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Human health impact of non-potable reuse of distributed wastewater and greywater treated by membrane bioreactors

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ABSTRACT

We assessed the annual probability of infection resulting from non-potable exposures to distributed greywater and domestic wastewater treated by an aerobic membrane bioreactor (MBR) followed by chlorination. A probabilistic quantitative microbial risk assessment was conducted for both residential and office buildings and a residential district using *Norovirus, Rotavirus, Campylobacter jejuni*, and *Cryptosporidium* spp. as reference pathogens. A Monte Carlo approach captured variation in pathogen concentration in the collected water and pathogen (or microbial surrogate) treatment performance, when available, for various source water and collection scale combinations. Uncertain inputs such as dose-response relationships and the volume ingested were treated deterministically and explored through sensitivity analysis. The predicted 95th percentile annual risks for non-potable indoor reuse of distributed greywater and domestic wastewater at district and building scales were less than the selected health benchmark of 10^{-4} infections per person per year (ppy) for all pathogens except *Cryptosporidium* spp., given the selected exposure (which included occasional, accidental ingestion), dose-response, and treatment performance assumptions. For *Cryptosporidium* spp., the 95th percentile annual risks for reuse of domestic wastewater (for all selected collection scenarios) and district-collected greywater were greater than the selected health benchmark when using the limited, available MBR treatment performance data; this finding is counterintuitive given the large size of *Cryptosporidium* spp. relative to the MBR pores. Therefore, additional data on MBR removal of protozoa is required to evaluate the proposed MBR treatment process for non-potable reuse. Although the predicted *Norovirus* annual risks were small across scenarios (less than 10^{-7} infections ppy), the risks for *Norovirus* remain uncertain, in part because the treatment performance is difficult to interpret given that the ratio of total to infectious viruses in the raw and treated effluents remains unknown. Overall, the differences in pathogen characterization between collection type (i.e., office vs. residential) and scale (i.e., district vs. building) drove the differences in predicted risk; and, the accidental ingestion event (although modeled as rare) determined the annual probability of infection. The predicted risks resulting from treatment malfunction scenarios indicated that online, real-time monitoring of both the MBR and disinfection processes remains important for non-potable reuse at distributed scales. The resulting predicted health risks provide insight on the suitability of MBR treatment for distributed, non-potable reuse at different collection scales and the potential to reduce health risks for non-potable reuse.

1. Introduction

Communities faced with water shortage and/or large wastewater flows are interested in community water systems that reuse reclaimed water for potable and non-potable purposes (National Academies of Sciences, 2016; NWRI Independent Advisory Panel, 2016). Distributed reuse systems, i.e., systems at the district or building scale, are of particular interest for non-potable reuse to minimize the import and export of water (NWRI Independent Advisory Panel, 2016). Sources of reclaimed waters collected at the distributed scale include, but are not limited to:

- Greywater (GW): wastewater from bathtubs, showers, bathroom sinks, and clothes washing machines, and
- Domestic wastewater (WW): GW mixed with toilet, and dishwasher and kitchen sink wastewaters.

Membrane bioreactor (MBR) systems have been used to produce

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reclaimed waters given the advantages of comparatively lower capital costs than conventional treatment and high-quality effluent (Kraemer et al., 2012) and have been successfully implemented at the distributed scale (e.g., Solaire residential building in New York City). The overall goal of this research effort is to assess the sustainability of distributed MBR systems for domestic, indoor non-potable reuse, i.e., toilet flushing and clothes washing. Our sustainability assessment follows the same principals described in previous work (Xue et al., 2015; Schoen et al., 2017a), in which we selected and demonstrated a set of technical metrics which we consider critical to evaluate built water services. This paper will focus on the metric of human health impact as determined by Quantitative Microbial Risk Assessment (QMRA). QMRA is a scientific approach that calculates the potential human health risk resulting from exposure to microbial hazards (e.g., human pathogenic viruses, protozoa, and bacteria) (Haas et al., 1999). For the waters listed above, the microbial hazards include enteric pathogens resulting from human fecal contamination and opportunistic pathogens (e.g., *Legionella pneumophila*) which may grow within the collection and distribution systems (O'Toole et al., 2014; Garner et al., 2016; Ashbolt, 2015). This study focuses on the former, which are more effectively managed by source water treatment.

In previous work, we reviewed the microbial risks and treatment requirements (in the form of $\log_{10}$ reduction targets [LRTs]) associated with non-potable uses of distributed waters as predicted by QMRA (Schoen and Garland, 2015). The review identified no studies that estimated the pathogen risk or LRTs associated with the non-potable reuse of domestic WW and a limited set for GW across reference hazards. Following, a general set of pathogen LRTs were proposed that corresponded with a benchmark infection risk of 10^{-4} per person per year (ppy) for non-potable uses of a variety of distributed waters, including distributed GW and WW (Schoen et al., 2017b) (Table 1 presents indoor use LRTs). The recommended distributed GW and WW LRTs are sensitive to collection scale (Schoen et al., 2017b) and potentially the type of water collected (e.g., residential or business), which affects the pathogen characterization of the waters (Jahne et al., 2016).

The proposed pathogen LRTs do not express the average treatment efficiency; rather, the treatment efficiency of a process should be greater than or equal to the LRT at all times to ensure that the benchmark health risk, as predicted by QMRA, is achieved. QMRA analysis of conventional drinking water treatment first demonstrated that variation in treatment performance impacts the predicted health risk (reviewed in Petterson and Ashbolt (2016) with examples: Teunis et al. (1997) and Westrell et al. (2003)). For more advanced treatment (e.g., direct potable reuse), the reliability and robustness of the treatment train and the resiliency provided by the environmental buffer (e.g., planned indirect potable reuse) are important factors that can reduce health risk sensitivity to inherent variability in inputs and treatment performance (Nasser 2015; Pecson et al., 2017). Distributed non-potable reuse systems are more flexible in design and may or may not have the same level of reliability and robustness as advanced treatment trains (NWRI Independent Advisory Panel, 2016). In the extreme case, significant but temporary reduction in treatment performance has been observed during simulated failure conditions for MBR systems (Branch et al., 2016; Hirani et al., 2014).

The primary objective of this work is to evaluate the predicted health risks for indoor non-potable reuse of MBR-treated GW and WWs for various collection scenarios (building vs. district, office vs. residential), accounting for variation in pathogen removal performance, when possible. The resulting predicted health risks fill the research gap of QMRA-derived risk from distributed non-potable reuse and provide insight on the suitability of MBR systems for distributed non-potable reuse at different collection scales.

Table 1
Non-potable indoor use Log_{10} pathogen reductions targets (LRTs) for healthy adults given the 10^{-4} ppy (infection) benchmark for locally-collected wastewater and greywater (only dominant hazards presented)[a].

	Norovirus (genome copies)[b]	*Rotavirus* (FFU)	*Cryptosporidium* (oocysts)[b]	*Campylobacter* (CFU)
Wastewater[c]	11.2	8.8	6.8	6.0
Greywater[c]	8.8	6.4	4.5	3.7

[a] Assumed 4×10^{-5} L of water consumed per day for 365 days a year with 10% of the population ingesting 2 L per day for 1 day of the year
[b] Greatest LRT from possible range presented
[c] Pathogen concentrations in distributed raw wastewater and greywater calculated assuming 1000- person residential collection system

2. Approach

2.1. Non-potable reuse scenarios and technologies

We evaluated six non-potable reuse scenarios, incorporating different scales of GW and WW collection: residential district collection and distribution (Res.Dist) treating 2 MGD (7570 $m^3\ d^{-1}$) of GW or WW per day; office building collection and distribution (Off.Build) treating 0.05 MGD (189 $m^3\ d^{-1}$) of GW or WW per day; and residential building (Res.Build) treating 0.05 MGD (189 $m^3\ d^{-1}$) of GW or WW per day. We refer to these systems in terms of scenario and source water, e.g., Res.Dist-WW or Off.Build-GW. Each has a unique pathogen characterization in the untreated, freshly collected source water (described further in Section 2.6).

The selected treatment technology (Figure SI1) includes preliminary treatment (screening and grit removal); aerobic (ultrafiltration) membrane bioreactor with a nominal pore size of 0.04 μm; and disinfection with free chlorine achieving a contact time (CT) value of 30 mg min L^{-1} (with at least a 1 mg L^{-1} chlorine residual and a 30-minute contact time). Given the lack of treatment performance data as input for QMRA for specific MBR configurations, the following MBR characteristics were utilized in the accompanying life cycle assessment: hydraulic retention time of 8 hours; a solids retention time of 20 days; a mixed-liquor suspended solids concentration of 9 g L^{-1}; and a reactor temperature of 20 °C (please refer to Table SI1 for additional MBR characteristics).

The selected collection systems are multi-user and collect waters with a high potential for human infectious pathogens, and therefore must include automated monitoring, control, alarm, and process control points (NWRI Independent Advisory Panel, 2016). This high level of monitoring and control influenced the treatment performance scenarios that we modeled, as described further in Section 2.7.

2.2. QMRA model

The traditional QMRA steps were used to calculate the annual probability of infection (Haas et al., 1999). Based on the methodology employed to establish the LRTs in Table 1 (Schoen et al., 2017b), the annual probability of infection ($\text{Pinf}_{\text{annual}}$) was calculated as:

$$\text{Pinf}_{\text{annual}} = S^{*}\left(1 - \prod_{n_i}\left[1 - DR\left(V_i^{*}\ 10^{\log_{10}(C)-\text{LRV}}\right)\right]\right) \quad (1)$$

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 use i
n_i is the number of days of exposure over a year for use i
C is the pathogen concentration in the untreated, freshly collected source water
LRV is the total log reduction value of the total treatment processes (i.e., $\text{LRV} = \text{LRV}_{\text{MBR}} + \text{LRV}_{\text{disinfection}}$)

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