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Microbial quality of reclaimed water for urban reuses: Probabilistic risk-based investigation and recommendations

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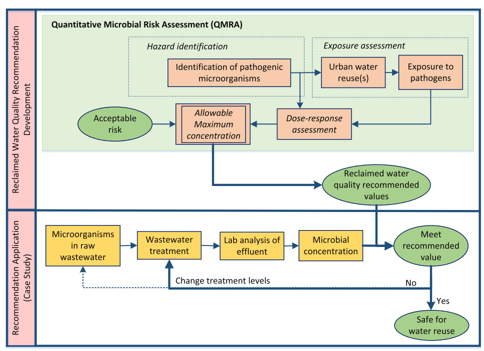
HIGHLIGHTS

- No universal guidelines exist for reclaimed water use.
- This study investigates the microbial quality of reclaimed water for urban reuses.
- Recommended values for microbial water quality have been proposed for urban reuses.
- The knowledgebase on dose-response modelling needs further development.

GRAPHICAL ABSTRACT



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ABSTRACT

Although Canada has abundant freshwater resources, many cities still experience seasonal water shortage. Supply-side and demand-side management is a core strategy to address this water shortage. Under this strategy, reclaimed water, which the Canadian public is willing to use for non-potable purposes, is an option. However, no universal guidelines exist for reclaimed water use. Despite the federal government's long-term goal to develop guidelines for many water reuse applications, guidelines have only been prescribed for reclaimed water use in toilet and urinal flushing in Canada. At the provincial level, British Columbia (BC) has promulgated guidelines for wide applications of reclaimed water but only at broad class levels. This research has investigated and proposed probabilistic risk-based recommended values for microbial quality of reclaimed water in various non-potable urban reuses. The health risk was estimated by using quantitative microbial risk assessment. Two-dimensional Monte Carlo simulations were used in the analysis to include variability and uncertainty in input data. The proposed recommended values are based on the indicator organism *E. coli*. The required treatment levels for reuse were also estimated. In addition, the recommended values were successfully applied to three wastewater treatment effluents in the Okanagan Valley, BC, Canada. The health risks associated with other bacterial pathogens (*Campylobacter jejuni* and *Salmonella* spp.), virus (adenovirus, norovirus, and rotavirus), and protozoa (*Cryptosporidium parvum* and *Giardia* spp.), were also estimated. The estimated risks indicate the effectiveness of the *E. coli*-based water quality recommended values. Sensitivity analysis shows the pathogenic *E. coli* ratio and morbidity are the most sensitive input parameters for all water reuses. The proposed recommended values could be further improved by using national or regional data on water exposures, disease burden per case, and the susceptibility fraction of population.

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1. Introduction

Canada has abundant freshwater supplies and is one of the water richest countries in the world based on per capita water availability (Asano et al., 2007; WRI, 2001). However, there is a large regional disparity in water availability. The annual precipitation of Canada is approximately 600 mm, ranging from 100 mm in the high Arctic to over 3500 mm along the Pacific Coast. Many agricultural lands in the Prairies and British Columbia (BC) interior receive an average annual precipitation of 300 to 500 mm (Schaefer et al., 2004). In 1994–99, about 26% of municipalities with water supply systems experienced water shortage due to droughts, deteriorating infrastructure, and increased consumption (Environment Canada, 2004). In addition, the water and wastewater infrastructure conditions are anticipated to decline in the future due to inadequate reinvestment (Canadian Infrastructure Report Card, 2016).

Water supply in urban areas is especially challenged by increasing population (Lallana et al., 2001; Schaefer et al., 2004), lower household occupancy (Inman and Jeffrey, 2006), higher cost of water and expanding supplies (Fagan et al., 2010; Schaefer et al., 2004), lifestyle changes (Princen, 1999; Lallana et al., 2001), and variability in source water due to climate change (IPCC, 2014). These factors result in increasing water demands and competition among water utilities even across the provincial and national boundaries (Schaefer et al., 2004). In recent times, seasonal water shortage has been experienced in various regions of Canada. Several cities in BC and Alberta, such as Vancouver, the Cowichan valley, Penticton, and Calgary undergo water restrictions in summer (Gulerian, 2015; Water Conservation Company, 2015). Water restriction is the municipal regulation to restrict water use in relatively less important activities. Some cities may even reach the severe Stage 3 restriction prohibiting certain water uses, such as lawn irrigation, park irrigation, residential vehicle washing, street cleaning, and outdoor decorative water features.

Water resources management requires careful planning to address urban water shortage and the associated uncertainties. Supply-side and demand-side management is a core strategy for water resources management (Kanta and Zechman, 2014; Schaefer et al., 2004). Supply-side management includes water availability augmentation, water infrastructure expansion related to water, and new water source development, whereas demand-side management incudes water conservation activities, leakage control, and price setting (Kanta and Zechman, 2014). Under supply-side management, reclaimed water use is an option. Reclaimed water refers to the municipal wastewater that is treated to meet specific water quality criteria, specially intended for beneficial uses. The term recycled water is also synonymously used for reclaimed water (Asano et al., 2007). Reclaimed water is an on-site water resource that can be generated at or near the vicinity of urban water consumption. Reclaimed water can be used for various purposes after treatment.

However, reclaimed water use can have human health risks, primarily associated with pathogenic microorganisms, disinfection by-products (DBPs), and pharmaceutical and personal care products (PPCPs). Pathogenic microorganisms in water primarily originate from sewage (faeces) contamination (EPHC/NHMRC/NRMMC, 2008) and also from natural freshwater bodies containing pathogens, such as *Lagionella* and *Aeromonas* (Health Canada, 2013a). DBPs are created during water disinfection, primarily by the reaction of natural organic matter contained in water and chemical disinfectants (Tian et al., 2013). PPCPs may be present in treated water due to their presence in wastewater, which may not have been effectively removed during wastewater treatment (Kosma et al., 2014). This research is focused only on the human health risk associated with pathogenic microorganisms. Several groups of wastewater microorganisms have been identified as being pathogenic (EPHC/NHMRC/NRMMC, 2008): a) Bacteria, e.g., *Campylobacter*, Pathogenic *Escherichia coli*, *Shigella*, *Lagionella*, *Salmonella*, and *Vibrio cholera*; b) Viruses, e.g., adenovirus, rotavirus, norovirus, enterovirus, and hepatitis A; c) Protozoa, e.g., *Cryptosporidium* and *Giardia;* and d) Helminths, e.g., *Taenia* (tapeworm), *Ascaris* (roundworm), *Trichuris* (whipworm), and *Ancylostoma* (hookworm). The human health risks posed by wastewater microorganisms have been estimated by quantitative microbial risk assessment (QMRA) since the 1980s (Haas et al., 2014).

Globally, no standard guidelines exist for reclaimed water use. Indeed, the development of a practical guideline is complex. The complexity can be understood from the historical development of the reclaimed water use guidelines by the leading health organization – World Health Organization (WHO). The WHO published *Health guidelines for the use of wastewater in agriculture and aquaculture* in 1989 as a 76-page report and prescribed microbiological quality guideline values for wastewater reuse in agriculture (WHO, 1989). The same organization published *WHO guidelines for the safe use of wastewater, excreta and greywater* in 2006 in four volumes with some of them above 200 pages for agriculture and aquaculture (WHO, 2006a). However, the risk-based four-volume guidelines have not prescribed any guideline value, rather procedures for developing guideline values suitable to local circumstances (WHO, 2006a), indicating the practical complexity involved.

At the federal level, Canada has the national plumbing code with an installation guide: *Design and installation of non-potable water systems/ maintenance and field testing of non-potable Water Systems* (Canadian Standards Association, 2011) and a treatment guide: *Performance of non-potable water reuse systems* (Canadian Standards Association, 2012). The treatment guidelines have been prescribed for very small water use systems with a capacity of 10,000 L/d or less and does not cover custom-engineered systems (AEDA, 2013; Canadian Standards Association, 2012). In addition, Canada has reclaimed water quality guidelines at the federal level: *Canadian guidelines for domestic reclaimed water for use in toilet and urinal flushing* (Health Canada, 2010). The federal guidelines are prescribed only for toilet and urinal flushing. The federal government has a long-term goal to develop reclaimed water use guidelines for many beneficial purposes besides toilet and urinal flushing (Health Canada, 2010).

At the provincial level, BC promulgated Municipal Wastewater Regulation (MWR) in 2012, which is a holistic legislation for reclaimed water applications in non-potable and potable uses. The regulation has proposed guidelines for broad water reuse classes (MWR, 2012): a) *Indirect potable reuse*, b) *High exposure potential* (e.g., agricultural and lawn irrigation, and toilet flushing) c) *Moderate exposure potential* (e.g., commercially processed agricultural crop irrigation, pasture, and nurseries) and d) *Low exposure potential* (e.g., industrial process water, dust control, and concrete production). The provincial approach is different from the federal approach that has prescribed guidelines for specific water reuse applications, e.g., toilet and urinal flushing.

Public perception plays an important role in reclaimed water use. A Canada-wide survey on the public perception on reclaimed water use was conducted by Dupont (2013). The survey results show that at least 80% or more of people are willing to use reclaimed water for toilet flushing and irrigating garden grass and flowers, public parks, and golf courses. In addition, for the irrigation of agricultural crops and garden vegetables, respectively 75% and 64% of people are willing to use reclaimed water. Moreover, they are willing to pay an additional annual amount of $142 to $155 per household for using reclaimed water to avoid water restrictions. The willingness to pay is approximately an additional 33% to their annual water bills. The results are consistent with another study on public attitudes on reclaimed water use in several cities in the Lake Simcoe Region in Ontario (LSRCA, 2010). This public willingness shows that water reuse has a large potential in Canada in non-potable urban purposes.

Based on the long-term goal of the Canadian federal government, the recommendations of WHO, existing urban water shortage, and public willingness for water reuse, further research is required for investigating and developing reclaimed water use guidelines for specific reuses in non-potable purposes besides toilet and urinal flushing. Furthermore, a probabilistic approach can be applied to analyze