban stormwater pollution, and not from the view of the utilisation of harvested roof runoff. This paper addresses the quality of water harvested from roof catchments. Various factors that affect the physico-chemical and microbiological water quality parameters including heavy metals and trace organic contaminants in roof runoff have been discussed. The review also focuses on the changes that may take place upon storage in the harvesting systems after the rainwater has been collected.

## FACTORS AFFECTING ROOF RUNOFF QUALITY

Quality of any water is determined by the quality of source water, its exposure to contaminants during collection, treatment and storage and when it reaches the consumer (Heijnen 2001). In a rooftop rainwater harvesting system which consists of a collection system (roof), a conveyance system (gutters or pipes) and a storage system (tank or cistern), contamination of water can occur at any of these stages. Rainwater is generally considered as nonpolluted, or at least not significantly polluted, but may be acidic, contain traces of lead, pesticides, etc., depending on the locality and prevailing winds. Contamination occurs when

it falls on the roof, collects dirt, dissolves some heavy metals in the case of metal surfaces, and then flows into storage. Changes may occur during storage also depending on the material used.

There are several factors which influence the quality of roof runoff. These can be summarised as (Förster 1996)

- roof material—chemical characteristics, roughness, surface coating, age, weatherability, etc;
- physical boundary condition of the roof—size, inclination and exposure;
- precipitation event—intensity, wind, pollutant concentration in the rain;
- other meteorological factors—season, weather characteristics, antecedent dry time;
- chemical properties of the substance—vapour pressure, solubility in water, Henry's constant, etc;
- concentration of the substance in atmospheric boundary layer—emission, transport, half-life, phase distribution, etc;
- location of the roof—its proximity to pollution sources.

Most of these factors are discussed in this paper.

It is well known that most substances show a distinct “first-flush phenomenon” – the concentrations are extremely high in the first minutes of a rain event, and decrease later towards a constant value (Martinson & Thomas 2005). Generally these dynamic effects are observed during the first 2 mm of runoff height. The first-flush effect is caused by one or a combination of the following three processes (Zinder *et al.* 1998):

- (i) Matter deposited on the roof during the preceding dry period is washed off by the falling rain.
- (ii) Weathering and corrosion products of roof cover are washed off.
- (iii) Concentrations in the falling rain itself are decreasing with increasing rainfall depth due to scavenging of particles, aerosols and gases by rain droplets.

It is clear that by diverting the first flush the quality of collected rainwater can be improved significantly. However, in many situations, not much care is taken to do this due to a variety of reasons. A properly maintained first-flush device alone would improve the quality of collected rainwater to a great extent.

## MICROBIAL QUALITY OF RAINWATER HARVESTING SYSTEMS

Microbial quality of roof-collected rainwater has been the subject of many investigations. Table 1 lists some of the recent studies on rainwater harvesting systems reported from different parts of the world. Water samples for these analyses were collected either directly from roof or from storage systems. Direct comparison between these studies is difficult because of variation in design, sampling and analytical procedures. However, these studies along with numerous other studies reported in the literature (Yaziz *et al.* 1989; Pinfold *et al.* 1993; Thomas & Greene 1993; Ariyananda & Mawatha 1999; Pushpangadan & Sivanandan 2001; Pushpangadan *et al.* 2001; Handia 2005) clearly show that rainwater harvesting systems do not often meet the microbiological drinking-water quality standards. Various sources have been attributed to the frequent presence of faecal contamination but, mostly, pollution is of animal origin as the faecal coliform/faecal streptococci ratio is less than unity (Appan 1997).

Microbiological quality of collected rainwater depends on several factors. These include the quality of roof materials and contamination of roofs. The bacteriological quality of rainwater from metallic roofs is generally better than that from other types of roof (Yaziz *et al.* 1989; Vasudevan *et al.* 2001; Ghanayem 2001). The dry heat typical of a metal roof under bright sunlight especially in tropical countries will effectively kill many of the organisms. The characteristics of a rainfall event also influence the microbial quality. Yaziz *et al.* (1989) reported that contamination of rainwater increased with longer dry periods between rainfall events as a result of increased levels of deposition on roofs. They also found that rainfall intensity affected the quality of runoff.

There have been studies on the influence of storage time on the microbiological quality of rainwater. While some studies showed bacterial population declines with storage, some other investigators found that the numbers of bacteria increased with storage. A study by Lye (1989) revealed that certain bacterial strains of *Pseudomonas* and *Aeromonas* were able to grow from low initial levels (1 CFU/mL) to higher concentrations (100 CFU/mL) during storage of collected rainwater. Additional studies by Lye (1991)

showed that long term storage of rainwater did not cause a decrease in levels of certain bacterial strains. However, Vasudevan *et al.* (2001) reported that faecal coliforms, total coliforms and faecal streptococci decline rapidly in rainwater storage tanks. These reported differences are presumably linked to the availability of nutrients and suitability of environmental conditions for growth in rainwater storage tanks. Plazinska (2001), based on a survey of over 100 rainwater tanks used by indigenous communities in rural Australia, reported that most prominent factor influencing the microbiological quality was the tank capacity, with smaller tanks showing higher levels of bacterial contamination. None of the tanks had any mechanical devices for protecting the water quality, and thus for the same catchment area, tanks of lower capacity received a relatively greater share of contaminating microorganisms. Further, in smaller tanks, there was a higher probability that sludge accumulated at the bottom of the tank might become agitated and mixed with standing water. This study thus indicated that installation of some first-flush devices alone would result in considerable improvement in microbiological water quality.

Traditional indicators such as total coliforms and faecal coliforms are generally used for assessing the microbial quality of rainwater. In addition to these organisms, some studies determined the presence of specific pathogenic and opportunistic organisms in harvested rainwater. Table 1 shows that bacterial pathogens such as *Salmonella* spp., *Vibrio* spp., *Aeromonas* spp. and *Legionella* spp. and protozoan pathogens such as *Giardia* spp. and *Cryptosporidium* are frequently detected in roof-collected rainwater. Concern has been expressed on the suitability of traditional indicators for assessing the possible health risks associated with the consumption of collected rainwater which may be contaminated with a variety of opportunistic and pathogenic microorganisms (Lye 2002). A recent study reported from rural areas of New Zealand showed a positive association between the presence of *Aeromonas* and the various indicator organisms in roof-collected rainwater (Simmons *et al.* 2001). Households reporting at least one member with gastrointestinal symptoms in the month prior to sampling were more likely to have *Aeromonas* spp. identified in their water supply than those household without symptoms. Further research is required on the suitability of the *Aeromonas* group as an indicator of

**Table 1** | Microbiological quality of roof-collected rainwater

Sl. No	Location/country	Samples collected from	No. of samples analysed	Parameters tested	Salient findings	Reference
1.	Rural areas of Auckland, New Zealand	Water faucet	125	HPC, TC, FC, ENT, <i>Salmonella</i> , <i>Aeromonas</i> , <i>Cryptosporidium</i> , etc.	56% samples exceeded microbiological criteria for drinking water. <i>Aeromonas</i> found in 16% samples, <i>Salmonella</i> in one sample, <i>Cryptosporidium</i> in two samples	Simmons <i>et al.</i> (2001)
2.	Port Harcourt, Nigeria	Roof catchments	–	HPC, <i>Pseudomonas</i> , <i>Salmonella</i> , <i>Shigella</i> , <i>Vibrio</i>	High HPC. <i>Pseudomonas</i> present in all except Zn roof. High number of pathogenic bacteria like <i>Salmonella</i> present	Uba & Aghogho (2000)
3.	Rural areas of South Australia	Rain water tanks	100	HPC, TTC, FS, TC, <i>E. coli</i>	59% samples contaminated with TTC. 84% contaminated with FS. High HPC	Plazinska (2001)
4.	Palestine	Roof catchments and water tanks	–	TC, FC	All samples contaminated with TC and FC. Less bacterial contamination from metal roofs	Ghanayem (2001)
5.	Thailand	Roof catchments and point of consumption	709	FC, FS	76% samples exceeded the WHO standards	Appan (1997)
6.	New Delhi, India	Roof runoff	54	FC, TC, HPC, FS	All indicator bacteria were present. Rough surfaces carried more contaminants. 13% met WHO standards for all the indicator bacteria and 25–30% met the relaxed standards	Vasudevan <i>et al.</i> (2001)
7.	US Virgin Island	Rainwater systems	13	<i>Giardia</i> , <i>Cryptosporidium</i>	45% samples positive for <i>Giardia</i> . 23% positive for <i>Cryptosporidium</i>	Crabtree <i>et al.</i> (1996)
8.	Kerala, India	Rainwater tanks	30	FC	93% samples contaminated with FC. FC > 500 MPN/100 ml in 13%	Pushpangadan & Sivanandan (2001)

HPC - heterotrophic plate count, TC - total coliforms, FC - faecal coliforms, TTC - thermotolerant coliforms, FS - faecal streptococci, ENT - enterococci

microbial quality and health risk with respect to roof-collected rainwater supplies. Studies are also needed to monitor the level of viruses in rainwater.

While microbial quality of rainwater is often suspect, it should be emphasised that collected rainwater still represents the best option in many situations in terms of microbiological quality. A study conducted in Thailand (Pinfold *et al.* 1993) showed that traditional rainjar water was superior in terms of microbiological quality. Other surveys by Ariyananda & Mawatha (1999), Pushpangadan *et al.* (2001) and Handia (2005) in Sri Lanka, India and Zambia, respectively, also revealed that microbial quality of stored rainwater is often better than that of other sources of drinking water such as shallow groundwater. Suitable interventions can still improve the quality of harvested rainwater in many situations.

## PHYSICO-CHEMICAL QUALITY

Many studies have been reported in the literature on the physico-chemical characteristics of roof-collected rainwater, and these studies from different parts of the world reveal that, in general, physico-chemical quality meets the drinking-water quality guidelines with the notable exception being pH (Ghanayem 2001; Simmons *et al.* 2001; Pushpangadan *et al.* 2001; Chang *et al.* 2004). Wide variations, however, are seen in the concentrations of major ions like calcium, magnesium, sodium, potassium, chlorides, sulfates and nitrates. Variation reflects differences in roofing material and its treatment, orientation and slope of roof, air quality of region, characteristics of precipitation, etc. (Förster 1996; Wu *et al.* 2001; Chang *et al.* 2004).

pH of rainwater usually ranges from 4.5–6.5 but increases slightly after falling on the roof and during storage in tanks. Water sampled from ferrocement tanks, which is the most commonly used material for storing collected rainwater in developing countries, was significantly more likely to be alkaline (Simmons *et al.* 2001; Pushpangadan & Sivanandan 2001; Handia 2005). pH value declines with age of tank and period of storage. Chemical analyses by Förster (1996) revealed pH differences between various roofing materials (concrete, fibrous cement, pantile, zinc and tarfelt). A shift towards alkaline values for fibrous cement

was attributed to dissolution of roof material and not to the deposited aerosols. The above finding was contradicted by studies by Gromaire *et al.* (2001) and Moilleron *et al.* (2002). They found dissolution of roof covering material negligible. Studies by Vasudevan *et al.* (2001) reported no significant differences in chemical quality with roof material and design of roof, gutter and storage types. Uba & Aghogho (2000) and Polkowska *et al.* (2002) found pH of roof runoff within acceptable limits. Runoff from a wood shingle roof had a pH lower than that of rainwater (Chang *et al.* 2004). Roughness and cracks of wood shingle trap water which allow wood rotting organisms to penetrate deeper into wood, plants to grow and organic matter to decay, and as a consequence additional H<sup>+</sup> ions are released due to weathering and decomposition of organic matter. This makes the care and maintenance of wood shingle very important with respect to quality of roof runoff.

Zobrist *et al.* (2000) detected cations like sodium, potassium and calcium, and anions like chlorides, sulfates and nitrates in all samples, and among the cations sodium and calcium had the highest concentration. The greatest increase of macroion concentration during passage over roof surface was found for potassium and sodium (Förster 1998). The differences within roofs clearly indicated that the ions originated from roof material; fibrous cement having greater calcium, and concrete tiles having greater potassium and calcium were susceptible to weathering, whereas dry deposition was of minor importance. But roof contribution of acidic ions like sulfates and nitrates was different, and they were transported by deposition. Study by Zobrist *et al.* (2000) found that a tile roof acted as a slight source of suspended particles and alkalinity, and weathering of a gravel roof produced calcium and alkalinity. The high particle load found in a zinc roof was attributed to its strong weathering in combination with smooth surface that has low resistance to particle wash off (Förster 1996). Analysis of roof runoff from four different materials (zinc, slate, interlocking tiles and flat tiles) by Gromaire *et al.* (2001) showed COD and BOD<sub>5</sub> concentration quite similar for all the roofs.

Another study was conducted by Förster (1998) to study the influence of location as well as to uncover seasonal behaviour of pollutants in runoff. Differences in concentrations of ions like NH<sub>4</sub><sup>+</sup> and Cl<sup>-</sup> deposited via atmosphere could be observed with change of season, and roofs

receiving local emission showed elevated suspended particle. Influence of antecedent dry time, precipitation intensity and roughness of material in the concentration profile of suspended solids and inorganic ions was also studied by Förster (1999). Typical run-off profile started with a high pollutant load and showed a decreasing trend while a modification was found when rain intensities were low and surfaces rough. Suspended solid concentration for tarfelt showed an increase within the course of an event. Gromaire *et al.* (1998) also found a good linear relationship between suspended solid concentration from roof runoff and the following rain event characteristics, viz. dry weather duration, intensity and duration of rain.

## HEAVY METALS

Heavy metals are of particular interest in rainwater harvesting due to their toxicity, ubiquitousness and the fact that metals cannot be chemically transformed or removed easily by simple treatment processes (Davis *et al.* 2001). While rooftops are efficient collectors of particle fallout from the atmosphere, roofs themselves can act as a source of heavy metals through leaching and disintegration of roofing materials. A number of investigators have found varying levels of heavy metals in roof runoff, and Table 2 summarises the concentration of heavy metals in roof runoff reported in some recent studies.

Metal roofs have been repeatedly shown to be a source of zinc (Yaziz *et al.* 1989; Förster 1996, 1999; Ghanayem 2001; Wallinder *et al.* 2000; Zobrist *et al.* 2000; Simmons *et al.* 2001; Davis *et al.* 2001; Gromaire *et al.* 2001, 2002; Sorme & Lagerkvist 2002; Metre & Mahler 2003; Chang *et al.* 2004). Zinc and copper concentrations in roof runoff as measured by Förster (1996) were so high that they constituted an environmental hazard. Chang *et al.* (2004) found that violation of water quality standards was most severe for zinc and copper. Presence of lead and cadmium is also reported in most of the studies. Lead was observed in runoff from polyester roof (Zobrist *et al.* 2000), slate roof (Gromaire *et al.* 2001), galvanized iron roof (Simmons *et al.* 2001) and asphalt shingle roof (Metre & Mahler 2003), and cadmium was found in zinc roof (Förster 1996; Gromaire *et al.* 2002)

and tarfelt roof (Förster 1999). Iron, manganese and aluminium are some other metals reported in roof runoff.

Attempts have been made to determine the relative contribution of atmospheric deposition and roofing materials to heavy metal contamination from rooftops. Differences in copper concentration between roof runoff and rainwater, and between runoff from any of the four roof types studied were found statistically insignificant though copper concentration often violated freshwater quality standards (Chang *et al.* 2004). This means that the roofing materials did not contribute appreciable quantities of copper. However, this was not true for all metals as zinc concentration of rainwater increased as it contacted the four types of roofs. Förster (1996) found that metals surfaces in contact with water running off will dominate the runoff pollution pattern. This was supported by Förster (1999), Uba & Aghogho (2000) and Gromaire *et al.* (2002). This was especially striking for zinc, cadmium and lead. High zinc and cadmium concentrations were measured for a zinc-covered roof (Förster 1996; Gromaire *et al.* 2002; Metre & Mahler 2003) due to erosion of zinc roof, and to a lesser extent by zinc gutters. Cadmium is a minor constituent of zinc roofs. Ghanayem (2001) found high zinc contamination from galvanized iron roof indicating leaching action but its concentration was below the WHO guideline value for drinking water. All metal levels from commercial and institutional buildings were significantly larger than those from residences (Davis *et al.* 2001). This clearly depicts the influence of atmospheric pollutant level at a specific site.

Most metal surfaces exposed to the environment will be subjected to atmospheric corrosion during which a corrosion product (patina) layer is formed. The release of copper induced by atmospheric corrosion from naturally patinated copper of varying age (0 and 30 years) was investigated by Karlen *et al.* (2002). Their studies indicated that copper in runoff increased with patina age and the released copper was present as hydrated cupric ion, the most bioavailable copper species. The total copper concentration ranged between 0.9 and 9.7 mg/l. Chang *et al.* (2004) found zinc concentration from new roofs significantly higher than that from old roofs.

Some studies have been reported on the partitioning of metals present in roof runoff which has a bearing on its toxicity. The particulate/dissolved partitioning of metals was found to depend on the type of roofing and runoff depth

**Table 2** | Heavy metals in roof-collected rainwater

Sl. no.	Location/country	Samples collected from	No. of samples analysed	Heavy metals tested	Concentrations	Salient findings	Reference
1.	Tuffeon wies, Zurich	Roof catchment	14 rain events	Cu, Zn, Pb, Cd, Cr, Mn, Fe	Concentration in $\mu\text{g/l}$ in the first 0.2 mm run off depth: Cr 0.6–1.7, Fe 90–415, Pb 2.7–41, Zn 9–115, Cu 18–842, Cd 0.1–0.4	Fe and Pb exceeded quality standard in drinking water. Cu, Pb, Cd in moderately reactive forms. Gravel roof retained heavy metals	Zobrist <i>et al.</i> (2000)
2.	Marais, Paris	Roof catchment	31 rain events	Cd, Cu, Pb, Zn	Median values: Pb 392 $\mu\text{g/l}$ , Zn 29 998 $\mu\text{g/l}$	High Zn and Cd concentration observed for Zn roof, and Pb for slate roof	Gromaire <i>et al.</i> (2001)
3.	Auckland, Newzealand	Water faucet	125 Samples	Zn, Cu, Pb, As	Median values: Pb < 0.01 mg/l Cu 0.06 mg/l Zn 0.4 mg/l As < 0.005 mg/l	14.4% samples exceeded maximum acceptable values of Pb. For Cu, Zn and As 2.4%, 0.8% and 7.1% exceeded maximum acceptable limit	Simmons <i>et al.</i> (2001)
4.	Zurich Switzerland	Roof catchment	–	Cu, Zn, Cd, Pb	Average conc. from tile and polyester roofs: Pb 16 $\mu\text{g/l}$ , Cd 0.17 $\mu\text{g/l}$ , Cu 225 $\mu\text{g/l}$ , Zn 42 $\mu\text{g/l}$	Storm water from roof accounted for 60% Cu in combined sewer	Boller (1997)
5.	Texas, USA	Roof catchment	31 storms	Cu, Mn, Pb, Zn, Mg, Al	Median values in mg/l: Al 0.169–0.224, Mg 0.292–0.646, Mn 0.01–0.022, Cu 0.018–0.22, Pb 0.025, Zn 0.859–9.717	Cu and Zn exceeded US freshwater standards. Zn increased as rainwater contacted all four types of roofs	Chang <i>et al.</i> (2004)
6.	Austin Texas, USA	Roof catchments	12	As, Cd, Cr, Cu, Hg, Ni, Pb, Zn	Metal concentration from different roofs: Metal Asphalt roof GI roof ( $\mu\text{g/m}^2$ ) As 0.97–8.0 1.3–5.7 Cd 0.32–3.4 1.1–5.7 Cr 6.9–69.0 8.1–44 Cu 7–91 11–75 Hg 0.012–0.24 0.04–0.062 Ni 3.9–30 5.1–27 Pb 28–310 21–93 Zn 120–1,200 680–3,500	Metal roof tops were a source of particle-bound Zn, and Cd. As, Cr, and Cu found to be from atmospheric sources. Pb found high for asphalt roof	Metre & Mahler (2003)
7.	Maryland, USA	Roof catchment	38	Cu, Zn, Cd, Pb	Zinc concentration > 100 $\mu\text{g/l}$ in all samples. Mean Zn concentration from residential, commercial and institutional buildings 100, 1,100 and 1,100 $\mu\text{g/l}$ respectively and Cu 7.5, 200 and 5,000 $\mu\text{g/l}$	Metal levels in institutional and commercial buildings were higher than that in residences	Davis <i>et al.</i> (2001)

(Zobrist *et al.* 2000). For a polyester roof, the above ratio did not change with runoff depth whereas it decreased for a tile roof. In a gravel roof all heavy metals existed in dissolved form. Acid rain is generally associated with high metal levels in rainwater, and a low pH was associated with greater lead level (Simmons *et al.* 2001). Zobrist *et al.* (2000) found the labile species of zinc, copper, lead and cadmium increased when the pH of rainwater was reduced from 7.0 to 5.0. Metals were mostly found in dissolved form in Paris due to lower pH (Garnaud *et al.* 1999). Chang *et al.* (2004) found that cadmium and zinc remained in dissolved form whereas copper and lead were in particulate form.

The effect of exposure direction and inclination on runoff quality of copper and zinc roofs was studied by Wallinder *et al.* (2000). Higher runoff rates of copper and zinc occurred for lower inclination. The effect of orientation on the concentration of manganese was observed by Chang *et al.* (2004). It was found that orientation influenced runoff from a wood shingle roof only and there was no influence on other types of roofs.

In summary, it should be emphasized that water quality has to be monitored for heavy metals such as zinc, copper and lead particularly from metal roofs if the harvested water is to be used for direct drinking purpose as practised in many developing countries. However, not many studies have been reported from developing regions of the world on heavy metal contamination in roof runoff. It is expected that the quality of roof-collected rainwater will be different in these regions due to differences in climatic conditions and the materials used for roofing.

## TRACE ORGANICS

Trace organic compounds such as pesticides are one of the most common groups of pollutants found in roof runoff. Table 3 presents concentrations of some trace organics in roof-collected rainwater reported from different parts of the world. Several studies indicate that the precipitation often contains levels of pesticides high enough to make it unsuitable as a source of drinking water according to current standards (Bucheli *et al.* 1998a, b).

Both roof characteristics and chemical properties of organic pollutants seem to affect the level of trace organics

in roof runoff (Moilleron *et al.* 2002). Polkowska *et al.* (2002) found petroleum hydrocarbons like toluene higher for runoff from a roof covered with tar paper. Organic carbon was high for a polyester roof, and most of the organic pollutants appeared in high concentration in the first minutes or first tenth millimeter of runoff depth (Zobrist *et al.* 2000). They also found that a polyester roof acted as a conveyor of pesticides but gravel and tile roofs retained pesticides. There were only a few cases where a roof acts as a sink but its function as the source of pollution was dominating. High concentrations of pesticides of organo-chlorine (aldrin and lindane), organo-nitrogen and organo-phosphorus groups (propazine, malathion, fenitrothion, etc.) were detected from sheet metal by Polkowska *et al.* (2002). Förster (1996) also observed concentration of organic micropollutants like nitrophenol and  $\gamma$ -HCH for different types of roofs.  $\gamma$ -HCH, an insecticide, showed no significant differences in runoff except for fibrous cement where the porous material was able to adsorb  $\gamma$ -HCH from the gas phase during dry periods (Förster 1998).

Polycyclic aromatic hydrocarbons (PAHs), largely the product of incomplete combustion of petroleum, oil, coal, etc., represent the largest class of suspected carcinogens prevalent in urban atmospheric deposition. PAH concentration was found high for clay tiles in an urban locality in Paris (Moilleron *et al.* 2002). The higher concentration of these compounds in roof runoff compared to that in precipitation indicated that these were released from roofing materials (Förster 1996; Polkowska *et al.* 2002). Förster (1999) studied the variability of runoff characteristics of PAHs represented by fluoranthene and pyrene. PAHs were found at the highest levels in runoff from roofs neighbouring local emitters like chimneys or traffic. His studies found no evidence that asphalt shingle roofs were a source of PAHs. The concentration of PAHs was found to be different on opposite sides of the same roof as one side received distinctly higher net precipitation than the other due to changes in wind speed, direction and photodecomposition (Förster 1999).

A similar trend, that physical and chemical features of roof surfaces influence the concentration of organic trace pollutants, was observed for total aliphatic hydrocarbons by Moilleron *et al.* (2002). Aliphatic hydrocarbons were found high for zinc roofs, and PAHs for flat clay tiles, while the concentration of these were quite similar for other types of roofs. Since atmospheric deposition was assumed to be the

**Table 3** | Trace organics in roof-collected rainwater

Sl. No	Location/ country	Samples collected from	No. of samples analysed	Parameters tested	Concentration	Salient findings	Reference
1.	Gdansk, Poland	Roof catchment	45	Petroleum hydrocarbons, pesticides	Organonitrogen and organo-phosphorus values ranged from 15.26 ng/l for sheet metal to nil for asbestos. For organo-chlorine, 4.58 ng/l for sheet metal to nil for tar paper	More than half of the samples were found toxic with inhibition exceeding 20%. Toxicity weakly related to levels of organo- nitrogen and organo-phosphorus pesticides	Polkowska <i>et al.</i> (2002)
2.	Zurich, Switzerland	Roof runoff	14 rain events	Pesticides	For tile roof pesticide concentration > 100 µg/l for a few events	Polyester roof acted as a conveyer of pesticide whereas gravel and tile retained them. High organic content for polyester roof	Zobrist <i>et al.</i> (2000)
3.	Le Marais, Paris, France	Roof catchments	33 rain events	Aliphatic hydrocarbons	Mean value of total aliphatic hydrocarbons: 345 ng/l for interlocking clay, 847 ng/l for Zn sheets. Highest PAH concentration of 50 ng/l observed for flat clay tile with Zn sheet	Emission from vehicle along with atmospheric fallout responsible for aliphatic hydrocarbon. Both roof characteristics and chemical properties of organic pollutants should be taken into account in order to evaluate the level of pollution in roof runoff	Moilleron (2002)
4.	Austin, Texas, USA	Roof catchments	12	PAH	PAH values in µg/m <sup>2</sup> : asphalt 3.9–13, GI 5.2–13	Yield of PAH was higher in roofs located near expressway. No difference was found between roof types	Metre & Mahler (2003)

same, it was likely that total aliphatic hydrocarbon and PAH content of a given roof might be driven by the roof itself. The phase contribution to dissolved and adsorbed components was strongly influenced by adsorption sites (as approximated by suspended solids concentration) rather than individual roof properties. This resulted in high dissolved PAH concentrations in rain and runoff from roofs in an urban background (Förster 1998). AOX (sum parameter for adsorbable organically bound hydrocarbon) values were also found high for roofs receiving local emissions. AOX values were influenced by season. Rain and roofs showed low AOX values in summer except for tarfelt. Tarfelt had low winter values due to its unipolar surface which acted as an adsorber when temperature was low and released AOX when the temperature was high (Förster 1998).

## CONCLUDING REMARKS

Water quality of rooftop rainwater harvesting systems is an issue of increased interest particularly in developing countries where the collected water is used as a source of drinking water. Studies reported from different parts of the world reveal that the water quality is often suspect, especially in terms of its microbiological quality. Among various factors that affect the water quality of roof runoff, roof material, rainfall intensity, dry period preceding a rainfall event and proximity to pollution sources seem to determine the physicochemical quality of the collected rainwater. As for microbiological quality, roof material and any dry period could play a significant role in determining the quality. A few studies, however, show that well-kept rainwater is a good quality source, usually within the WHO “low risk” category (Ariyananda & Mawatha 1999; Coombes *et al.* 2000; Vasudevan *et al.* 2001). Poor collection and maintenance practices will reduce the quality considerably. This indicates the need for proper design and maintenance strategies to minimise the contamination of potable roof-collected rainwater supplies. All studies suggest that some form of treatment of the harvested rainwater is necessary before it can be used as a source of drinking water.

More studies are needed to assess the microbial risk associated with the consumption of water from domestic

rainwater harvesting systems. A few studies reported in the literature indicate that consumption of untreated rainwater is a definite risk to the health of consumers (Crabtree *et al.* 1996; Simmons *et al.* 1999, 2001; Lye 2002). Diseases attributed to the consumption of untreated rainwater include bacterial diarrhea, bacterial pneumonia, botulism, protozoal diarrhea, and diarrheas from *Giardia* and *Cryptosporidium*. Most of the studies reported on this aspect are from developed countries. There is a need to assess the health implications of the use of rooftop rainwater harvesting systems in developing countries, where the use of rainwater as a source of drinking water is becoming more widespread. There is also a need to develop some simple and rapid field-testing methods for use in developing countries to indicate microbial contamination of drinking water. The H<sub>2</sub>S strip test based on the production of H<sub>2</sub>S by sulfate reducing bacteria appears to be promising in this regard (Vasudevan *et al.* 2001). A good correlation was observed between the results of conventional indicators of microbial pollution and the H<sub>2</sub>S strip test. However, more studies are needed to standardise the procedure. Further, more research is needed on how to improve the quality of rainwater collected from roof catchments through improvements in design features and maintenance practices. The HACCP (hazard analysis and critical control point) approach, introduced by the WHO in its latest edition of *Drinking-Water Quality Guidelines* (WHO 2003) is suitable for design, construction, management and operation of rooftop rainwater harvesting systems (Heijnen 2001). HACCP also allows an assessment of risks related to the use of different roof surfaces and fittings would help the public health authorities to develop their own strategies to improve the collected rainwater quality.

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