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Pathogen reduction requirements for direct potable reuse in Antarctica: Evaluating human health risks in small communities

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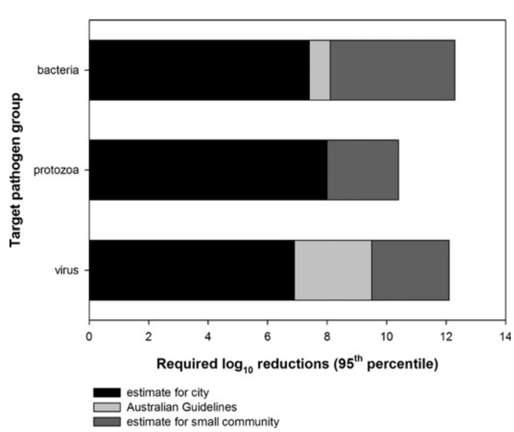
HIGHLIGHTS

- Direct potable reuse (DPR) projects should consider population size.
- Small community pathogen load in outbreak sewage is higher ($p<0.001$) than municipal.
- LRVs for municipal sewage: 6.9 (norovirus), 8.0 (giardia), 7.4 (Campylobacter).
- LRVs for small community: 12.1 (norovirus), 10.4 (giardia), 12.3 (Campylobacter).
- Additional treatment barriers required for small community DPR to meet 10−6 DALYs.

GRAPHICAL ABSTRACT



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ABSTRACT

Small, remote communities often have limited access to energy and water. Direct potable reuse of treated wastewater has recently gained attention as a potential solution for water-stressed regions, but requires further evaluation specific to small communities. The required pathogen reduction needed for safe implementation of direct potable reuse of treated sewage is an important consideration but these are typically quantified for larger communities and cities. A quantitative microbial risk assessment (QMRA) was conducted, using norovirus, giardia and *Campylobacter* as reference pathogens, to determine the level of treatment required to meet the tolerable annual disease burden of 10^{-6} DALYs per person per year, using Davis Station in Antarctica as an example of a small remote community. Two scenarios were compared: published municipal sewage pathogen loads and estimated pathogen loads during a gastroenteritis outbreak. For the municipal sewage scenario, estimated required $\log_{10}$ reductions were 6.9, 8.0 and 7.4 for norovirus, giardia and *Campylobacter* respectively, while for the outbreak scenario the values were 12.1, 10.4 and 12.3 (95th percentiles). Pathogen concentrations are higher under outbreak conditions as a function of the relatively

Abbreviations: DALYs, disability adjusted life years; DPR, direct potable reuse; IPR, indirect potable reuse; LRV, $\log_{10}$ reduction values; QMRA, quantitative microbial risk assessment.

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Norovirus
Quantitative Microbial Risk Assessment (QMRA)
Sewage

greater degree of contact between community members in a small population, compared with interactions in a large city, resulting in a higher proportion of the population being at risk of infection and illness. While the estimates of outbreak conditions may overestimate sewage concentration to some degree, the results suggest that additional treatment barriers would be required to achieve regulatory compliance for safe drinking water in small communities.

1. Introduction

Small remote communities sometimes struggle to adequately meet basic services such as power and water. In Australia, for example, there are many small remote communities. This is exemplified by the many remote indigenous communities, with nearly 13% of people living in the 838 communities with a population of less than 50 people and a significant number in communities with between 50 and 199 residents (ABS, 2008). More than half of the people living in remote indigenous communities rely on bore water as their main water source, 62% rely on community generators for electricity, only 30% are connected to a town sewerage system while 28% and 3.2% use septic tanks or pit toilets, respectively and high proportions of people experience interruptions in supply of services (ABS, 2008). In some of these communities, where water scarcity is an issue of concern, alternative sources of water may be needed. While recent droughts in Australia were accompanied by a drastic rise in the domestic use of grey water (ABS, 2007a, 2010a, 2010b), alternative sources of potable water have received less attention.

Indirect potable reuse schemes for the recycling of wastewater (IPR is the discharge of treated water into a receiving body prior to extraction and re-treatment for potable use) can be found in many countries; however, direct potable reuse (DPR is reuse without environmental mixing) is rare. There are currently only three DPR schemes in the world: Windhoek in Namibia (Lahnsteiner and Lempert, 2007), Cloudcroft in New Mexico and Big Springs in Texas (Tchobanoglous et al., 2011). While the more immediate driver of DPR is extreme water scarcity, various other factors also favor DPR systems, including whole-of-system life-cycle costs, reliability of water supply and quality and the exhaustion of economically feasible non-potable reuse options (Leverenz et al., 2011). An important consideration for system design and operation is the impact of population size on disease outbreaks, sewage quality and ultimately the required level of treatment. A greater understanding of these impacts is needed before the technology is implemented broadly.

Quantitative microbial risk assessment (QMRA) is a useful tool to assess pathogen reduction requirements for wastewater recycling and has been used to inform the regulatory environment relevant to wastewater schemes for non-potable reuse, IPR and DPR scenarios (NRMMC et al., 2006b; NRMMC et al., 2008; NRMMC et al., 2009; WHO, 2006). Reuse guidelines are usually based on water quality characteristics of municipal sewage from large cities and, using a tolerable annual disease burden of $\leq 10^{-6}$ disability adjusted life years (DALYs) per person per year, QMRA has been used to inform guidelines where recommended pathogen $\log_{10}$ reduction values (LRV) are presented (NRMMC et al., 2008). Municipal sewage is typically of consistent or relatively stable quality, as a function of the dilution effect from a large population base (NRMMC et al., 2008), although differences between peak and non-peak seasons may be detectable; for example norovirus concentrations in sewage may be up to 1 or 2 logs units higher during peak season (Katayama et al., 2008; Nordgren et al., 2009; Victoria et al., 2010). Localized disease outbreaks and changes in population size may significantly alter sewage microbial quality from a small population, potentially affecting treatment requirements.

The objective of this study was to determine the required LRVs for DPR in small communities as this has not been specifically considered in reuse guidelines. While any of a number of small remote communities could have been chosen as a representative population for the model, Davis Station, the largest of three permanent Australian research stations in Antarctica, was selected for this exercise as there is current interest in DPR. The Australian Antarctic Division is undertaking a project to reduce the environmental impact of sewage treatment and disposal at Davis Station. As part of this project, research is being conducted into the potential implementation of DPR which, in addition to providing a reliable potable water supply, could provide considerable energy savings as compared with the existing water system. While Davis Station may not be a typical small community, only minor modifications (volume of drinking water and days of exposure) would be required to adequately reflect other populations. Regardless, the results of this assessment were considered generalizable to a range of other small communities, of which there are many in Australia and around the world.

2. Methods

The focus of this model was human health risks from waterborne pathogens, in particular diarrheal diseases, from ingestion of treated drinking water. Two complementary approaches were employed to estimate sewage pathogen concentrations: published values from municipal sewage treatment plants and estimated gastroenteritis outbreak conditions. Further detail is provided in supplementary materials.

2.1. QMRA

The QMRA method was used to determine required LRVs for direct potable reuse of wastewater starting from a health target—a tolerable annual burden of disease (DB) of $\leq 10^{-6}$ DALYs person^{-1} year^{-1}—that has been widely adopted for both drinking water and non-potable reuse (NRMMC et al., 2006b; WHO, 2006; WHO, 2011). All model input parameters are listed in Table 1. Using the annual burden of disease calculation

$$DB = P_{ill} B S_f, \qquad (1)$$

the tolerable annual probability of illness (P_{ill}) was determined, where B is the disease burden (DALYs per case of illness) and S_f is the proportion of the population susceptible to the disease.

While country-specific estimates of disease burden (B) are preferred, they are often non-existent. In this model, published values from a range of countries were used. For norovirus, a Uniform distribution (Cressey and Lake, 2009; Haagsma et al., 2008; Kemmeren et al., 2006; Lake et al., 2010; Masago et al., 2006) was used to represent the range of available values and similarly using Dutch data for giardia (Havelaar, 2012; Vijgen et al., 2007) and *Campylobacter* (Havelaar, 2012; Havelaar and Melse, 2003).

Disease susceptibility (S_f) is used to exclude the proportion of the population shown to be resistant to infection. There is evidence of resistance to norovirus infection (Johnson et al., 1990; Lindesmith et al., 2003; Teunis et al., 2008) related to both histo-blood group antigens and secretor status (Le Pendu, 2006) although it has been suggested