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Assessment of public health risk associated with viral contamination in harvested urban stormwater for domestic applications

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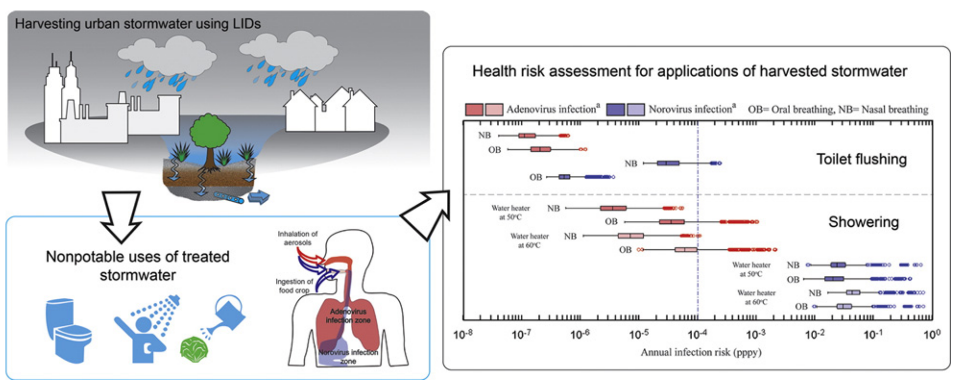
HIGHLIGHTS

- Human health risks for three non-potable uses of treated stormwater are modeled.
- Crop irrigation poses the highest risk, followed by showering and toilet-flushing.
- Only toilet-flushing is deemed acceptable based on the U.S. EPA risk benchmark.
- Both toilet-flushing and showering are within the WHO recommended disease burdens.

GRAPHICAL ABSTRACT



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ABSTRACT

Capturing stormwater is becoming a new standard for sustainable urban stormwater management, which can be used to supplement water supply portfolios in water-stressed cities. The key advantage of harvesting stormwater is to use low impact development (LID) systems for treatment to meet water quality requirement for non-potable uses. However, the lack of scientific studies to validate the safety of such practice has limited its adoption. Microbial hazards in stormwater, especially human viruses, represent the primary public health threat. Using adenovirus and norovirus as target pathogens, we investigated the viral health risk associated with a generic scenario of urban stormwater harvesting practice and its application for three non-potable uses: 1) toilet flushing, 2) showering, and 3) food-crop irrigation. The Quantitative Microbial Risk Assessment (QMRA) results showed that food-crop irrigation has the highest annual viral infection risk (median range: 6.8×10^{-4}–9.7×10^{-1} per-person-per-year or pppy), followed by showering (3.6×10^{-7}–4.3×10^{-2} pppy), and toilet flushing (1.1×10^{-7}–1.3×10^{-4} pppy). Disease burden of each stormwater use was ranked in the same order as its viral infection risk: food-crop irrigation > showering > toilet flushing. The median and 95th percentile risk values of toilet-flushing using treated stormwater are below U.S. EPA annual risk benchmark of $\leq 10^{-4}$ pppy, whereas the disease burdens of both toilet-flushing and showering are within the WHO recommended disease burdens of

Abbreviations: DALYs, disability adjusted life years; GI, genogroup I; GII, genogroup II; LID, low impact development; MNV, murine norovirus; NRMMC–EPHC–NHMRC, Natural Resource Management Ministerial Council–Environment Protection and Heritage Council–National Health and Medical Research Council; OSHA, Occupational Safety and Health Administration; PFU, plaque forming units; pppy, per-person-per-year; QMRA, Quantitative Microbial Risk Assessment; $TCID_{50}$, median tissue culture infectious dose; U.S. EPA, United States Environmental Protection Agency; WHO, World Health Organization; WSUD, water sensitive urban design.

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$\leq 10^{-6}$ DALYs pppy. However, the acceptability of showering risk interpreted based on the U.S. EPA and WHO benchmarks is in disagreement. These results confirm the safety of stormwater application in toilet flushing, but call for further research to fill the data gaps in risk modeling as well as risk benchmarks.

1. Introduction

Sustainable urban stormwater management is emerging as one of the solutions to alleviate the negative impact of rapid urbanization. Stormwater harvesting systems are receiving attentions from the water sectors following the revived interest in rainwater harvesting in intermittently drought-ridden regions (Fletcher et al., 2008; Grant et al., 2013; Hatt et al., 2006). The rationale for harvesting stormwater for beneficial uses is to capture the excess stormwater before it contaminates the receiving water body and changes the stream hydrology, while providing a new source of water supply that may require less treatment than sewage for various non-potable uses. Development of stormwater harvesting systems as a water source, however, is often impeded by social and institutional barriers resulting from a complicated mix of risk perceptions by multiple stakeholders (Dobbie and Brown, 2012). While there is an increasing recognition that other associated risks such as technical, socio-economics, and environmental risks also play influential roles in risk management, public health risk has been the focal point of technical risk assessment that guides risk management within the water sector in developed countries.

Stormwater is water that is collected by storm drain systems without any engineered treatment, and can include urban runoff from irrigation, car washes, and rainwater that is intercepted by paved surface. In urban settings stormwater carries a large number of chemical and microbiological pollutants, which have a detrimental impact to coastal water quality (e.g., Ahn et al., 2005; Handler et al., 2006; Lipp et al., 2001). Stormwater collection systems are usually underground channels that are separated from—but often in close proximity to—sanitary sewer lines. Many of these systems in older cities suffer leakage, which results in unintended cross-contamination of the two types of water (Brownell et al., 2007; Jiang, 2006; Sidhu et al., 2012). A review of stormwater harvesting practices in Australia (Hatt et al., 2006) identified that most of the stormwater (in ~60% of the large-scale systems) collected using conventional urban drainage techniques such as gutters, pipes, and channels, is contaminated by sewage. In spite of the presence of contaminants, harvested stormwater should require less treatment than sewage if it is to be used for non-potable purposes, such as toilet-flushing, irrigation of lawns, car washing, and laundry. Sustainable urban water management systems, frequently termed low-impact development (LID) systems in the U.S. or water-sensitive urban design (WSUD) in Australia, are presumed to be able to provide passive treatment of stormwater that is needed for its safe non-potable uses with much less energy requirements than conventional water treatment technologies (Fletcher et al., 2013; Hatt et al., 2006). These systems include biofilters, rain gardens, bioswales and filter strips, as well as wetlands and ponds. Ultimately, the main concern of using harvested stormwater for household uses lies in the transmission of pathogens to humans, which may translate to disease outbreak in more severe cases.

Human-specific fecal waste markers have been detected in urban stormwater in the cities of U.S. (Sauer et al., 2011) and Australia (Sidhu et al., 2013, 2012; Tang et al., 2013), in which human enteric viruses generally pose the greatest threat to public health (Scallan et al., 2011). Of these, noroviruses' high potency to cause gastroenteritis (Lopman et al., 2011) and adenoviruses' ubiquitous presence in environmental waters (Jiang, 2006) have rendered them two of the most studied viruses. Adenoviruses, double stranded DNA viruses, contain 51 known serotypes. Illnesses associated with adenoviruses range from acute respiratory disease, pneumonia, conjunctivitis, and gastroenteritis, all of which could potentially be transmitted environmentally through non-potable uses of harvested stormwater (Arnone and Walling, 2007). Noroviruses are frequently reported as the leading cause of viral gastroenteritis outbreaks worldwide, with some literature estimating that they account for ~50% of all gastroenteritis cases (Lopman et al., 2012; Patel et al., 2009).

Direct measurements of viral concentration in stormwater, however, are sparse due to the difficulties facing the quantification technologies, which are often plagued by poor recoveries in environmental water and inhibitory effects of PCR used for detecting viral genomes (Rajal et al., 2007). Our previous work has shown that viruses were more frequently detected in the receiving water affected by urban stormwater flow than directly from the stormwater itself due to the PCR inhibition and co-concentrated suspended solids (Choi and Jiang, 2005; Jiang et al., 2001; Jiang and Chu, 2004; Jiang et al., 2007). In fact, a molecular quantitative analysis of human viruses in stormwater conducted by Rajal et al. (2007) yielded results that effectively comprise of non-detects only.

These challenges in enumerating enteric viruses in stormwater have translated to a very poor understanding of removal by basic treatment processes. In fact, the only removal efficacy study for stormwater treated through a LID system (biofilters in this case) is for the removal efficiency of an indicator virus, F-RNA coliphage (Li et al., 2012), and not human-pathogenic viruses.

Consideration of risk associated with stormwater reuse needs to look beyond the water quality itself to include the various ways in which the water is likely to be used. Toilet flushing, showering, and food-crop irrigation are three likely uses, yet they represent distinctly different pathogen-human transmission routes and different infection sites (respiratory vs. intestinal system). Variation within such systems can also be significant. For instance, flush energy associated with different types of toilets can result in marked variation in aerosol production, with high-energy toilets generating larger droplets and greater aerosol production (Johnson et al., 2013). Rapid gravitational sedimentation or shrinkage of large aerosol droplets usually occurs in the first 15–30 s immediately after flushing, and the dynamic regime of aerosol concentration in the air translates to inconsistent results across the literature (Johnson et al., 2013; O'Toole et al., 2009). Complicating matters further, the deposition rate of aerosols in the respiratory system varies with physical properties of aerosol, such as size, density, and shape, and also the breathing patterns of humans (e.g., breathing cycle, breathing intensity) (Heyder et al., 1986). While most individuals breathe predominantly through the nose, habitual and obligatory nasal-oral breathers are not uncommon (Warren et al., 1988). These are important considerations as our noses retain and remove large deposited particles through mucociliary clearance (up to 83% for 2.5–10 μm particles) before they reach human's lower respiratory tract (Couch et al., 1966; Fry and B.A., 1973). Particles deposited within macrophages or upon the mucus layer itself are primarily cleared to the gastrointestinal tract, which represents a transmission pathway for pathogens causing gastrointestinal illness (Stuart, 1984).

Similarly, the size distribution of aerosols produced by shower heads varies as a function of the water flow rate, water temperature, relative humidity, and also configuration of the shower room (e.g., ventilation) (Zhou et al., 2007). In addition, an individual's shower temperature preference is greatly influenced by season. Heating shower water can also affect risk. Viruses can be inactivated thermally, the kinetics of which are determined by the water temperature, contact time, and also the types of viruses (Bozkurt et al., 2013; Maheshwari et al.,