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A risk-based evaluation of onsite, non-potable reuse systems developed in compliance with conventional water quality measures

Mary E. Schoen, Michael A. Jahne and Jay Garland

ABSTRACT

Water quality standards (WQSs) based on water quality measures (e.g., fecal indicator bacteria (FIB)) have been used by regulatory agencies to assess onsite, non-potable water reuse systems. A risk-based approach, based on quantitative microbial risk assessment, was developed to define treatment requirements that achieve benchmark levels of risk. This work compared these approaches using the predicted annual infection risks for non-potable reuse systems that comply with WQSs along with the benchmark risk levels achieved by the risk-based systems. The systems include a recirculating synthetic sand filter or an aerobic membrane bioreactor (MBR) combined with disinfection. The greywater MBR system had predicted risks in the range of the selected benchmark levels. However, wastewater reuse with systems that comply with WQSs had uncertain and potentially high predicted risks (i.e., $>10^{-2}$ infections per person per year) in residential applications, due to exposures to viruses and protozoa. The predicted risks illustrate that WQSs based on FIB treatment performance do not ensure adequate treatment removal of viruses and protozoa. We present risk-based $\log_{10}$ pathogen reduction targets for intermediate-sized non-potable systems, which are 0.5 $\log_{10}$ less than those previously proposed for district-sized systems. Still, pathogen treatment performance data are required to better manage non-potable reuse risk.

Key words | greywater, MBR, non-potable, QMRA, reuse, wastewater

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INTRODUCTION

There is an increased interest in non-potable reuse systems in which greywater (GW) and wastewater (WW) from local sources are collected, treated, and used for non-potable indoor and outdoor applications at a location near the point of generation (Sharvelle *et al.* 2017). GW, defined here as wastewaters from bathtubs, showers, bathroom sinks, and clothes washing machines, and domestic WW, defined here as GW mixed with toilet, dishwasher, and kitchen sink wastewaters, contain enteric pathogens resulting from human fecal contamination. Many state regulatory agencies in the USA use water quality standards (WQSs) to evaluate the treatment performance of a candidate system (see Appendix A in Sharvelle *et al.* (2017)). The NSF/ANSI Standard 350 for Onsite Residential and Commercial Water Reuse Treatment Systems (NSF 350) was created to unify the existing microbial water quality requirements (NSF International Standard/American National Standard 2017).

NSF 350 sets minimum requirements for fecal indicator bacteria (FIB; i.e., fecal coliforms) as well as other conventional water quality parameters (e.g., biochemical oxygen demand and suspended solids) for indoor non-potable reuse (i.e., toilet or urinal flush water) and outside surface irrigation. Classes include 'Residential' (i.e., single-family residences) or 'Commercial' waters (e.g., multi-family residences, business parks, public assembly areas, and laundering facilities). Throughout this paper, the NSF 350 classes will be capitalized (e.g., Residential or Commercial); in addition, waters generated within homes will also be described as residential.

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To achieve NSF certification, a treatment system must meet the minimum requirements outlined in NSF 350 during a 26-week testing period (NSF International Standard/American National Standard 2017). The NSF/ANSI reuse standard limits the NSF certification to onsite, non-potable systems for Residential or Commercial use with a treatment capacity of less than 5,700 L d^{-1} (1,500 G d^{-1}) (NSF International 2019).

An alternative, risk-based approach requires that systems meet pathogen reduction targets for specific uses based on quantitative microbial risk assessment (QMRA), a scientific method that calculates the potential human health risk resulting from exposure to microbial hazards (i.e., human pathogenic viruses, protozoa, and bacteria; Haas *et al.* 2014). The risk-based approach is exemplified by the Risk-Based Framework for the Development of Public Health Guidance for Decentralized Non-Potable Water Systems from the National Water Research Institute (risk-based guidance; Sharvelle *et al.* 2017) as well as water reuse guidelines worldwide (NRMMC *et al.* 2006, 2009; World Health Organization 2006a, 2006b). The risk-based guidance specifies the level of treatment required for non-potable reuse in the form of pathogen $\log_{10}$ reduction targets (LRTs) that correspond with a health benchmark of 10^{-4} or 10^{-2} infections per person per year (ppy) (Sharvelle *et al.* 2017). The LRTs are specific to the collection scale and type of water collected (e.g., GW vs. WW), which affects the pathogen characterization of the waters (Jahne *et al.* 2016). The LRTs for indoor use (i.e., toilet flush water and clothes washing) or outdoor irrigation are included in the risk-based guidance for single-family residences (treating <946 L d^{-1} or 250 G d^{-1}) and multi-family systems with a treatment capacity of roughly 192,000 L d^{-1} (50,700 G d^{-1}) but not specifically for the intermediate-sized systems certified by NSF for NSF 350 (i.e., <5,700 L d^{-1} or 1,500 G d^{-1}). Both the computed and missing LRTs across system sizes are detailed in Table 1 for indoor use for single- and multi-family residences. In addition, LRTs for commercial systems for businesses or laundering have not been calculated.

This paper applied QMRA to compare the different approaches used to evaluate the treatment performance of non-potable reuse systems for microbial hazards. First, we evaluated if NSF 350-certified systems met the indoor reuse LRTs corresponding to either a 10^{-4} or 10^{-2} ppy infection health benchmark (Table 1). Due to the lack of LRTs for all classes and sizes certified by NSF, we also simulated the pathogen infection risk for NSF-certified, non-potable systems. We then compared the predicted annual risks for systems that comply with NSF 350 to the health benchmarks achieved by the risk-based systems. In this process, we estimated the risk-based treatment requirements for intermediate-sized onsite systems not yet reported in guidance and thus missing from Table 1 (Sharvelle *et al.* 2017).

Table 1 | Non-potable indoor use LRTs for single- and multi-family residences for healthy adults given the 10^{-4} (10^{-2}) infection ppy benchmark for onsite WW and GW[a]

Water (capacity)	Virus	Protozoa	Bacteria
WW (192,000 L d^{-1}/ 50,000 G d^{-1})[b]	8.5 (6.5)	7.0 (5.0)	6.0 (4.0)
WW (5,700 L d^{-1} or 1,500 G d^{-1})	NA (NA)	NA (NA)	NA (NA)
WW (946 L d^{-1}/250 G d^{-1})[c]	7.5 (NA)	0 (0)	0 (0)
GW (121,000 L d^{-1}/ 32,000 G d^{-1})[b]	6.0 (4.0)	4.5 (2.5)	3.5 (1.5)
GW (5,700 L d^{-1} or 1,500 G d^{-1})	NA (NA)	NA (NA)	NA (NA)
GW (600 L d^{-1}/160 G d^{-1})[c]	5.0 (NA)	0 (0)	0 (0)

[a]Assumed 4×10^{-5} L of water consumed per day for 365 days a year for clothes washing and toilet flushing with 10% of the population ingesting 2 L for 1 day of the year. NA indicates that the LRT was not published. A 0 indicates that the LRT is zero for that particular pathogen.
[b]*Source:* Sharvelle *et al.* (2017).
[c]*Source:* Schoen *et al.* (2017).

APPROACH

We used two approaches to evaluate the health risk from NSF-certified systems for onsite, non-potable reuse: comparison to LRTs and QMRA simulation of annual risk. For both, we separated the Commercial class into three subclasses, multi-family residential (e.g., lodging or apartments), business (e.g., business park, public assembly, and shopping), and laundering (not assessed in this analysis) in order to capture the unique microbial characteristics of each. First, we compared the treatment capabilities of the NSF-certified systems (specified as log reduction values (LRVs)) outlined in the 'Treatment performance (LRV)'

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section to the LRTs for indoor reuse of residential GW and WW (Table 1). This comparison assessed if the NSF-certified systems are 'safe' (i.e., achieving infection risk benchmarks) for toilet flushing and clothes washing in single-family and multi-family residences. This comparison did not specifically address combined indoor and outdoor use; larger, single-family residences; or business waters, as Sharvelle *et al.* (2017) does not specify LRTs for these conditions. Therefore, we also simulated the annual risk from indoor and outdoor non-potable reuse of Residential and Commercial GW and WW across the collection sizes of interest (described in the 'NSF-certified onsite, non-potable reuse systems' section).

NSF-certified onsite, non-potable reuse systems

NSF has certified three commercial proprietary treatment systems for NSF 350 (see Supplementary Material, Figure SI1 and refer to the NSF product and service listings; NSF International 2019). The first is a septic tank and recirculating synthetic sand filter (RSF) followed by ultraviolet disinfection (National Small Flows Clearinghouse 1998), which is certified for Residential WW reuse for systems treating less than 4,500 L d^{-1} (1,200 G d^{-1}). Membrane bioreactors (MBRs, both aerobic and moving bed (MBs)) are certified for Commercial GW and Residential WW reuse for systems treating less than 5,700 L d^{-1} (1,500 G d^{-1}). We assumed that the RSF or MBR could soon be applied to Residential GW systems (which require lower LRTs than Residential WW; Table 1). Although not required by NSF, we also included an additional treatment step of disinfection with free chlorine for the MBR system, to comply with state requirements (see Appendix A in Sharvelle *et al.* (2017) for a summary of state requirements).

Simulating the annual infection risk using NSF-certified systems

Based on the QMRA methodology initially employed to establish the LRTs in Table 1 (Schoen *et al.* 2017) and later to evaluate MBR technologies for non-potable reuse (Schoen *et al.* 2018b), the annual probability of infection ($Pinf_{annual\_p}$) for pathogen (p) from non-potable reuse was calculated as follows:

$$Pinf_{annual\_p} = 1 - \prod_{n_i} [1 - DR(V_i \times 10^{\log_{10}(C_p) - LRV_p})] \quad (1)$$

where DR(…) is a function, the dose–response relationship 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 activity for use i over a year; C_p is the pathogen concentration in the untreated, freshly collected source water; and LRV_p is the pathogen-specific total $\log_{10}$ reduction value of the total treatment processes.

Monte Carlo analyses were implemented with 10,000 iterations (each representing a year) in R 3.2.3 to capture the daily variation in pathogen concentration (R Core Team 2015). The 95th percentile of the annual probability of infection was compared to the selected annual health benchmark. The LRVs, ingestion volume, and dose–response relationships were treated deterministically and explored by constructing various scenarios. Note that we treated each pathogen separately and did not calculate a total, annual pathogen risk.

Equation (1) was modified to include an accidental ingestion event of treated non-potable water by summing the $Pinf_{annual}$ for populations with and without accidental ingestion, weighted by the relevant fraction of the population, as described in the 'Exposure routes' section. The following sections describe the remaining input parameters to Equation (1), which are summarized in the Supplementary Material, Table SI1.

Exposure routes

When simulating the risk from non-potable reuse using Equation (1), the volume ingested was the sum across the NSF 350 uses that occurred each day, including toilet and urinal flushing as well as outdoor surface or subsurface irrigation (NSF International Standard/American National Standard 2017). For a fair comparison of the different approaches used to evaluate the treatment performance of non-potable reuse systems, the exposure assumptions used to calculate the risk-based LRTs for indoor and outdoor non-potable reuse were adopted for the simulation of the NSF-certified systems (Schoen *et al.* 2017), i.e., 4×10^{-5} L of water consumed per day for 365 days a year for indoor

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use and 1×10^{-3} L of water ingested 50 times per year for unrestricted surface irrigation. These exposure assumptions were based on those previously used for indoor use and municipal irrigation (NRMMC *et al.* 2006). While the indoor exposures were originally described by NRMMC for the ingestion of aerosols, they are likely conservative and of a magnitude that covers potential hand-to-mouth exposures as well (for a full discussion on indoor and irrigation use ingestion volumes, refer to Schoen *et al.* (2017)). Overall, the ingested volumes for indoor and municipal irrigation remain uncertain given the lack of data. We assumed 100% recovery for hand-to-mouth exposures, and thus a transfer efficiency was not included in Equation (1).

Onsite reuse systems present the opportunity for contamination of potable water with the treated WW or GW (e.g., Pimpama Coomera, Australia; Sinclair 2010) as well as the accidental ingestion of non-potable water. The characteristics of accidental or cross-connection events are generally uncharacterized in the literature, as discussed at length by Schoen *et al.* (2018a). The reported (or target) fraction of connections (or people served) with events per year for non-potable systems ranged between 10^{-3} households per year (Storey *et al.* 2007) and 0.14 households per year (630 of 4,400 dwellings) (Sinclair 2010). In the exposure assessment, we included the accidental ingestion event assumed in Schoen *et al.* (2017), i.e., the ingestion of 2 L of treated water 1 day of the year for 10% of the population.

Reference pathogens

Reference hazards represent classes of pathogens with potential adverse health impacts. Of the human-infectious enteric viruses, bacteria, and protozoa previously considered in the QMRA of non-potable systems (Schoen *et al.* 2018b), we narrowed the list to *Norovirus* and *Cryptosporidium* spp., which required the largest treatment removal. We did not calculate risks from exposure to bacteria since these risks were extremely small compared to the selected reference hazards in similar non-potable systems (Schoen *et al.* 2018b).

Pathogen dose–response relationships

We selected dose–response relationships that relate the ingested dose to a probability of gastrointestinal infection for a healthy adult. When simulating *Norovirus* risk (doses in genome copies (gc)), two dose–response models were used to represent the lower- and upper-bounds of predicted risk across the range of available models (Van Abel *et al.* 2016). The upper-bound, a hypergeometric model for disaggregated *Norovirus* GI developed by Teunis *et al.* (2008), predicts relatively high risks among the available models in the relevant dose range. The lower-bound, a fractional Poisson model for *Norovirus* GI and GII (Messner *et al.* 2014), predicts similar risks as the majority of the published *Norovirus* dose–response models with good empirical fit to the available data (reviewed in Van Abel *et al.* (2016)).

For *Cryptosporidium* spp. (doses in oocysts), we adopted an exponential model (with $r = 0.09$) for the lower-bound based on the U.S. EPA Long Term 2 Enhanced Surface Water Treatment Rule (LT2) Economic Analysis (U.S. EPA 2005) and the more recently proposed fractional Poisson model (Messner & Berger 2016), which results in risks that are much greater than previously predicted in the LT2 (Messner & Berger 2016). Although the assumptions of the upper-bound fractional Poisson model remain controversial (Schmidt & Chappell 2016), it is the most conservative estimate of risk among the three better-fitting model options explored by Messner & Berger (2016). Overall, the dose–response models do not include data for the low-dose exposures anticipated from non-potable water use, and the true dose–response relationships at these levels of exposure remain uncertain.

Characterization of pathogens in waters

In the previous work, we developed a set of reference business and residential GW and WW pathogen concentration characterizations for various collection sizes (i.e., 5, 100, and 1,000-person collections) using an epidemiological modeling approach (Jahne *et al.* 2016; Schoen *et al.* 2018b). We selected from the reference set to characterize the pathogen concentrations in raw waters.

To convert the system size to the number of people connected, we adopted a per-capita indoor residential water use of 192 L d^{-1} (50.7 G d^{-1}) assuming negligible leakage (DeOreo *et al.* 2016) for WW reuse and a per-capita GW generation of 121 L d^{-1} (32 G d^{-1}) (NSF International

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Standard/American National Standard 2017). For offices, we assumed that the GW was generated only from sinks at 16 L d^{-1} (4.2 G d^{-1}) per person (Dziegielewski *et al.* 2000). We estimated that the maximum system capacity certified by NSF 350 of 5,700 L d^{-1} (1,500 G d^{-1}) corresponded to approximately 30 people in a residential WW system, 47 people in a residential GW system, and 357 people in an office GW system. The 30-person (single-family) Residential reuse systems are vacation rentals for large parties. From the available collection sizes with characterized pathogen densities (i.e., 5, 100, and 1,000-person collections), we selected the 100-person systems' influent pathogen concentrations to simulate risk for the largest-sized residential systems certified by NSF and the 100- and 1,000-person systems to simulate risk for the largest-sized business systems.

The influent pathogen concentrations are presented in Table 2. In small systems, pathogen infections are sporadic, and there is limited dilution from non-infected individuals when an infected individual is shedding pathogens. This leads to highly variable predicted pathogen loads in the WW (Table 2), ranging from frequent non-occurrences to occasional high concentrations when there are multiple active shedders. Secondary transmission, which was not included in the pathogen simulation, would further increase concentrations. Also note that the model did not consider seasonality (clustering of infections in time), and peak concentrations may therefore be underestimated.

Treatment performance (LRV)

The treatment performance was narrowly focused on the performance of NSF 350-certified systems. For the MBR systems, we adopted the reported performance of the certified MB-MBR Aqualoop system (Table 3). The Aqualoop system, with hollow tube filtration and a pore size of 0.02 μm, had a reported average bacterial removal of 6.0 $\log_{10}$ and viral removal of 3.0 $\log_{10}$ (Ecovie 2019). For comparison, the mean LRVs adopted in the previous MBR QMRA work (Schoen *et al.* 2018b) were 3.8 $\log_{10}$ for *Norovirus* ($n = 48$) and 5.0 $\log_{10}$ for *Clostridium perfringens* (a protozoa surrogate) ($n = 25$), as reported in a comprehensive review across MBR systems (Branch 2016). Given the lack of data, we set the unreported protozoa LRV to the viral LRV (i.e., 3.0 $\log_{10}$), which falls in the recommended range of protozoa LRV in the Australian guidance of 2.0–4.0 (Branch & Le-Clech 2015). Based on California's residual free chlorine requirements of 0.5–2.5 mg/L for non-potable reuse, we assumed a virus LRV of 4.0 $\log_{10}$ for chlorine disinfection (Sharvelle *et al.* 2017).

Pathogen LRVs were not reported for the NSF-certified RSF system or for similar systems in the non-potable reuse risk-based guidance (Sharvelle *et al.* 2017). Additionally, we were unable to identify LRVs for RSF systems in the literature except for bench-scale (Gold *et al.* 1992).

Table 2 | Simulated pathogen concentrations in residential and business GW and WW: rate of occurrence, net mean including non-occurrences, and 95th percentile when occurring. Concentrations are expressed as $\log_{10}$ per L[a]

	5-persons			100-persons			1,000-persons		
	Occur	Mean	95th%	Occur	Mean	95th%	Occur	Mean	95th%
Business GW									
Cryptosporidium (oocysts)	NA	NA	NA	1.2%	0.15	2.72	11.3%	0.16	1.94
Norovirus (gc)	NA	NA	NA	44.8%	4.15	5.11	99.7%	4.15	4.77
Residential GW									
Cryptosporidium (oocysts)	0.1%	1.83	4.87	1.2%	1.85	3.57	11.3%	1.87	2.77
Norovirus (gc)	2.8%	5.82	6.82	44.8%	5.63	5.78	99.7%	5.93	5.73
Residential WW									
Cryptosporidium (oocysts)	0.1%	3.59	7.38	1.2%	3.72	6.07	11.3%	3.71	5.11
Norovirus (gc)	2.8%	7.66	9.47	44.8%	7.70	8.34	99.7%	7.70	8.21

[a]Adapted from Jahne *et al.* (2017) and Schoen *et al.* (2018b). NA indicates that the system size is not applicable.

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Table 3 | Pathogen treatment removal assumptions (NR: not reported)

Technology	Virus	Protozoa	References
MBR	3.0	3.0	Ecovie (2019)
Chlorine disinfection	4.0	0.0	Sharvelle *et al.* (2017)
RSF	NR	NR	
Total MBR and disinfection	7.0	3.0	
Total RSF and disinfection	NR	NR	

RESULTS

Comparison of LRVs to LRTs for single-family residential or multi-family indoor reuse

Wastewater

Both MBR and RSF systems are certified by NSF for onsite Residential reuse of WW up to 5,700 L d^{-1} (1,500 G d^{-1}). By comparing the LRVs of the NSF 350-certified MBR system in Table 3 to the LRTs in Table 1 for single-family residences treating less than 600 L d^{-1} (160 G d^{-1}) (see Supplementary Material, Table SI2, for comparison), the certified MBR system does not achieve the viral LRTs for onsite, non-potable reuse of WW at the 10^{-4} ppy infection benchmark (viral LRTs for the 10^{-2} ppy infection benchmark were not published). Given this information, the certified MBR system would also fall short of the LRTs for any larger-sized WW system (both Residential or Commercial) for this benchmark. We were unable to characterize the treatment performance of the certified RSF system; thus, the RSF LRVs could not be compared to the LRTs for WW or GW reuse (the 'Greywater' section).

Greywater

Although there are no systems certified for onsite Residential GW reuse, we assumed that this remains a possibility in the future. The MBR system achieves the LRTs of both virus and protozoa for non-potable reuse (i.e., toilet flushing and clothes washing) of GW in single-family residences treating less than 600 L d^{-1} (160 G d^{-1}) for the 10^{-4} infection ppy benchmark (and thus the more relaxed benchmark of 10^{-2} ppy as well) (Supplementary material, Table SI2); however, the Residential systems certified by NSF can be much larger than 600 L d^{-1} (160 G d^{-1}).

The MBR, which is also certified for Commercial GW reuse, falls short of the multi-family LRT for protozoa assuming the 10^{-4} ppy infection benchmark but achieves the LRTs for the 10^{-2} ppy infection benchmark. However, again, the multi-family LRT is aimed at systems larger than those currently accepted by NSF ($\leq$5,700 L d^{-1} (1,500 G d^{-1})) and thus acts as a conservative treatment target.

Simulated risk of onsite reuse of GW and WW

Given the lack of LRTs for systems in the size range certified by NSF (Table 1), we simulated the annual risk from non-potable reuse (both indoor uses and outdoor irrigation) for a range of treatment performance using the 5, 100, and 1,000-person collection reference pathogen concentration characterizations for WW and GW.

Residential WW

Use of the certified NSF 350 MBR system for non-potable reuse of WW in residential systems treating 19,200 L d^{-1} (5,070 G d^{-1}) (modeled using a 100-person system) results in predicted 95th percentile annual infection risks greater than the 10^{-2} and 10^{-4} infection ppy health benchmarks using the best estimate protozoa LRV (Figure 1(b)). The annual risk for the 100-person WW reuse system is dominated by the *Cryptosporidium* spp. risk assuming the lower-bound *Norovirus* dose–response that was used to set the non-potable LRTs in Table 1 (Sharvelle *et al.* 2017); otherwise, both the protozoa and virus upper-bound risks are roughly equivalent (not presented). Considering the uncertainty associated with the unreported protozoa LRVs, it may be possible for the NSF-certified MBR system to achieve the more relaxed benchmark if performance approaches the mean LRV from across systems (but not certified for NSF 350) of 5.0 (see the 'Treatment performance (LRV)' section). On the lower end of the NSF 350-certified size range, a 5-person MBR system treating 946 L d^{-1} (250 G d^{-1}) has a predicted annual risk less than 10^{-2} infections ppy (but greater than 10^{-4} infections

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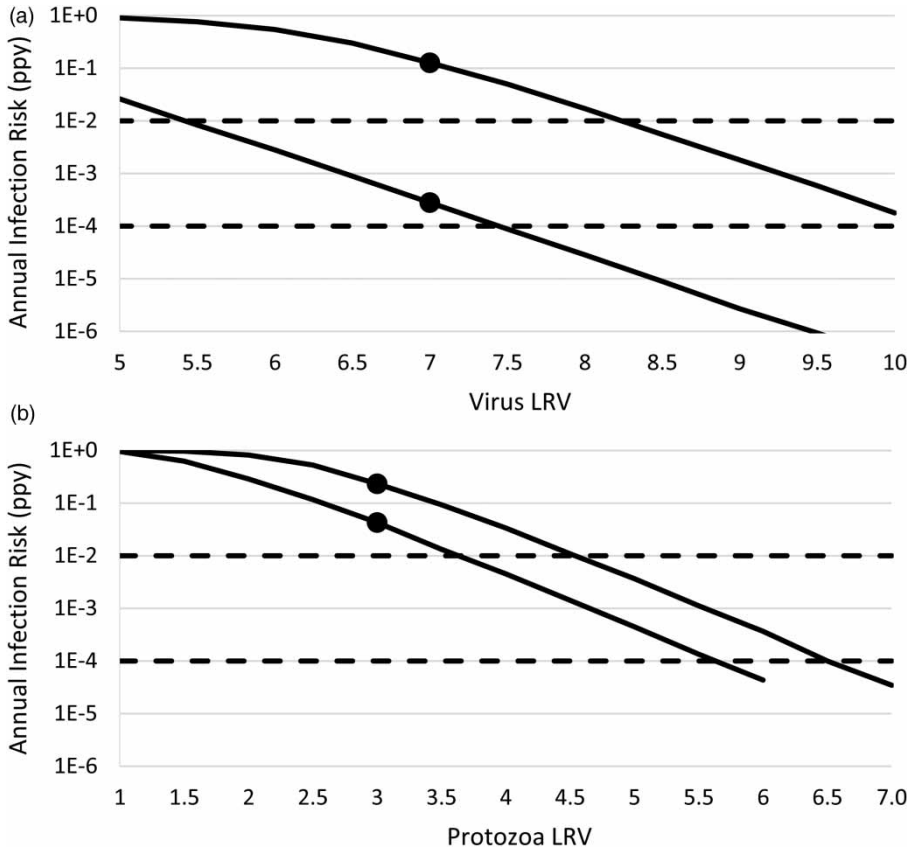

Figure 1 | 95th percentile annual probability of infection from onsite, non-potable reuse of WW for (a) a 5-person system achieving a range of *Norovirus* LRVs (*x*-axis) or (b) a 100-person system achieving a range of *Cryptosporidium* spp. LRVs (*x*-axis). Horizontal lines indicate the health benchmark risks. Both the upper- and lower-bound dose–response results are presented. LRVs are indicated by circles for the MBR system.

ppy) using the lower-bound *Norovirus* dose–response (Figure 1(a)).

Residential GW

Use of the MBR system for non-potable reuse of GW in residential water systems treating 12,100 L d^{-1} (3,200 G d^{-1}) (modeled using a 100-person system) results in 95th percentile annual infection risks less than (or equal to) the 10^{-2} ppy infection benchmark but greater than the 10^{-4} ppy benchmark using the best estimate protozoa LRV (Figure 2(b)). The annual risk for the 100-person GW reuse system is dominated by the protozoa risk assuming the lower-bound *Norovirus* dose–response used to set non-potable LRTs (Sharvelle *et al.* 2017); otherwise, both the protozoa and virus upper-bound risks are of the same order of magnitude (not presented). The 5-person simulation (Figure 2(a)) corroborates the findings from the 'Greywater' section, with predicted annual risks below the 10^{-4} ppy infection benchmark using the lower-bound dose–response for *Norovirus*.

Commercial GW

We divided the NSF Commercial class into three sub-classes based on microbial characteristics: multi-family, business, and laundering (the later not included in this analysis). Only the MBR system is certified by NSF for Commercial GW applications (up to 5,700 L d^{-1} (1,500 G d^{-1})). The risk resulting from use of the MBR system for non-potable reuse of GW in a multi-family system is analogous to the risks for large Residential systems presented previously in the 'Residential GW' section.

Given the lack of LRTs for business waters, we simulated the risk from non-potable reuse of business GW from 100-person and 1,000-person systems, roughly corresponding to 1,590 L d^{-1} (420 G d^{-1}) and 15,900 L d^{-1} (4,200 G d^{-1})

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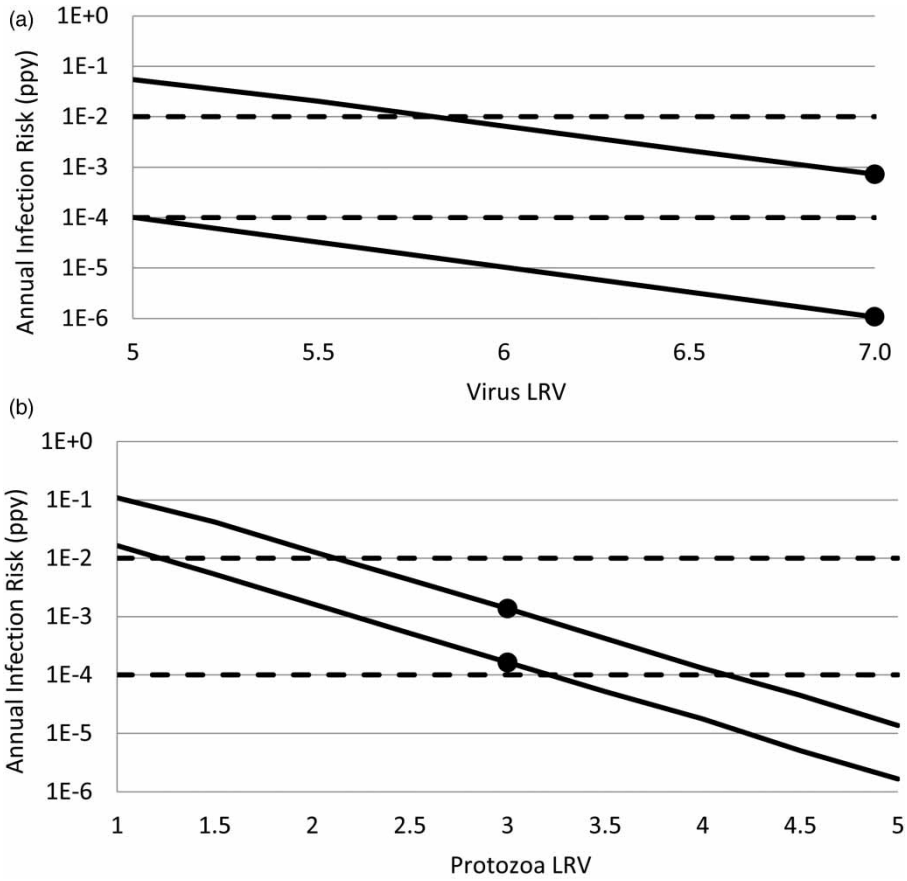

Figure 2 | 95th percentile annual probability of infection from onsite, non-potable reuse of GW for (a) a 5-person system achieving a range of *Norovirus* LRVs (*x*-axis) or (b) a 100-person system achieving a range of *Cryptosporidium* spp. LRVs (*x*-axis). Horizontal lines indicate the health benchmark risks. Both the upper- and lower-bound dose–response results are presented. LRVs are indicated by circles for the MBR system.

GW (Figure 3). Again, annual risks are dominated by the protozoa risk when assuming the lower-bound *Norovirus* dose–response previously used to set non-potable LRTs (Table 1). Use of the MBR system for non-potable reuse of business water in systems treating <1,590 LD (420 G d^{-1}) results in 95th percentile annual infection risks less than or equal to the selected health benchmark using the best estimate *Cryptosporidium* LRVs; for larger business systems, treating <15,900 L d^{-1} (4,200 G d^{-1}) GW, the 10^{-4} ppy infection benchmark falls within the range of risk predicted by the lower- and upper-bound dose–response.

Level of protection

The NSF 350-certified systems have a range of predicted annual risk depending on the selected system, class, type of water, and system size (Figures 1–3). For GW reuse with the NSF 350-certified MBR system, the 95th percentile annual risk range is from approximately 10^{-6} infections ppy (for small Residential GW systems) to 10^{-3} infections ppy (for larger Residential or multi-family systems) using the upper-bound predicted risks for *Cryptosporidium* spp. (Table 4). For WW reuse with the NSF 350-certified MBR system, the infection risk is greater than 10^{-4} ppy for the smallest sized Residential systems using the lower-bound dose–response for *Norovirus*. Larger Residential WW reuse systems have predicted risks well above 10^{-2} infections ppy (Table 4).

LRTs for intermediate-sized onsite systems

The virus and protozoa LRTs (summed across all treatment units including disinfection) that correspond with

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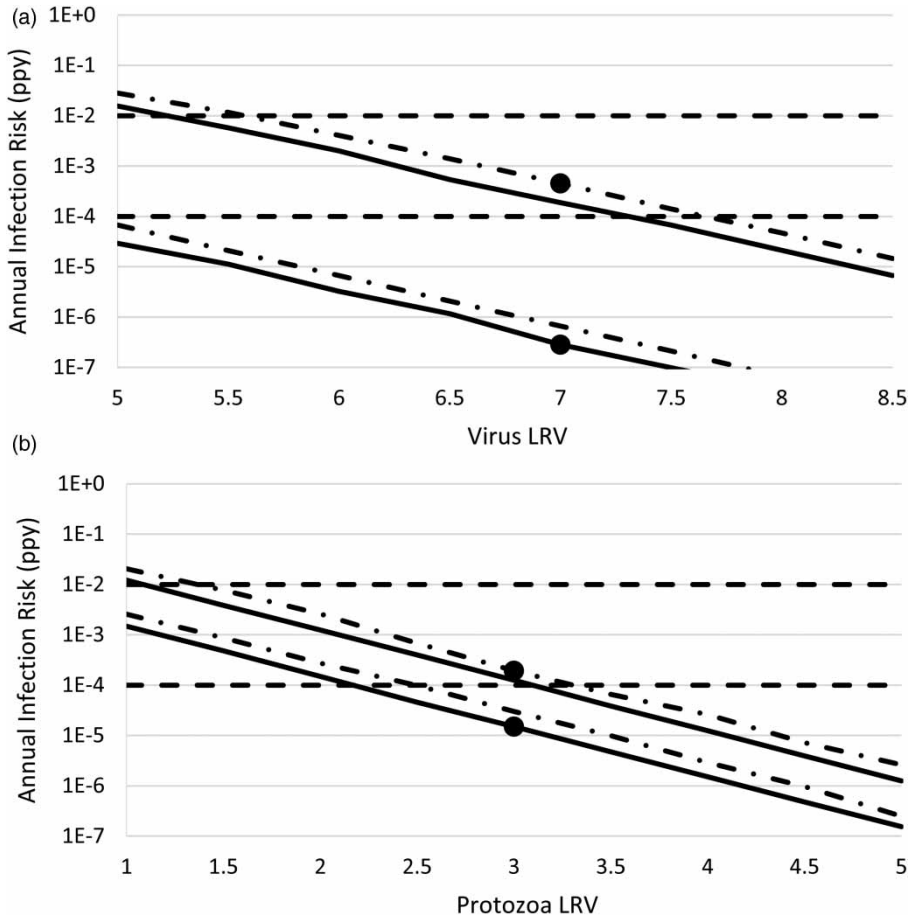

Figure 3 | 95th percentile annual probability of infection from (a) *Norovirus* and (b) *Cryptosporidium* spp. from onsite, non-potable reuse of business GW for 100-person (solid font) and 1,000-person (dashed font) systems. Horizontal lines indicate the health benchmark risks. Both the upper- and lower-bound dose–response results are presented. LRVs for the MBR system are indicated by circles.

Table 4 | 95th percentile annual probability of infection from onsite, non-potable reuse of GW or WW with the NSF 350-certified MBR system based on the dominant pathogen for each scenario (i.e., either *Cryptosporidium* spp. using the upper-bound dose–response or *Norovirus* using the lower-bound dose–response)

System	Annual probability of infection
GW Residential (600 L d^{-1}/160 G d^{-1})	1×10^{-6}
GW Residential (12,100 L d^{-1}/ 3,200 G d^{-1})	1×10^{-3}
GW Business (1,590 L d^{-1}/420 G d^{-1})	1×10^{-4}
GW Business (15,900 L d^{-1}/ 4,200 G d^{-1})	2×10^{-4}
WW Residential (946 L d^{-1}/250 G d^{-1})	3×10^{-4}
WW Residential (19,200 L d^{-1}/ 5,070 G d^{-1})	2×10^{-1}

the health benchmarks of 10^{-2} and 10^{-4} infections ppy for non-potable indoor and outdoor reuse (i.e., toilet flush, clothes washing, and irrigation) in intermediate-sized Residential and Commercial systems are presented in Table 5 for NSF systems at the upper limit of the certified size range (i.e., 5,700 L d^{-1} or 1,500 G d^{-1}). The LRTs for intermediate-sized residential systems are slightly reduced from the residential district requirements (i.e., >121,000 L d^{-1} or 32,000 G d^{-1}) in Table 1, but greater than the requirements for protozoa for the 5-person, single-family residences. Business GW requires additional protozoa treatment than a residential system with a similar capacity (Table 1) due to the greater number of people contributing.

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Table 5 | LRTs for NSF 350-scale onsite systems given the 10^{-4} (10^{-2}) infection ppy benchmark assuming upper-bound/lower-bound dose–response relationships summed across all treatment units including disinfection[a,b,c]

Water	Virus	Protozoa	Bacteria
Residential			
WW	10.5/8.0 (9.0/6.0)	6.5/6.0 (4.5/4.0)	NR (NR)
GW	8.5/5.5 (6.5/3.5)	4.0/3.5 (2.0/1.5)	NR (NR)
Business			
GW	8.0/4.5 (6.0/2.5)	3.0/2.5 (1.0/0.0)	NR (NR)

[a]Treated WW and GW reuse assumed 4×10^{-5} L of water consumed per day for 365 days a year for clothes washing and toilet flushing; 10^{-3} L of water consumed per day for 50 days a year for irrigation; with 10% of the population ingesting 2 L for 1 day of the year. NR indicates that LRT was not calculated.

[b]Virus LRTs use *Norovirus* lower-bound dose–response; protozoa use *Cryptosporidium* spp. upper-bound dose–response (see the 'Pathogen dose–response relationships' section for explanation) for healthy adults given the 10^{-4} (10^{-2}) ppy infection benchmark.

[c]Residential WW capacity of 19,200 L d^{-1} (5,070 G d^{-1}); Residential GW capacity of 12,100 L d^{-1} (3,200 G d^{-1}); and Business GW capacity of 1,590 L d^{-1} (420 G d^{-1}).

DISCUSSION

Do onsite, non-potable systems that meet WQSs provide the same level of health protection as risk-based systems?

The NSF-certified treatment systems for onsite, non-potable reuse comply with conventional indicator-based water quality requirements, but the potential infection risk to users of these systems from exposure to pathogens was not explicitly considered in the NSF 350 standard (NSF International Standard/American National Standard 2017). On the other hand, the decentralized non-potable LRT framework explicitly sets the pathogen-specific risk level to either 10^{-2} or 10^{-4} infections ppy. Do the different approaches and microbial requirements specified by NSF 350 and the risk-based LRTs equally impact the health risk from enteric pathogens for users of these systems?

To answer this question, we used the QMRA to predict a user's annual risk of infection from exposure to enteric pathogens from NSF-certified non-potable systems (with the addition of a disinfection step) (Supplementary material, Figure SI1). Users of systems that meet the NSF 350 WQSs for onsite, non-potable reuse have a predicted annual risk that varies from unknown to extremely high, depending on the source water type, size of the system, and selected treatment. For the certified Commercial GW reuse system (an MB-MBR system), the predicted annual risk is less than 10^{-3} infections ppy, which falls between the selected risk benchmarks for risk-based systems (i.e., either 10^{-4} or 10^{-2} infections ppy). However, the predicted risks for the Residential WW reuse application are above the selected health benchmarks given the assumed LRVs, with a range of roughly 10^{-4} to 10^{-1} infections ppy across systems. The results suggest that conventional water quality requirements may not be providing enough infection risk protection for WW reuse in NSF-certified Residential systems. These findings are system-specific and may not apply to future systems certified by NSF.

Why do non-potable WW reuse systems that comply with WQSs have higher risks than those certified for GW reuse?

The predicted annual risk from using the NSF-certified onsite Commercial GW non-potable reuse system (or Residential – although not certified) is less than (or equal to) the more relaxed health benchmark due to the relatively low risk-based treatment requirements for pathogen removal in GW (Table 4). The risk-based requirements for WW reuse are much higher (a $\log_{10}$ removal roughly 2.5 greater than GW for viruses and protozoa) due to the greater pathogen loading of WW vs. GW. Given our assumptions about the LRVs of the accepted systems (Table 3), the NSF-certified MBR system falls short of the risk-based protozoa removal requirements for non-potable WW reuse (Table 4). However, there remains outstanding uncertainty about the LRVs presented in Table 3 (the 'Treatment performance (LRV)' section and further discussed in the 'Which LRT is appropriate?' section), particularly for the protozoa treatment reduction. It is possible that the NSF-certified systems may achieve the LRTs corresponding to the more relaxed health benchmark for non-potable WW reuse given additional technology verification.

Why are standards based on conventional water quality measures not protective against microbial exposures for non-potable reuse?

The WQSs adopted by various states for WW reuse and enforced in the NSF 350 standard (NSF International Standard/American National Standard 2017) rely on culturable FIB as a measure of treatment performance. As shown by

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the QMRA of non-potable reuse (Schoen *et al.* 2017, 2018a, 2018b), virus and protozoa exposures drive the predicted risk from non-potable reuse, not bacteria. Since bacteria are easily removed through treatment relative to viruses and protozoa (see Sharvelle *et al.* (2017) for LRVs across treatment systems), acceptable FIB treatment performance does not ensure adequate treatment removal of the pathogens of interest, i.e., viruses and protozoa. As a result, the water quality approach to protecting public health results in a range of pathogen exposures and potentially high health risk. This work demonstrates that exposures to virus and protozoa in treated non-potable waters potentially result in high levels of predicted risk for non-potable use, indicating the additional need for virus and protozoa treatment performance data within WQSs.

Which LRT is appropriate?

The set of non-potable LRTs, incorporating those estimated in this work, includes those for district size, small single-family residences, and now intermediate (100-person) systems. This work shows that smaller-scale systems, such as those already certified by NSF 350, have less stringent treatment requirements, particularly for GW derived from business parks, public spaces, or shopping centers (i.e., primarily from bathroom sinks vs. residential showers and laundry). These vary due to differences in influent pathogen characterizations (densities and frequencies of occurrence) resulting from the scaling effects of the contributing population; in small systems, there is limited dilution of WW/GW from infected individuals (i.e., those shedding pathogens), but in large systems, there is a greater frequency of pathogen occurrence due to the increased likelihood of infected user(s) (Jahne *et al.* 2016). Of course, there is a wide range of potential system sizes, and it is not realistic to estimate LRTs for every system. However, there appears to be an important shift in requirements from the small to intermediate size range. There is a noticeable jump in the protozoa requirements from the 5-person to 100-person collections. The 5-person Residential GW and WW systems, due to the low occurrence of pathogens, have no treatment requirements for protozoa and bacteria. However, the 100-person Residential GW and WW systems have protozoa LRTs of 2.0 and 4.5 for the more relaxed benchmark and 4.0 and 4.5 for the 10^{-4} ppy infection benchmark. We do not know the shape of the relationship between system size and LRTs in this size range, which is the size range of interest for NSF 350. Further, note that the 99th percentile LRTs for the 5-person systems (vs. 95th percentiles reported) would be similar to those for the larger system (Schoen *et al.* 2017). Therefore, we recommend that systems adopt LRTs for larger-sized systems, rather than smaller-sized systems, to ensure an acceptable level of public health protection.

In addition to various system sizes, the pathogen reduction targets (Table 5) are presented for either a 10^{-2} or 10^{-4} ppy infection benchmark. International guidance for non-potable reuse has implemented a tolerable burden of disease of 10^{-6} Disability Adjusted Life Years (DALYs) ppy (WHO 2006a, 2006b; NRMMC *et al.* 2009; 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* (WHO 2006a, 2006b; NRMMC *et al.* 2009). In the United States, an infection risk of 10^{-4} ppy for giardiasis has been used for finished drinking water (Macler & Regli 1993; U.S. EPA 2006). Refer to Sinclair *et al.* (2015) for a discussion of the evolution of risk-based targets for drinking water. As an alternative, the less restrictive benchmark risk of 10^{-2} ppy may be appropriate for voluntary exposures. It is reasonable to select 10^{-4} infections ppy, given that non-potable uses are not voluntary and the possibility of accidental (or intentional) potable exposures. It is also reasonable to select a less restrictive benchmark for single-family residences where exposure is more voluntary and the risk from person-to-person spread of enteric disease is likely dominant.

Which uncertain QMRA assumptions are most important?

There are several uncertain inputs and assumptions in our analysis; our goal here is to identify those that are important and for which we can collect additional data in the near-term. There are outstanding uncertainties associated with the form and assumptions of the dose–response relationships used in this study, which have been discussed in our previous work (Schoen *et al.* 2017). Therefore, when simulating risks, we present upper- and lower-bound estimates of risk (Figures 1–3). However, when estimating the LRTs

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and comparing the levels of risk, we default to the dose–response relationships used in the risk-based non-potable LRTs (Sharvelle *et al.* 2017) to keep assumptions consistent in our comparative analysis.

Uncertain exposure assumptions that affect pathogen dose and may be further studied include those related to influent pathogen concentrations, pathogen treatment performance, and volumes ingested during non-potable water use. The comparison of risks across scenarios demonstrates that the influent pathogen concentration is an important factor in the calculation of risk. We used modeled pathogen concentrations in GW and WW due to the lack of data (described in the 'Characterization of pathogens in waters' section). Modeled *Cryptosporidium* spp. concentrations in onsite WW (mean 3.6–3.7 $\log_{10}$ oocysts per L; Table 2) were near the upper range reported in municipal WW (0.3–3.7 $\log_{10}$ oocysts per L; Hamilton *et al.* 2018); modeled *Norovirus* concentrations (mean 5.6–5.9 $\log_{10}$ gc per L) were 1–2 $\log_{10}$ greater than predicted by recent meta-analyses of available measurement data (3.9 or 4.7 $\log_{10}$ gc per L; Eftim *et al.* 2017). This difference may be associated with greater sensitivity of detection in fresh fecal samples of infected individuals (input for the epidemiological approach) vs. dilute municipal WW, or suggest *Norovirus* decay prior to reaching centralized WW treatment plants in the meta-analysis, in addition to the scaling effects noted above. Indeed, modeled *Norovirus* concentrations agree well with WW measurements from an intermediately sized decentralized system (mean 6.3 $\log_{10}$ gc per L; Jahne *et al.* 2017).

Figures 1–3 illustrate that the predicted risk is sensitive to the selected treatment systems' viral and protozoa treatment removal. The protozoa removal was unreported for the certified MBR systems, and we assumed a conservative LRV. Additional data could change our assessment of the acceptability of the NSF-certified non-potable WW reuse systems from unacceptably high to meeting the more relaxed health benchmark. Our health risk assessment results corroborate the need for additional performance data for MBRs identified in a comprehensive review (Branch 2016), particularly for protozoa given their resistance to subsequent disinfection. The performance of the RSF also remains uncertain given the limited published performance data (see the 'Treatment performance (LRV)' section). The format of Figures 1–3 facilitates LRV sensitivity analysis and updated risk estimates if alternative or system-specific LRV data are generated.

Although the non-potable volume ingested is uncertain (the 'Exposure routes' section), our previous work has illustrated that a 4 $\log_{10}$ decrease in volume has less than a $\log_{10}$ impact on total predicted risk for systems greater than 100 persons (based on the sensitivity analysis presented in Schoen *et al.* (2018b)). Future work will further explore the sensitivity of the LRTs to the ingestion volume assumptions, which remain uncertain for indoor and outdoor irrigation reuse.

CONCLUSIONS

There are several important implications from this work:

- The selected non-potable GW reuse systems that comply with WQSs (but are not risk-based) have a predicted level of health protection that ranges from unknown to comparable with systems that comply with risk-based treatment requirements.
- The selected non-potable WW reuse systems that comply with WQSs (but are not risk-based) have either unknown or unacceptable predicted annual infection risk.
- The pathogen LRTs for 100-person residential systems are slightly reduced from the residential 1,000-person requirements but are much greater than the 5-person single-family residences for protozoa.
- Commercial GW (not including multi-family units) had lower LRTs than similarly sized residential systems due to the difference in predicted pathogen density in the source waters.
- To better characterize pathogen risk for non-potable reuse, improved treatment performance data are required, particularly for virus and parasite removal.
- The variable predicted risks for non-potable reuse systems that comply with conventional water quality measures illustrate that acceptable FIB treatment performance does not ensure adequate treatment removal of viruses and protozoa.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/wh.2020.221.

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