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Risk-based enteric pathogen reduction targets for non-potable and direct potable use of roof runoff, stormwater, and greywater

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A B S T R A C T

This paper presents risk-based enteric pathogen log reduction targets for non-potable and potable uses of a variety of alternative source waters (*i.e.*, locally-collected greywater, roof runoff, and stormwater). A probabilistic Quantitative Microbial Risk Assessment (QMRA) was used to derive the pathogen $\log_{10}$ reduction targets (LRTs) that corresponded with an infection risk of either 10^{-4} per person per year (ppy) or 10^{-2} ppy. The QMRA accounted for variation in pathogen concentration and sporadic pathogen occurrence (when data were available) in source waters for reference pathogens in the genera *Rotavirus*, *Mastadenovirus* (human adenoviruses), *Norovirus*, *Campylobacter*, *Salmonella*, *Giardia* and *Cryptosporidium*. Non-potable uses included indoor use (for toilet flushing and clothes washing) with occasional accidental ingestion of treated non-potable water (or cross-connection with potable water), and unrestricted irrigation for outdoor use. Various exposure scenarios captured the uncertainty from key inputs, *i.e.*, the pathogen concentration in source water; the volume of water ingested; and for the indoor use, the frequency of and the fraction of the population exposed to accidental ingestion. Both potable and non-potable uses required pathogen treatment for the selected waters and the LRT was generally greater for potable use than non-potable indoor use and unrestricted irrigation. The difference in treatment requirements among source waters was driven by the microbial quality of the water – both the density and occurrence of reference pathogens. Greywater from collection systems with 1000 people had the highest LRTs; however, those for greywater collected from a smaller population (∼ 5 people), which have less frequent pathogen occurrences, were lower. Stormwater had highly variable microbial quality, which resulted in a range of possible treatment requirements. The microbial quality of roof runoff, and thus the resulting LRTs, remains uncertain due to lack of relevant pathogen data.

1. Introduction

Interest in using alternative waters in community water systems has increased in the United States and worldwide (National Academies of Sciences, 2016). Possible alternative waters include, but are not limited to:

- *Greywater*: wastewater from bathtubs, showers, bathroom sinks, and clothes washing machines, excluding toilet and—in most cases—dishwasher and kitchen sink wastewaters;
- *Roof runoff (rainwater)*: precipitation collected from roof surfaces or other above ground collection surfaces not impacted by human activity; and
- *Stormwater*: precipitation and runoff collected from ground level.

Given the lack of federal recommendations in the United States, communities face a challenge when using alternative waters for non-potable and potable purposes. Many states and communities have adopted standards based on fecal indictor bacteria concentrations in finished water (*e.g.*, the NSF/ANSI Standard 350 for non-potable onsite reuse of greywater (NSF International, 2015)). However, these standards lead to an unknown level of protection of human health for consumers (National Academies of Sciences, 2016).

In previous work, we reviewed the microbial risks associated with non-potable uses of alternative waters as predicted by Quantitative Microbial Risk Assessment (QMRA) (Schoen and Garland, 2015). QMRA is a scientific approach to estimate the potential human health risks resulting from exposures to microbial hazards (*i.e.*, human pathogenic viruses, protozoa, and bacteria) (Haas et al., 1999) and has been applied across multiple water

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regulatory processes (Petterson and Ashbolt, 2016; U.S. EPA, 2014; NRMMC et al., 2006; WHO, 2016). For the waters listed above, the microbial hazards include enteric pathogens resulting from human or animal fecal contamination; opportunistic pathogens (*e.g., Legionella pneumophila*) which may grow within the collection and distribution systems (Chapman et al., 2008; O'Toole et al., 2014; Garner et al., 2016; Ashbolt, 2015); antimicrobial resistant bacteria (including pathogens) (Ashbolt et al., 2013); and possibly endotoxins (Barker et al., 2016). In the previous review of QMRA-derived microbial risks, we concluded that risks associated with non-potable use of untreated or minimally treated alternative waters exceeded previously employed benchmark levels of risk. Yet, risk-based pathogen treatment targets aimed to lower the risk to benchmark levels were widely missing, apart from targets for stormwater for domestic and municipal purposes (Schoen and Garland, 2015; NRMMC et al., 2009).

Pathogen treatment targets, referred to as pathogen $\log_{10}$ reduction targets (LRTs), are the difference between the $\log_{10}$-transformed pathogen concentrations pre-treatment and post-treatment. (This is equivalent to the proportional reduction in the non-log scale.) Pathogen reduction targets that are "risk-based" are calculated to achieve a specific level of health protection for consumers. Please refer to Sinclair et al. (2015) for a discussion of the evolution of risk-based targets for drinking water. The level of health protection is typically expressed as a tolerable burden of disease (*e.g.*, Disability Adjusted Life Years [DALYs], the sum of years of life lost by premature mortality and years lived with disability (Murray and Acharya, 1997)) or as a tolerable/benchmark level of infection or illness risk per person per year [ppy] (*e.g.*, Regli et al., 1999).

The World Health Organization (WHO) and Australian government established risk-based LRTs of enteric pathogens for a limited number of uses for stormwater and municipal wastewater (NRMMC et al., 2006; NRMMC et al., 2009, 2008; WHO, 2006a). For potable water consumption, the WHO used a tolerable burden of disease of 10^{-6} DALYs ppy (WHO, 2011), which was also used for non-potable purposes (NRMMC et al., 2009; WHO, 2006a, 2006b; Health Canada, 2010). This tolerable burden of disease roughly corresponds to an infection risk of 10^{-3} ppy for *Cryptosporidium* spp., 7.2×10^{-4} ppy for *Campylobacter* spp., and roughly 10^{-4} ppy for *Rotavirus* (NRMMC et al., 2009; WHO, 2006a, 2006b). In the United States, an infection risk of 10^{-4} ppy for giardiasis has been used for surface water treatment requirements producing drinking water (Macler and Regli, 1993; U.S. EPA, 2006). As an alternative, the less restrictive illness risk of 10^{-2} ppy, based on the U.S. EPA Recreational Water Quality Criteria (U.S. EPA, 2012), may be applicable for voluntary exposures (Appendix A). Thus, a benchmark risk for non-potable uses in the U.S. likely falls within the range already adopted for potable and recreational exposures.

To support the development of microbial LRTs for the management of alternative waters, we computed risk-based pathogen reduction targets for enteric pathogens suited to both non-potable and potable uses of alternative source waters, assuming a benchmark rate of infection (not illness) of either 10^{-4} or 10^{-2} ppy. We present LRTs in two parts: first, using literature values for the pathogen concentration in each source water (or sources of contamination) accounting for the observed or modeled variation across collection locations and conditions; and second, using a set of alternative pathogen concentration characterizations so that site-specific targets may be estimated.

2. Methods

Schoen and Garland (2015) described the reverse QMRA methods previously used to calculate LRTs. While not adopted by other agencies, due to complications in computation, Schoen and Garland (2015) recommended a stochastic, forward approach, rather than a reverse approach, to allow for the inclusion of factors either missing or difficult to incorporate in the reverse approach. These factors included sporadic and variable pathogen occurrence and concentration, variation in pathogen dose over the course of a year, and occasional accidental ingestion.

2.1. QMRA model

The forward QMRA included the traditional QMRA steps used to calculate the annual probability of infection (Haas et al., 1999), but rearranged to solve for the LRT. To solve for the pathogen $\log_{10}$ reduction target (LRT) for a set of activities, the annual probability of infection ($\mathrm{Pinf}_{\mathrm{annual}}$) was set equal to the benchmark infection risk as follows:

$$\mathrm{Pinf}_{\mathrm{annual}} = \text{Benchmark infection risk}$$
$$= S * \left(1 - \prod_{n_i}\left[1 - DR\left(V_i * 10^{(\log_{10}(C) - LRT)}\right)\right]\right) \tag{1}$$

where

S is the fraction of people in the exposed population susceptible to each reference pathogen.
DR(…) is a dose-response function for the reference pathogen.
V_i is the volume of water ingested per day for the activity set i.
n_i is the number of days of exposure over a year for activity set i.
C is the pathogen concentration in the untreated, freshly collected source water.

The annual probability of infection for an activity set in Eq. (1) was calculated assuming independent, daily risks; each daily risk was computed from a daily accumulated pathogen dose from all relevant activities (*e.g.*, clothes washing and toilet flushing). Eq. (1) was modified to include accidental ingestion of treated non-potable water (or cross-connection with potable water) by summing the annual probabilities of infection for populations with and without accidental ingestion, weighted by the relevant fraction of the population.

Pathogen concentrations were characterized using probability distributions based on literature values (described in Section 2.5) or alternative characterizations (described in Section 2.6.1). The remaining exposure and dose-response assessment parameters (described in Sections 2.2 and 2.4) were fixed at expected or best-estimate values. Please refer to the Supporting Information (SI) Table SI1 for a summary of how the input variables in Eq. (1) were treated.

2.2. Exposure routes

The selected uses included: (1) potable consumption; (2) toilet flush water; (3) unrestricted irrigation use (*i.e.*, dust suppression and municipal irrigation, excluding food crops); and (4) indoor use (*i.e.*, toilet flush water, clothes washing, and accidental cross-connection of treated water to potable water or accidental ingestion of treated water). The assumed volume of water consumed during each activity (for healthy adults), the frequency of use, and the fraction of the population exposed are presented in Table 1.

The volume of water inhaled after toilet flushing is potentially very small, *e.g.*, 10^{-9} L (Lim et al., 2015). The total volume of water ingested due to other routes of exposure such as hand contact with bathroom surfaces during cleaning or repair activities; hand contact during clothes washing; and unrestricted irrigation remains uncertain due to lack of data. We selected best-estimate,