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Review of pathogen treatment reductions for onsite non-potable reuse of alternative source waters

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ABSTRACT

Communities face a challenge when implementing onsite reuse of collected waters for non-potable purposes given the lack of national microbial standards. Quantitative Microbial Risk Assessment (QMRA) can be used to predict the pathogen risks associated with the non-potable reuse of onsite-collected waters; the present work reviewed the relevant QMRA literature to prioritize knowledge gaps and identify health-protective pathogen treatment reduction targets. The review indicated that ingestion of untreated, onsite-collected graywater, rainwater, seepage water and stormwater from a variety of exposure routes resulted in gastrointestinal infection risks greater than the traditional acceptable level of risk. We found no QMRAs that estimated the pathogen risks associated with onsite, non-potable reuse of blackwater. Pathogen treatment reduction targets for non-potable, onsite reuse that included a suite of reference pathogens (i.e., including relevant bacterial, protozoan, and viral hazards) were limited to graywater (for a limited set of domestic uses) and stormwater (for domestic and municipal uses). These treatment reductions corresponded with the health benchmark of a probability of infection or illness of 10^{-3} per person per year or less. The pathogen treatment reduction targets varied depending on the target health benchmark, reference pathogen, source water, and water reuse application. Overall, there remains a need for pathogen reduction targets that are health-protective for non-potable reuse of onsite-collected waters. Also, future QMRA efforts should evaluate the importance of factors that are often overlooked such as the collection scale, sporadic pathogen occurrence, and possibly exposures resulting from misuse or failure events.

Introduction

Decentralized approaches to the reuse of alternative waters for non-potable purposes are of increasing interest in water-stressed regions to reduce pressure on drinking water supplies, as exemplified by the city of San Francisco's active program in non-potable water reuse (San Francisco Public Utilities Commision 2015). The onsite reuse of alternative water involves the collection, treatment, redistribution and reuse of water at different scales from an individual building to a district. For domestic and municipal purposes, potential sources of water for onsite treatment and reuse include:

- *Graywater*: wastewater from bathtubs, showers, bathroom sinks, and clothes washing machines, excluding toilet and—in most cases—dishwasher and kitchen sink wastewaters;
- *Blackwater*: wastewater from toilets and sometimes including kitchen sink wastes;
- *Rainwater*: precipitation collected from roof surfaces or other above ground collection surfaces;
- *Stormwater*: precipitation collected from the ground level; and
- *Seepage water:* precipitation that has passed through soil.

These waters contain both chemical and microbial contaminants that can result in a range of human health outcomes when ingested, inhaled, or absorbed through the skin (Chapman et al. 2008; Deere et al. 2006; McBride et al. 2013). Communities face a challenge when implementing onsite reuse for non-potable purposes given the lack of national microbial standards. NSF/ANSI Standard 350 for non-potable onsite reuse of graywater recommends the monitoring of fecal indicators to test for acceptable finished water quality (NSF International 2015). However, the lack of a relationship between fecal indicators and human-infectious pathogens in graywaters, as well as rainwaters, remains a major problem when relying on fecal indicators to indicate finished water quality and potential human health risk (Ahmed et al. 2011; Ahmed et al. 2010a; O'Toole et al. 2012).

Quantitative Microbial Risk Assessment (QMRA) is a scientific approach that calculates the potential human health risk resulting from exposure to microbial hazards (e.g., human pathogenic viruses,

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protozoa, and bacteria) (Haas et al. 1999). A limited number of QMRAs predicted the potential health risk associated with onsite reuse applications (see the literature review summary in the Results for a full list of studies). These QMRAs followed the traditional steps in a forward process: problem formation, exposure assessment, dose-response assessment, and risk characterization (Haas et al. 1999). In a forward QMRA process, reference hazards are selected for the exposure scenario of interest in the problem formation step; reference hazards represent classes of pathogens with potential adverse health impacts. For the waters listed above, the reference hazards include enteric pathogens resulting from human or animal fecal contamination as well as opportunistic pathogens (e.g., *Legionella pneumophila*) which may grow within the collection and distribution systems (Chapman et al. 2008; O'Toole et al. 2014). In the exposure assessment, the dose of each reference hazard is estimated while accounting for exposures from all intended uses (e.g., for domestic use this may include household and garden exposures) and, for some QMRAs, accidental exposures. Following, the dose is used in a peer reviewed dose-response relationship to estimate the probability of infection (or illness) per person exposed. In the final risk characterization, the resulting predicted risk is compared to a health benchmark either reported as a probability of infection (or illness) or converted to Disability Adjusted Life Years (DALYs) (i.e., the sum of years of life lost by premature mortality and years lived with disability (Murray and Acharya 1997)).

QMRA can also be conducted in the reverse order, starting with a health target, to predict either the tolerable pathogen densities or pathogen treatment requirements. Using the reverse approach, the World Health Organization (WHO) and Australian government published guidelines for pathogen $\log_{10}$ treatment reductions of fecal pathogens (e.g., human pathogenic viruses, protozoa, and bacteria) for a limited number of reuse applications (see Supporting information for more details on the reverse approach used by WHO and others) (NRMMC et al., 2006, 2008, 2009; World Health Organization, 2006b). In the mentioned guidelines, the treatment reductions corresponded to the health benchmark of 10^{-6} DALYs per person per year (ppy). This benchmark is consistent with the WHO Guidelines for Drinking-Water Quality (World Health Organization, 2011) and is approximately equivalent to an annual diarrheal risk of infection of approximately 10^{-3} ppy for *Rotavirus* or *Cryptosporidium* and 10^{-4} ppy for *Campylobacter*.

To identify health-protective pathogen treatment requirements for onsite non-potable reuse, we reviewed the QMRA literature and summarized the human health risks associated with the reuse of onsite-collected waters as well as pathogen treatment reduction targets. We reviewed both the forward and reverse QMRA literature in order to:

1. Identify onsite non-potable reuse scenarios with little or no previous risk assessment;
2. Identify onsite non-potable reuse scenarios that may require pathogen treatment;
3. Summarize reported treatment reductions that correspond with the WHO target health benchmark; and
4. Identify factors that are important for the calculation of pathogen $\log_{10}$ treatment reductions for onsite reuse systems, including gaps in our current understanding.

Methods

We conducted a literature review of QMRA publications to identify assessments of onsite domestic, commercial, and municipal reuse of alternative waters. Databases included Biological Abstracts, Environmental Databases, PubMed, Sci Search, Current Contents, and Waternet. Search terms included (("quantitative microbial risk assessment" OR (QMRA and "risk assessment")) AND (reuse OR re-use OR recycl*) AND ("non-potable water" OR Rainwater* OR stormwater* OR graywater OR graywater* OR wastewater* OR "waste water" OR blackwater*)). The findings from the literature review were converted to median or mean annual probability of infection or illness using the assumptions and calculations from each individual publication. Generally, risk was reported for the individual and not over the population at large. When risk was reported over the population (e.g., annual infection risk per 10,000 people in Ahmed et al. (2010b)), we used the risk divided by the population to avoid reproducing individual risk estimates. In this case, the risk to specific individuals may be higher than the average risk over the population. For studies that reported results for numerous sites or scenarios for the same exposure scenario, we report the highest and lowest predicted risk.

Results

Summary of non-potable reuse publications

The literature search returned 46 publications. Forward QMRA studies with a focus on centralized systems and industrial or agricultural applications were not reviewed. QMRA studies with unreported pathogen removal were not reviewed. Of those remaining, non-potable reuse was modeled in 1 study of wastewater/blackwater (NRMMC et al., 2006), 5 of graywater (Barker et al., 2013a; Deere et al., 2006; Ottoson and Stenström, 2003; Schoen et al., 2014; World Health Organization, 2006b), 5 of stormwater (de Man et al., 2014b; Lim et al., 2015; NRMMC et al., 2009; Page et al., 2012; Sales-Ortells and Medema, 2014), 7 of rainwater (Ahmed et al., 2010b; de Man et al., 2014a; Fewtrell and Kay, 2007; Lim and Jiang, 2013; NRMMC et al., 2009; Oesterholt et al., 2007; Schoen et al., 2014), and 1 of seepage water (Oesterholt et al., 2007). Of the studies on non-potable reuse of blackwater and graywater, onsite applications were specifically addressed or discussed in 0 studies of blackwater and 4 of graywater (Barker et al., 2013a; Deere et al., 2006; Ottoson and Stenström, 2003; Schoen et al., 2014). Page et al. (2012) was not included in the review because it discussed the NRMMC et al. (2009) stormwater QMRA work, but did not present new risk estimates.

Onsite non-potable reuse scenarios ranked by risk

The results of the QMRA literature review are presented for graywater (Fig. 1 and Supporting information Table 1), stormwater (Fig. 2 and Supporting information Table 2), rainwater (Fig. 3 and Supporting information Table 3), and seepage water (Fig. 4 and Supporting information Table 4). In Figs. 1–4, the median or mean $\log_{10}$ pathogen reductions are plotted against the corresponding mean or median annual probability of infection (or illness), as reported in the original studies, for each reference hazard. Multiple predicted risks are presented for reuse scenarios that have more than one risk assessment (e.g., rainwater reuse for toilet flushing). The mid-range value (i.e., mean or median, as reported) of the $\log_{10}$ pathogen reductions is plotted when variable treatment performance was assumed (e.g., graywater reuse for irrigation or stormwater reuse for showering), or, in the case of reverse QMRA, when variability in the pathogen dose was estimated (e.g., graywater reuse for toilet and garden use).

The scenarios with at least one reference pathogen with a reported annual probability of infection greater than 10^{-3} ppy; between 10^{-4} and 10^{-3} ppy; or less than 10^{-4} ppy are listed below. The reference pathogen with the highest probability of infection (or highest required log reduction) for the exposure scenario is listed in parenthesis. When different levels of treatment were applied to the reference pathogens in the same exposure scenario, the pathogen with the highest risk could not be determined in some cases.

Scenarios with annual probabilities of infection greater than 10^{-3} ppy, and ordered with the highest risk first, included:

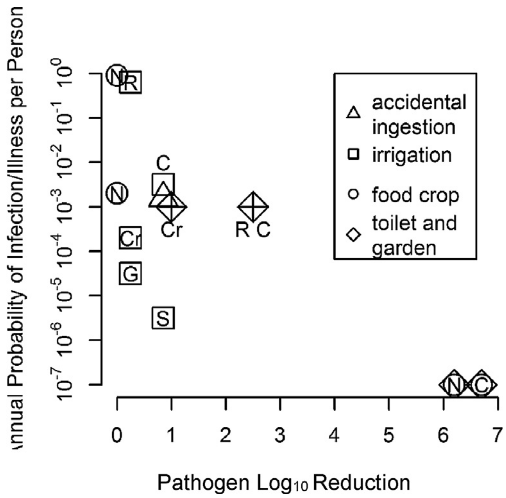

Fig. 1. Pathogen Log_{10} treatment reductions for onsite graywater non-potable reuses and the corresponding annual probabilities of infection (or illness) per person. Reference hazards include: *Rotavirus* (R), *Campylobacter* (C), *Salmonella* (S), *Cryptosporidium* (Cr), *Giardia* (G), and *Norovirus* (N). Risk estimates expressed as annual probabilities of illness (rather than infection) are indicated by "+". Accidental ingestion target reduction corresponds with reference hazard "C". See Supporting information Table 1 for references.

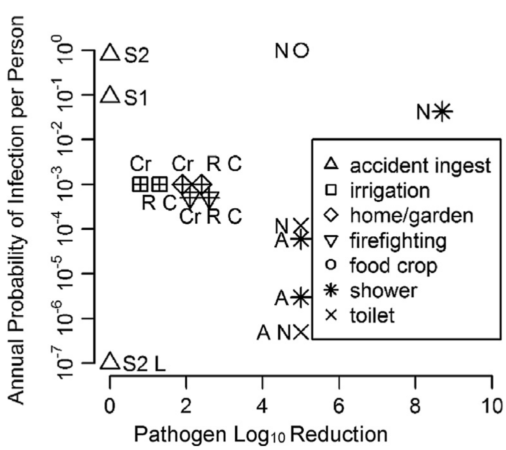

Fig. 2. Pathogen Log_{10} treatment reductions for stormwater non-potable reuses and the corresponding annual probabilities of infection (or illness) per person. Reference hazards include: (A) adenovirus, (N) *Norovirus; Rotavirus* (R); Campylobacter (C); *Cryptosporidium* (Cr); combined *Norovirus, Campylobacter*, and *Cryptosporidium* (S1); combined *Norovirus, Campylobacter, Cryptosporidium, Giardia* and *Enterovirus* (S2). Risk estimates expressed as annual probabilities of illness (rather than infection) are indicated by "+". To avoid overlapping symbols, firefighting symbols are shifted down the *y*-axis. Reference hazards "R" and "C" often have the same predicted target reductions. See Supporting information Table 2 for references.

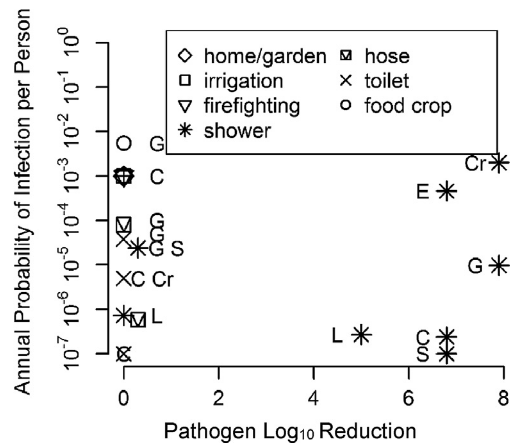

Fig. 3. Pathogen Log_{10} treatment reductions for rainwater non-potable reuse and corresponding annual probabilities of infection (or illness) per person. Reference hazards include: *Campylobacter* (C), *Cryptosporidium* (Cr), *Legionella* (L), *Giardia* (G), *E.coli* 0157:H7 (E), and *Salmonella* (S). Risk estimates expressed as annual probabilities of illness (rather than infection) are indicated by "+". To avoid overlapping symbols, some reference hazards are not presented, and some uses are shifted along the *x*-axis. Target "C" reductions for home/garden, irrigation, and firefighting overlap. See Supporting information Table 3 for references.

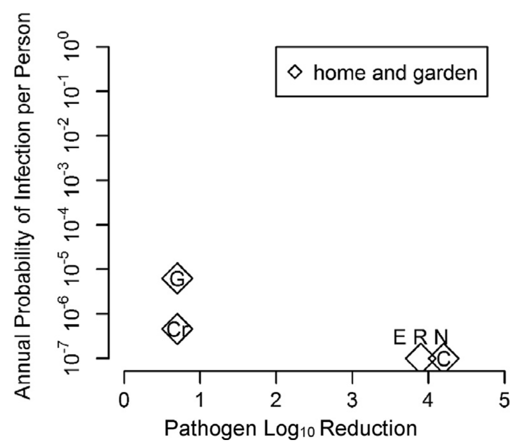

Fig. 4. Pathogen Log_{10} treatment reductions for seepage water non-potable reuse and corresponding annual probability of infection per person. Reference hazards include: *Campylobacter* (C), *Cryptosporidium* (Cr), *Giardia* (G), *E.coli* 0157:H7 (E), and *Norovirus* (N). The original risks reported as "less than". See Supporting information Table 4 for references.

- watering homegrown food crops with untreated graywater (*Norovirus*) (Fig. 1) (Barker et al., 2013a),
- irrigation with minimally treated graywater (Fig. 1) (*Rotavirus*) (Ottoson and Stenström, 2003),
- watering homegrown food crops with treated stormwater (*Norovirus*) (Fig. 2) (Lim et al., 2015),
- accidental ingestion of untreated stormwater (combination of pathogens) (Fig. 2) (de Man et al., 2014b),
- showering with treated stormwater (*Norovirus*) (Fig. 2) (Lim et al., 2015),
- playing in untreated stormwater (combination of pathogens) (Fig. 2) (Sales-Ortells and Medema, 2014),
- accidental ingestion of minimally treated graywater (*Campylobacter)* (Fig. 1) (Ottoson and Stenström, 2003),
- watering homegrown food crops with untreated rainwater (*Salmonella* and *Giardia*) (Fig. 3) (Lim and Jiang, 2013), and
- showering with highly treated rainwater (*Cryptosporidium*) (Fig. 3) (Schoen et al., 2014).

Scenarios with the highest reported annual probabilities of infection (or illness) between 10^{-4} and 10^{-3} ppy included:

- toilet flushing and garden use of treated graywater (*Rotavirus*) (Fig. 1) (Deere et al., 2006),
- toilet flushing with treated stormwater (*Norovirus*) (Fig. 2) (Lim et al., 2015),
- municipal irrigation with treated stormwater (*Rotavirus* and *Campylobacter*) (Fig. 2) (NRMMC et al., 2009),
- toilet flushing, laundry use, watering food crops, and garden irrigation with treated stormwater (*Rotavirus* and *Campylobacter*) (Fig. 2) (NRMMC et al., 2009),
- firefighting with treated stormwater (*Rotavirus* and *Campylobacter*) (Fig. 2) (NRMMC et al., 2009),
- municipal irrigation with untreated rainwater (*Campylobacter*) (Fig. 3) (NRMMC et al., 2009),

Table 1
Pathogen treatment reductions that correspond with an annual probability of infection (or illness) between 10^{-4} and 10^{-3} ppy for non-potable reuse.

Water	Scale[a,b]					Log_{10} Reductions[e]							
	S	M	L	Pathogens [c,d]	Use	0	1	2	3	4	5	6	Reference
Wastewater			X	R, C, Cr	firefighting							X	(NRMMC et al. 2006)
			X	R, C, Cr	home and garden							X	
			X	R, C, Cr	municipal irrigation						X		
Graywater		X		R, C, Cr	toilet and garden		X	X	X				(Deere et al. 2006)
		X		Cr	irrigation	X							(Ottoson and Stenström 2003)
Stormwater		NA		R, C, Cr	home and garden			X					(NRMMC et al. 2009)
				R, C, Cr	firefighting			X					
				R, C, Cr	municipal irrigation		X						
				N	toilet						X		(Lim et al. 2015)
Rainwater		NA		C	home and garden	X							(NRMMC et al. 2009)
				C	firefighting	X							
				C	municipal irrigation	X							
				E	shower							X	(Schoen et al. 2014)

[a] Scale describes the assumptions used to characterize the pathogen density: small (S) is single household, medium (M) is multi-home systems, large (L) is community-wide.
[b] NA is not applicable.
[c] R is *Rotavirus*, C is *Campylobacter*, Cr is *Cryptosporidium*, *N* is Norovirus, E is *E. coli* O157:H7.
[d] *Rotavirus* reductions are displayed (instead of C or Cr) for wastewater, graywater, and stormwater.
[e] Log_{10} Reductions column X represents target reductions in a range $X \leq Log_{10}$ Reductions $< X + 1$. A range of reduction is due to various scenarios assumed for pathogen density.

- toilet flushing, laundry use, watering food crops, and garden irrigation with untreated rainwater (*Campylobacter*) (Fig. 3) (NRMMC et al., 2009), and
- firefighting with untreated rainwater (*Campylobacter*) (Fig. 3) (NRMMC et al., 2009).

The target pathogen reductions that corresponded with the health benchmark of an annual probability of infection (or illness) between 10^{-4} and 10^{-3} ppy (corresponding to 10^{-6} DALYs ppy) for onsite non-potable reuse scenarios are summarized in Table 1.

Scenarios with the highest reported annual probabilities of infection (or illness) less than 10^{-4} ppy included:

- outside hose use with untreated rainwater (*Giardia*) (Fig. 3) (Ahmed et al., 2010b),
- toilet flushing with untreated rainwater (*Giardia*) (Fig. 3) (Fewtrell and Kay, 2007; Oesterholt et al., 2007),
- toilet flushing, laundry use, watering food crops, and garden irrigation with treated seepage water (cannot be determined) (Fig. 4) (Oesterholt et al., 2007), and
- toilet flushing and outside hose use with highly treated graywater (*Norovirus* and *Campylobacter*) (Fig. 1) (Schoen et al., 2014).

Discussion

Onsite non-potable reuse scenarios with little or no previous risk assessment

We found no studies that estimated the pathogen risk associated with the onsite non-potable reuse of blackwater; however, there was guidance on pathogen treatment requirements for the reuse of wastewater from centralized collection systems (NRMMC et al., 2008; World Health Organization, 2006a).

Onsite non-potable reuse scenarios that may require pathogen treatment

Pathogen treatment reductions have already been proposed for stormwater reuse for home and garden, municipal irrigation, and firefighting (Table 1) with a pathogen reduction target greater than zero to achieve an annual probability of illness of approximately 10^{-3} ppy. In addition, reuse scenarios that included consumption of homegrown food crops watered with untreated graywater, irrigation with minimally treated graywater, or the accidental ingestion of minimally treated graywater had predicted annual risks greater than 10^{-3} ppy (Barker et al., 2013a; Ottoson and Stenström, 2003). Presuming that onsite-collected, untreated blackwater has pathogen densities as high as those in untreated graywater, annual risks greater than 10^{-3} ppy apply to the same exposure routes for untreated blackwater as well. If the health benchmark is equivalent to an annual risk of 10^{-3} ppy, then all onsite graywater reuse schemes that include watering of homegrown food crops, irrigation, or accidental ingestion should require pathogen treatment based on the reviewed QMRA estimates of risk.

There was a range in predicted risk from ingestion of rainwater. The predicted annual probability of infection for ingestion of untreated rainwater through homegrown food crop consumption was greater than 10^{-3} ppy (Lim and Jiang, 2013) for reference pathogens *Salmonella* and *Giardia* as well as showering with highly treated rainwater considering *Cryptosporidium* (Schoen et al., 2014); however, the predicted annual probability of infection for ingestion of untreated rainwater through showering was less than 10^{-3} ppy for reference pathogens *Legionella, Giardia*, and *Salmonella* (Ahmed et al., 2010b) and for various uses for *Campylobacter* (NRMMC et al., 2009).

The range in predicted risk for rainwater exposures may partially be due to differing assumptions about input parameters such as volume ingested (e.g., Ahmed et al. (2010b) assumed a daily shower consumption of 8.4×10^{-7} L while Schoen et al. (2014) assumed 1.9×10^{-3} L). The differences in risk are also likely a result of different characterizations of pathogen density and occurrence as a result of natural variability across locations (e.g. different characterizations for *Legionella* and *Giardia* in Ahmed et al. (2010b) vs. Schoen et al. (2014)). Finally, lack of data also likely adds to the differences in prediction. For example, Schoen et al. (2014) assumed that *Cryptosporidium* densities in rooftop-collected rainwater were the same as natural waters due to lack of data. For the Australian guidelines, the rainwater *Campylobacter* density was estimated assuming that rainwater had the same fecal indicator to pathogen ratio as wastewater (NRMMC et al., 2009). So, although Australian reuse guidelines recommend that zero $\log_{10}$ reductions are required for various municipal and domestic reuses of rainwater, there was not consensus among the various rainwater QMRAs that the non-potable reuse of untreated rainwater has annual risks less than 10^{-3} ppy.

Treatment reductions that correspond with a health benchmark for onsite non-potable reuse

We found target pathogen reductions that corresponded with the health benchmark of an annual probability of infection (or illness) between 10^{-4} and 10^{-3} ppy (corresponding to 10^{-6} DALYs ppy) for a limited set of onsite non-potable reuse scenarios (summarized in Table 1). The scenarios included toilet and garden use of treated graywater collected from handbasins and sinks (Deere et al., 2006); irrigation with minimally treated graywater (Ottoson and Stenström, 2003); and firefighting, municipal irrigation, and the combination of toilet flushing, laundry use, watering food crops, and garden irrigation with treated stormwater (NRMMC et al., 2009). However, the stormwater QMRA performed by Lim et al. (2015) using *Norovirus* as reference pathogen indicated that much higher $\log_{10}$ reductions would be required than proposed by NRMMC et al. (2009) for home use. There was a set of target reductions for reuse of rainwater, but only one pathogen was considered, *Campylobacter*, and the rainwater pathogen density was estimated assuming that rainwater had the same fecal indicator to pathogen ratio as wastewater (NRMMC et al., 2009). Also, a rainwater QMRA performed by Schoen et al. (2014) using *E. coli* O157:H7 as reference pathogen indicated that much higher $\log_{10}$ reductions would be required than proposed by NRMMC et al. (2009) for shower use. Seepage water was not included in Table 1 because we found no studies that estimated target pathogen reductions correspond with the selected health benchmark. Table 1 also includes the pathogen reduction recommendations for non-potable reuse of wastewater from large, municipal systems.

Mara et al. (2010) criticized the 10^{-6} DALYs ppy benchmark as too strict for scenarios where more risk may be acceptable. A more lenient tolerable disease burden would result in less stringent pathogen treatment requirements. For a less strict health benchmark, say greater than an infection risk of 10^{-3} ppy, we found no studies with pathogen reduction targets for a complete suite of reference pathogens (e.g., virus, bacteria, and protozoa). If a more strict health benchmark is of interest, we found log reductions that corresponded with low risk scenarios (e.g., seepage water in Oesterholt et al. (2007) or graywater in Schoen et al. (2014)).

Common factors that affect the pathogen treatment requirements

There were numerous common factors that affected the predicted pathogen $\log_{10}$ reductions across scenarios and water types in the papers reviewed. The most obvious factors were water source, reference pathogen, and exposure route. With regard to water source, the Australian guidelines suggested a 2.4 $\log_{10}$ reduction of *Campylobacter* for the reuse of stormwater in the home and a 0.0 $\log_{10}$ reduction of *Campylobacter* for the reuse of rainwater in the home (Supporting information Tables 2 and 3) (NRMMC et al., 2009). Given that all the other input parameters were the same, the difference in the pathogen treatment requirements was due to the differences in pathogen occurrence and density between stormwater and rainwater.

The importance of pathogen density and occurrence was highlighted in many studies that predicted risk, rather than target pathogen reductions (Barker et al., 2013a; Deere et al., 2006; de Man et al., 2014b). For graywater reuse, Barker et al. (2013a) compared the predicted risk from consumption of homegrown crops watered with onsite graywater collected from laundry and bathrooms. The difference between predicted *Norovirus* density in graywater collected from laundry (median of 8.3×10^{-2} no. mL^{-1}) and that collected from bathrooms (median of 4.7×10^{-4} no. mL^{-1}) resulted in a higher predicted annual risk of infection for the reuse of laundry graywater (median range of 2.6×10^{-1}–8.9×10^{-1} ppy) than the collected bathroom graywater (median range of 2.8×10^{-3}–2.3×10^{-2} ppy) (Supporting information Table 1). For rainwater reuse, de Man et al. (2014b) compared the risk resulting from the ingestion of rainfall-generated surface runoff from 5 different sites, each with a separate characterization of pathogen density and ingestion volume. The resulting predictions of event risk of infection for adults ranged from 0 to 2.1×10^{-3} (Supporting information Table 2). These studies highlighted the impact of the variability in pathogen density and occurrence among water types and locations on predicted risk.

The selection of reference pathogen was also important in the calculation of the recommended $\log_{10}$ reductions. The reference pathogens used in the reviewed studies included: for graywater, *Cryptosporidium, Rotavirus, Norovirus, Campylobacter, Salmonella*, and *Giardia*; for stormwater, adenovirus, enteroviruses, *Cryptosporidium, Rotavirus, Norovirus, Campylobacter, L. pneumophila,* and *Giardia;* for rainwater, *Cryptosporidium, Campylobacter, E. coli* O157:H7, *Salmonella, L. pneumophila,* and *Giardia;* and for seepage water, *Cryptosporidium, Rotavirus, Norovirus, Campylobacter, E. coli* O157:H7, and *Giardia.* Given the different treatment levels applied and different modeling assumptions across studies, it was difficult to explicitly rank the pathogens in terms of importance for each water type. However, the viruses, *Norovirus* and *Rotavirus*, had either relatively higher predicted risks or required larger pathogen reductions across studies and exposure routes for graywater (Supporting information Table 1) (Barker et al., 2013a; Deere et al., 2006; Ottoson and Stenström, 2003), and *Norovirus, Rotavirus* and *Campylobacter* required relatively larger pathogen reductions across exposure routes for stormwater (Supporting information Table 2) (Lim et al., 2015; NRMMC et al., 2009).

With regard to exposure route, the NRMMC et al. (2009) results showed a difference in the predicted $\log_{10}$ reduction for different exposure routes using the same pathogen and water source; for example, firefighting with stormwater required a 0.2 and 1.3 higher pathogen reduction than required for home use and municipal irrigation when assuming the same reference pathogens (i.e., *Rotavirus, Campylobacter*, and *Cryptosporidium*) (Supporting information Table 2). A similar trend was reported by NRMMC et al. (2006) for the same exposure routes of centrally collected wastewater (Table 1). These differences were due to the volume of water ingested per event and the frequency of exposure. There was also evidence of the importance of exposure volume and frequency from the studies that predicted risk, rather than target pathogen reductions. de Man el at. (2014a) showed differences in predicted risk between adults and children due to different ingested volumes of urban stormwater and contact exposure time (Supporting information Table 2). de Man et al. (2014a) also demonstrated through sensitivity analysis that increased frequency of exposure resulted in increased annual predicted risk for adults and chlidren. Lim and Jiang (2013) showed through sensitivity analysis that variations in the consumption rate of crops and pathogen concentration were equally significant in predicting infection risk.

A less obvious factor that was also important in the calculation of target pathogen reductions was the inclusion of intentional or unintentional misuse of treated water that results in large ingestion volumes. Deere et al. (2006) reported higher treatment requirements when misuse or accidental events (i.e. cross-connection of non-potable water with potable water) were considered in the calculation of the pathogen $\log_{10}$ reduction (Supporting information Table 1).

There are a number of issues that may be important in the calculation of target pathogen reductions, but have not been thoroughly explored in the reviewed studies. Although the importance of the variability in pathogen density and occurrence among water types and locations was identified, there remains disagreement as to the best approach to characterize or estimate the pathogen density and occurrence when data is scarce or missing. Multiple approaches for characterizing pathogen density without observations have been discussed for graywater (Deere et al., 2006; O'Toole et al., 2014) and wastewater (Barker, 2014; Keuckelaere et al., 2015). In general, pathogen densities can be estimated using: (1) a ratio of the densities of fecal indicators to pathogen, or (2) an estimate of the incidence of pathogen illness in the population to estimate the occurrence of the pathogen in the collected waters in combination with an estimate of the density of fecal contamination in the collected waters. Barker et al. (2013a) compared the predicted *Norovirus* density in bathroom water using two alternative approaches, one based on disease incidence and the other based solely on fecal indicators, and the fecal indicator approach resulted in higher risk estimates. When pathogen density observations include non-detections, Lim et al. (2015) employed a left-censored data regression technique (Tobit regression) to characterize stormwater pathogen density, and Lim and Jiang (2013) used a two-step process to characterize pathogen density in rainwater using an estimate of the pathogen occurrence in rainwater based on the non-detection rate and a distribution of pathogen density using the detected pathogen densities.

Another potental important factor is the influence of scale on the pathogen density and occurrence. Again, we are not aware of any studies that estimated changes in target pathogen reductions for non-potable reuse due to changes in scale. However, Barker et al. (2013b) demonstrated that the pathogen density may be extremely high in onsite blackwater collection systems during times of outbreak, and more treatment may be required to meet acceptable levels of risk for potable reuse than required for centrally collected systems. This finding suggests that the maximum expected pathogen density maybe inversely related to the number of people contributing to a collection system for graywater and blackwater reuse. Further quantification of the importance of scale is needed.

A separate, but potentially important, issue is the method of calculating the log reductions. The Supporting information details the steps for three reverse methods from the reviewed papers, two are deterministic and one is stochastic. The deterministic approaches estimate the tolerable pathogen density for a scenario, either assuming multiple identical exposure events (World Health Organization 2006) or accumulating the pathogen exposures into an annual dose and exposure volume (NRMMC et al., 2006). The stochastic approach proposed by Barker et al. (2013b) incorporates variability in the characterization of *Norovirus* density, number of exposure events throughout the year, disease burden per case of illness, volume of exposure, and susceptible fraction. Barker et al. (2013b) compared the predicted $\log_{10}$ reductions for potable reuse of centralized wastewater using the simple, deterministic reverse approach and the stochastic reverse method. The 95th percentile of the $\log_{10}$ reduction distribution using the full stochastic approach for *Campylobacter* of 7.4 was less than the reduction of 7.7 using comparable inputs and the deterministic, simple approach.

A limitation of the reverse approaches is that all the events over the course of one year are assumed identical. We are not aware of any studies that compared the log reductions estimated using a reverse approach (with assumed identical events over the course of a year) with an alternative approach to account for the sporadic and variable pathogen density across events for the reuse of onsite waters.

Finally, we are not aware of any studies that estimated changes in target pathogen reductions due to changes in the health benchmark; however, using the methods commonly reported and described in the Supporting information, a decrease/increase in the health benchmark would result in a decrease/increase in the required log reductions. The change in the target pathogen reduction is not necesarily linear, but determined by the dose-reponse relationship of the reference pathogen.

The above factors are potentially important in the calculation of the pathogen $\log_{10}$ reductions for all (or most) onsite, non-potable reuse scenarios. Other factors, that are unique to either each water source or exposure route, have been identified and may also require additional research to inform the estimation of pathogen $\log_{10}$ reductions (e.g. fraction of infectious pathogens in rainwater (Ahmed et al., 2011; Schoen et al., 2014) or pathogen persistence on food crops (Keuckelaere et al., 2015)).

Recommendations for the calculation of target pathogen reductions for onsite systems

This review identified a lack of available target pathogen $\log_{10}$ reductions for non-potable, onsite reuse of graywater, blackwater, and seepage water, and conflicting evidence about the level of treatment required to be health protective for stormwater and rainwater. This review also identified numerous onsite exposure scenarios that were associated with risk levels, as determined by QMRA, above the traditional health benchmarks. Given these findings, there remains a need for additional QMRA to inform the selection of pathogen reduction targets that are health-protective for non-potable reuse of onsite-collected waters.

Future QMRA efforts to estimate target pathogen treatment reductions could be conducted using the reverse approaches outlined in the Supporting information and verified by an iterative forward approach where the pathogen reduction is changed until the health benchmark is met. A forward approach would allow the inclusion of factors either missing or difficult to incorporate in the reverse approach such as sporadic and variable pathogen occurrence and densities, variation in pathogen dose over time, and occasional system misuse or failure events.

To avoid drafting new guidance, decision makers may look toward guidance developed for conventionally-collected and treated wastewater as a starting point (see Table 1) (NRMMC et al., 2006; NRMMC et al., 2009; World Health Organization, 2006a, 2006b). For reuse of rainwater and stormwater, the conventionally collected and treated wastewater reductions may be too restrictive (see Table 1). However, the opposite may be true for blackwater. The pathogen density may be extremely high in onsite blackwater collection systems during times of outbreak, and more treatment may be required to meet acceptable levels of risk than required for centrally-collected systems (Barker et al. 2013b). Overall, there remains a need for additional QMRA to evaluate the importance of the characteristics of onsite systems in the prediction of pathogen treatment reductions including scale and pathogen density and occurrence.

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Supplementary Materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.mran.2015.10.001.

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