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Quantitative microbial risk assessment with respect to *Campylobacter* spp. in toilets flushed with harvested rainwater

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Abstract

In light of increasing pressures on water supplies in some areas, water demand management and water conservation techniques are likely to become increasingly prevalent. In-house systems using alternatives to mains supplies for nonpotable uses present one such option for reducing potable water demand. This paper, through a formal desk-based health impact assessment (HIA) and quantitative microbial risk assessment (QMRA), examines *one* of the possible health implications (*Campylobacter* infection from toilet flushing) resulting from the use of rainwater harvesting in the home in the United Kingdom. This is investigated using data from the literature and a hypothetical case study population of over 4000 people (based on data for the 'average' population in England), with the results being expressed as disability-adjusted life years (DALYs) (on an annual basis) and placed in context of the 'tolerable' risk from drinking-water supplies.

Introduction

Health impact assessment (HIA) is a useful nonstatutory tool with which to examine possible impacts on health (both positive and negative) of any proposal before its implementation. It has formally been defined as 'a combination of procedures, methods and tools by which a policy, programme or project may be judged as to its potential effects on the health of a population, and the distribution of those effects within the population' (WHO European Centre for Health Policy 1999). One of the problems associated with conducting HIAs is the short timescale available in order to influence decision making and there has been a call for more off-the-shelf reviews (Joffe & Mindell 2002; Mindell *et al.* 2004). This paper aims to provide an insight into one of the possible health impacts of rainwater harvesting and presents a methodology by which microbial health impacts can be quantified, which can be easily and rapidly updated if more data become available.

Quantitative microbial risk assessment (QMRA) is a formal probabilistic process for estimating the microbial risks associated with defined scenarios and thus is an ideal adjunct to the HIA process. There are four distinct steps to QMRA, namely; hazard characterization, dose–response assessment, exposure assessment and risk characterization (NRC 1983).

The use of rainwater harvesting in the United Kingdom to provide in-house water for toilet flushing and other nonpotable uses is relatively recent. Given the increasing pressures on water supplies, especially in the south-east of England, it is likely that it could be more widely adopted in new developments, and so an assessment of possible health impact is timely.

In the United Kingdom, in-house systems typically consist of an underground storage tank with a filter to prevent the entry of leaves and large solids, a smoothing inlet to stop sediment on the bottom of the tank being disturbed, a pump for distributing the harvested water (either to a header tank or directly to appliances) via a separate and distinct plumbing system from that used for potable supplies and a suction filter to prevent the uptake of any floating material as the water is drawn up for use (Fig. 1). Some systems also have an automatic mains top-up device that may top-up the storage tank, supply a header tank or deliver the actual appliances with mains water if harvested supplies prove insufficient.

This work has been conducted as one of a series of research projects looking at water supply, water reuse, stormwater and wastewater management in new developments as part of the Engineering and Physical Sciences Research Council Water Cycle Management for New Developments (WaND) project (GRS 18373/01).

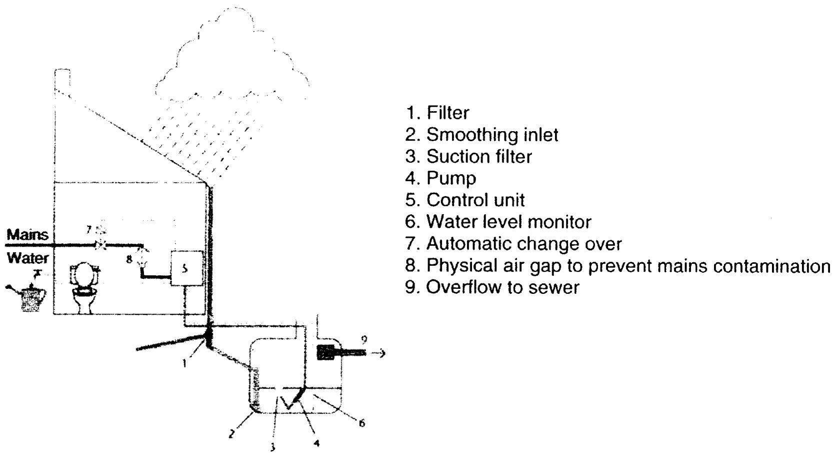

Fig. 1. Schematic of an in-house rainwater harvesting system (adapted from EA 2003).

Methodology

Literature review

A review of rainwater harvesting and the possible health impacts was principally conducted by searching a number of web-based databases (e.g. PubMed) and websites [e.g. Environment Agency (EA), Defra, Watersave] for key words including 'rainwater', 'rainwater harvesting', 'health', 'infection', 'pathogen' and 'micro-organisms'. In addition, reference lists from each document obtained were searched for relevant references. Identified possible health impacts were investigated by additional literature searches. No geographical restrictions were placed on the literature review, although foreign-language databases were not searched and, generally, only English-language papers were obtained for further examination.

QMRA

Where possible, parameters (such as water quality data) have been represented as probability distributions rather than point-estimates in order to examine the effects of uncertainty. Monte Carlo sampling (5000 iterations) was used for the simulation run using @Risk version 4.5 Professional edition (Palisade Corporation 2002).

Case study population

The HIA was conducted on a hypothetical population based on a newly built estate in the south of England comprising 1868 houses, with a total population of 4483. The population was based on an 'average' for England (from the 2001 census), with a household occupation density of 2.4 and the following age structure:

- 0–4: 5.96%;
- 5–15: 14.19%;
- 16–64: 63.97% and
- 65+: 15.89

with almost 70% of the population classifying their health as 'good' (National Statistics 2007).

It was assumed that an in-house rainwater harvesting system was installed in each house during construction. The rainwater harvesting system consisted of an underground tank with a filter preventing leaves and other solids from reaching the tank. Mains top-up, where required, was direct to the storage tank. All houses had a separate plumbing system to allow the harvested supplies to be used for toilet flushing.

Quantification

The identified health impacts were quantified using disability-adjusted life years (DALYs). DALYs are summary measures of health that allow comparison of effects across a wide range of health outcomes, including both mortality and morbidity. The measure combines years of life lost (YLL) as a result of premature mortality, with years lived with a disability (YLD), standardized using severity weights. The weights range from 0 (perfect health) to 1 (dead). The measure was derived to use in the ongoing Global Burden of Disease study, which aims to compare DALYs resulting from various illness and environmental risk factors (such as unsafe sanitation) across global regions (Murray & Lopez 1996; Prüss-Üstün *et al.* 2004). Severity weights and durations of illness or disability have been derived from the literature.

Results

The overall HIA, which is reported fully elsewhere (Fewtrell *et al.* 2008), identified a number of possible hazards associated with rainwater harvesting, including injury and infection. The infection risks examined included:

- ingestion of aerosols produced as a result of toilet flushing;
- direct ingestion of rainwater via the garden tap;
- inadvertent ingestion of rainwater through the contamination of drinking water supplies as a result of cross-contamination and
- ingestion of garden produce contaminated as a result of watering with harvested rainwater.

This paper concentrates on the possible risk of infection from flushing the toilet with microbially contaminated rainwater supplies, as the use of nonpotable water for toilet flushing has previously been raised as a possible area of concern (BSRIA 1997; Lücke 1998).

Hazard characterization

The main source of pathogenic micro-organisms in harvested rainwater in the United Kingdom is likely to be from bird faeces. From an examination of the literature, it is clear that a number of different bird species carry a variety of micro-organisms, pathogenic to humans, which could be deposited on roofs and washed off into harvested rainwater supplies. The two most commonly studied and (where a variety of pathogens have been studied) most frequently isolated pathogens are *Salmonella* spp. and *Campylobacter* spp. (e.g. Girdwood *et al.* 1985; Craven *et al.* 2000; Gautsch *et al.* 2000; Waldenström *et al.* 2002).

Campylobacter spp. has a lower infectious dose from water than *Salmonella* spp. and has been isolated from rainwater supplies and implicated in illness from rainwater supplies used for drinking water (Eberhart-Phillips *et al.* 1997), and so *Campylobacter* spp. has been used to illustrate this QMRA (although contamination with salmonellae was also examined – data not shown). *Campylobacter* is the most commonly reported cause of gastroenteritis in England and Wales (HPA 2005) and the illness, campylobacteriosis, is characterized by severe diarrhoea and abdominal pain. In some cases, secondary adverse health outcomes, such as Guillain–Barré syndrome (inflammation of the nerves, which may result in paralysis), may occur as a result of *Campylobacter* infection (Mead *et al.* 1999).

Dose–response assessment

A dose–response relationship is the quantitative relationship between dose and outcome, which may be summarized as an ID_{50}, which is the number of microbes required to initiate infection in 50% of the exposed population. A dose–response (β-poisson) model for *Campylobacter* spp. has been developed by Medema *et al.* (1996), based on the experimental data reported by Black *et al.* (1988). Infection precedes illness and, based on the literature, it has been assumed that 30% of infections result in illness (WHO 2004). The severity weight (0.086 – based on a weight of 0.067 for the majority of cases and 0.39 in 6% of the cases expected to visit their general practitioner) and duration (6 days) for uncomplicated campylobacteriosis (i.e. no secondary adverse outcomes) have been based on Havelaar *et al.* (2000). The severity weight (0.28) and duration (365 days) for complicated campylobacteriosis have been based on the mean value for severe Guillain–Barré syndrome (Havelaar *et al.* 2000). The incidence of complicated forms was based on the campylobacteriosis hospitalization rate of 0.5% (Mead *et al.* 1999). The case fatality rate for campylobacteriosis is 0.005% (Mead *et al.* 1999), with a median age at death of 78 years (Havelaar *et al.* 2000).

Exposure assessment

A number of studies have recorded the presence of *Campylobacter* spp. in harvested rainwater supplies (Bannister *et al.* 1997; Savill *et al.* 2001; Albrechtsen 2002) and in water samples from toilets flushed with rainwater (Albrechtsen 2002). Few studies, however, have attempted to quantify the levels of *Campylobacter* spp. in harvested rainwater (presence/absence data only). Savill *et al.* (2001) in New Zealand, however, did quantify levels and found a maximum concentration of 0.56/100 mL. *Campylobacter* concentrations have been assumed to range between 0 and 0.56/100 mL, with a homogenous distribution within the water. As thermophilic campylobacters do not multiply at temperatures below 30 °C (Koenraad *et al.* 1997), it has been assumed that these levels apply throughout the rainwater harvesting system.

It is unlikely that *Campylobacter* spp. will be present in rainwater supplies all the time. In Europe, Albrechtsen (2002) reported *Campylobacter* spp. in 20% of the samples examined ($n=10$), while Holländer *et al.* (1996) did not find it in over 140 samples analysed. Thus, for this assessment, it has been assumed that *Campylobacter* spp. will be present between 0 and 10% of the time. No account has been taken of possible seasonal variability; thus, every day is assumed to have the same likelihood of *Campylobacter* contamination.

Flushing a toilet produces an aerosol, which may spread micro-organisms present in the toilet bowl around the surrounding area. It has been demonstrated in seeding experiments that micro-organisms can be ejected, during flushing, to a height of at least 83 cm above the seat (Barker & Jones 2005), a height that could result in pathogens being in a position where they could be ingested. The volume of water ejected during a 'typical' flush is unknown, but is likely to be small and it has been speculated that between 1 and 2 mL is realistic. Only a proportion of this is likely to reach a susceptible host, say a tenth. Thus, a range of values between 0 and 0.25 mL, with a mean of 0.1 mL, were applied in the analysis. It has been assumed that people are exposed to flush aerosol 5% of the time (i.e. one flush in 20).

People typically use the toilet six times a day (MTP 2005). To account for home workers as well as those who work away from home (and thus will not be exposed to their domestic system during this period), a range of between three and six flushes/day has been assumed.

It has been assumed that every household member is equally susceptible, excluding children under the age of 1 (although children under the age of 3 are probably not fully toilet trained – AAP 2000 – it has been assumed that they may flush the toilet). Thus, the analysis has been conducted on a population of 4432.

Risk characterization

This brings together the hazard characterization, dose–response assessment and exposure assessment to produce an estimate of the probability of infection, which is combined with severity weights and duration of illness estimates to produce an annual DALY score for the whole case study population. The distributions and @Risk input values used in the QMRA are shown in Table 1. The probability of infection estimates shown in Table 2 are based on these input values, with the minimum and maximum estimates being based on the range of data input parameters, while the mean estimate is based on the mean values. Over a year, there are an estimated 0.023 cases of campylobacteriosis (based on the mean figures), which results in a mean DALY score of 6.8×10^{-5} for the case study population.

Adding in the estimate for salmonellosis (data not shown) for toilet flushing (assuming a *Salmonella* spp. concentration an order of magnitude greater than that for *Campylobacter* spp. and using the dose–response relationship of Haas *et al.* 1999) results in an overall DALY score of 7.14×10^{-5} for the case study population.

The DALY scores estimated to result from toilet flushing can be placed in context by considering other risks, such as that from drinking water supplies. In the WHO guidelines for drinking water quality (WHO 2004), it has been suggested that the tolerable disease burden from drinking water should be no more than 1×10^{-6} DALYs per person per year. For the case study population, this equates to a DALY score of 4.5×10^{-3}, virtually two orders of magnitude greater than the estimate for toilet flushing.

Discussion

This paper does not attempt to quantify the risk of illness as a result of improper sanitation as this is unlikely to be a factor related to the source of water used for toilet flushing (or not as the case may be). Clearly, when a member of the household has a stomach upset, there will be elevated numbers of pathogens within the toilet bowl before flushing (e.g. Hart & Cunliffe 1999), with a consequent hazard of infection for other household members. This research is interested in the hazard resulting from the introduction of other pathogens into the household system, which would not have been present had potable supplies been used for flushing.

Campylobacter spp. have been isolated from rainwater supplies; they have been implicated in illness from harvested rainwater supplies, and previous reports have speculated about the possible impact of flushing the toilet with nonpotable supplies (Lücke 1998; WRAS 1999), making it a suitable candidate for further exploration.

As part of the QMRA, it was necessary to make a number of assumptions, such as those relating to:

- the concentration and frequency of *Campylobacter* contamination in rainwater supplies;
- the amount of water ejected during flushing;
- the frequency with which people are exposed to flush aerosol and
- the applicability of the dose–response data.

A number of these assumptions could usefully be clarified by further empirical data acquisition, for example the concentration of *Campylobacter* spp. in rainwater supplies and the amount of water ejected during flushing are currently being investigated (Watkins J., pers. comm.). Others, however, such as the dose–response relationship, are less easy to examine (not least because of ethical considerations) and will probably always retain a large degree of uncertainty.

Table 1 @Risk input values

Input	Distribution	Mean	Standard deviation	Range
Volume ingested (mL)	Normal	0.01	0.05	0–0.25
Campylobacter concentration (mL)	Log normal	0.001	0.0025	0–0.0056
Frequency of contamination of harvested supplies (%)	Normal	3	1	0–10
Number of flushes	Discrete			3–6

Table 2 Risk characterization of campylobacteriosis from toilet flushing with rainwater

Estimate	Probability of infection	Probability of illness	Cases of campylobacteriosis	DALYs
Minimum	3.7×10^{-9}	1.1×10^{-9}	4.64×10^{-6}	1.4×10^{-8}
Mean	1.8×10^{-5}	5.4×10^{-6}	0.023	6.8×10^{-5}
Maximum	1.1×10^{-4}	3.4×10^{-5}	0.14	0.0004

DALYs, disability adjusted life years.

It is not possible to have a fraction of a stomach upset, but this method does illustrate the potential for illness and allows a DALY score to be calculated based on the best data currently available, with the results strongly suggesting that flushing the toilet with harvested rainwater supplies does not present a significant health hazard when compared with flushing with potable supplies. Where regional differences are suspected, these could be invested further using the same methodology, to ensure the appropriateness of the water management option.

A discussion on the acceptability of risk is beyond the scope of this paper, but the results obtained have been placed in context by considering the so-called tolerable disease burden from the consumption of drinking-water supplies (WHO 2004). The results were found to be two orders of magnitude less than this tolerable level and, as such, could be considered to be virtually negligible. In addition, a calculation based on the estimated annual cases of campylobacteriosis from all causes in England and Wales (which could be argued to be something the population 'accepts') resulted in a DALY score for the case study population of 0.12.

Conclusions

(1) Although it was necessary to make a number of assumptions in order to derive this estimate, it is felt that unless subsequent research shows that the amount of *Campylobacter* spp. (or other pathogens) to which people are exposed through toilet flushing has been drastically underestimated, any increased risk from flushing the toilet with harvested rainwater should probably be considered to be well within an acceptable range.
(2) The method described in this paper provides a transparent way of examining the problem, where the assumptions and the data used are both clearly outlined. This makes it easy for alternative assumptions to be examined and for the estimate to be rapidly updated if new data become available.

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