Reuse of Stormwater and Rainwater in Minnesota

A PUBLIC HEALTH PERSPECTIVE

January 2022

DEPARTMENT
OF HEALTH

CLEAN
WATER
LAND &
LEGACY
AMENDMENT

Reuse of Stormwater and Rainwater in Minnesota

Minnesota Department of Health
Environmental Health Division
St. Paul, MN 55155
651-201-4700
www.health.state.mn.us

To obtain this information in a different format, call: 651-201-4700.

Contents

Glossary

Aerosol: Tiny particles or droplets in the air, such as dusts, mists, or fumes.

Concentration: The amount of a component in a given area or volume. Example: Two *Cryptosporidium* oocysts in one liter of water or two oocysts/L.

Enteric pathogen: A microbe that affects the gastrointestinal track (stomach and intestines) and can make a person sick.

Fecal indicator bacteria (FIB): Bacteria that live in the gut of warm-blooded animals and are introduced into the environment through fecal matter. Most FIB are harmless to humans.

Infection: Occurs when pathogens invade a portion of the body. (This does not necessarily result in symptoms).

$\mathbf{Log_{10}}$ reduction targets (LRTs): The decrease in the number of pathogens in the water to reach an agreed upon treatment goal. (Technically, the $\log_{10}$ reduction target for a specified pathogen group [i.e., viruses, bacteria, or protozoa] to achieve the agreed level of risk to individuals [e.g., 10^{-4} infection per year] [Sharvelle et al., 2017]).

Microbe: A microorganism, such as a bacterium, virus, or protozoan.

Nonpotable water uses: Toilet flushing, irrigation, cooling, washing, industrial processes.

Pathogen: A microbe that can cause disease.

- **Opportunistic pathogen:** Waterborne pathogen adapted to survive and persist in manmade water systems.

Potable water uses: Drinking, culinary and bathing.

Quantitative microbial risk assessment (QMRA): A method for calculating the risk of infection or illness after contact with a specific type of microbe.

Source water: collected water (e.g., rainwater, stormwater) before it is treated or used.

- **Stormwater**: Water made by rainfall or snowmelt that causes runoff.
  - **Rainwater**: Water made by rainfall or snowmelt that can be collected directly from roof surfaces.
- **Wastewater**: Used or discharged water from homes, institutional or public buildings, commercial establishments, farms, or industries.
  - **Graywater**: Wastewater segregated from a domestic wastewater collection system, typically from laundry and bathing water.
- **Subsurface water**: Water collected from below the ground surface to maintain the structural integrity of a building, discharged through dewatering, or pumped for pollution containment.

Water reuse: The collection, storage, treatment, and use of stormwater, wastewater, and subsurface water. Stormwater reuse is also called "capture and use."

Zoonotic pathogen: A pathogen naturally spread between animals and humans.

These reports are commonly referenced in this paper.

WE&RF Report:

Final Report: Risk Based Framework for the Development of Public Health Guidance for Decentralized Non-Potable Water Systems (PDF) (https://watereuse.org/wp-content/uploads/2019/11/Risk-Based-Framework-for-DNWS-Report_FINAL.pdf)

Interagency Report:

Advancing Safe and Sustainable Water Reuse in Minnesota (PDF) (https://www.health.state.mn.us/communities/environment/water/docs/cwf/2018report.pdf)

Australian Guidelines for Water Recycling:

Managing Health and Environmental Risks (Phase 1) (PDF) (https://www.waterquality.gov.au/sites/default/files/documents/water-recycling-guidelines-full-21.pdf)

Managing Health and Environmental Risks (Phase 2): Augmentation of Drinking Water Supplies (PDF) (https://www.waterquality.gov.au/sites/default/files/documents/water-recycling-guidelines-augmentation-drinking-22.pdf)

Executive Summary

There has been an increasing level of interest in water reuse in Minnesota in recent years. Water reuse is the collection, storage, treatment, and use of stormwater, wastewater, and subsurface water. Rainwater from roofs is considered a subset of stormwater. Stormwater can also fall and travel on land surfaces. Stormwater reuse for nonpotable uses such as irrigation, toilet flushing, or doing laundry are the main topic of this paper.

There are many benefits to stormwater reuse. Stormwater reuse can save water by decreasing our need to use clean groundwater or treated surface water for everything, so that these sources can be saved for drinking water. Reuse can also help make the consequences of dry periods and droughts less severe and help manage stormwater in wet periods.

However, there are some potential threats to public health that need to be considered. We know very little about what (such as pathogens or chemicals) is in the source water of some stormwater reuse systems, how people could be exposed to reused water, and how easily people could get sick if there are pathogens or chemicals in the water they may be exposed to. We need to learn more and make sure stormwater reuse is safe for people.

The Minnesota Department of Health's (MDH) mission is to protect, maintain, and improve the health of all Minnesotans. Under this mission, we are required to identify and assess potential threats to public health. The questions we ask to evaluate the safety of stormwater reuse from a public health perspective include:

- What is in stormwater and rainwater that could be harmful to people?
- How likely are people to get sick from stormwater reuse?
- Who could be affected?
- Is there a way to reduce the hazard or the exposure of reused water to prevent potential illness or injury?

This paper is focused on stormwater and rainwater reuse. To prepare this paper we:

- Studied reports that have explored the risks and benefits of stormwater reuse.
- Partnered with the University of Minnesota and the Minnesota Public Health Laboratory to collect data about the microbial and chemical content in stormwater reuse systems in Minnesota.
- Reviewed stormwater reuse guidelines and risk-based frameworks from other states and countries to see how they handled concerns about human pathogens.
- Assessed the potential human health risk from Minnesota stormwater reuse systems.
- Made recommendations to inform policymakers, regulators, and stormwater reuse implementers.

This white paper provides guidance on what to consider from a public health perspective when approaching stormwater reuse in Minnesota. It gives an overview of potential health risks from stormwater reuse, presents a quantitative assessment of microbial risk with Minnesota data, and describes a risk-based framework that could be one approach to managing risks.

After reviewing the data, we have determined that stormwater and rainwater used in water reuse systems contain some microbes. Many of the microbes come from human sewage or animal waste. This could lead to potential health risks and possible illness for people exposed to the water.

People who are designing and operating stormwater reuse systems can reduce these risks. The recommendations at the end of this document were developed based on the quantitative microbial risk assessment described in this paper and are ways to reduce potential human health risks.

Next, an expanded workgroup will convene to decide on actionable steps for stormwater reuse in Minnesota.

Introduction

Water reuse is the collection, storage, treatment, and use of stormwater, wastewater, and subsurface water. Despite increasing interest in water reuse, there is no comprehensive statewide guidance or policy in Minnesota on water reuse to ensure that projects are safe and sustainable. The Water Reuse Interagency Workgroup (Interagency Workgroup) was formed in 2016. Its work was based on a legislative request to study and provide recommendations for regulatory and non-regulatory approaches to water reuse in Minnesota. The goal was to support development of state policy around water reuse. In 2018, the Interagency Workgroup published a report, Advancing Safe and Sustainable Water Reuse in Minnesota (PDF).

This report will be referred to as the "Interagency Report" throughout this paper.

The Interagency Workgroup developed Minnesota-specific recommendations in the Interagency Report. They include:

- Create an expanded workgroup with practitioners, advisors, and stakeholders to continue development of standards and programs.
- Prioritize research needs and integrate ongoing research to address questions about reuse.
- Define roles and responsibilities to oversee and monitor water reuse.
- Establish an information and collaboration hub on the web to share information and resources.
- Develop a risk-based management system to determine if regulation or guidance is needed.
- Develop water quality criteria for a variety of reuse systems based on the $\log_{10}$ reduction target approach for pathogens to manage human health risks.
- Resolve unique issues related to graywater reuse to determine the feasibility of expanding graywater reuse.
- Provide education and training to support water reuse.

Some of these recommendations are underway in part but ongoing effort and support is still needed. Specifically, an expanded workgroup will convene to develop actionable steps for implementing the recommendations. The intent of this paper is to provide the scientific basis for protecting and maintaining public health as applied to stormwater reuse in Minnesota. This paper will serve as a resource for the expanded workgroup.

In 2017, the Water Environment & Reuse Foundation (WE&RF) published a report titled, *A Risk-based Framework for the Development of Public Health Guidance for Decentralized Non-Potable Water Systems* (WE&RF Report) (Sharvelle et al., 2017). The framework allows creativity in design and function of water reuse systems while still providing reasonable expectations for public health protection. The framework is intended to be flexible and relatively easy to implement in a variety of settings around the United States. In addition, the guidance could assist state and local health departments in supporting wider use of water reuse systems that will still protect public health.

The WE&RF Report was used as a resource for the Interagency Report. The use of this framework is one way to help move the workgroup recommendations forward. However, we heard from stakeholders that they were not sure if the assumptions and data used for determining the health benchmarks and risk-based targets in the report were applicable to Minnesota. Therefore, we partnered with the University of Minnesota (U of M) and the Minnesota Public Health Laboratory to collect data about the microbial and chemical content in water reuse systems in Minnesota. We used the data to assess potential human health risk from Minnesota stormwater reuse systems. This Minnesota effort focused on stormwater and rainwater reuse for nonpotable uses, as these are the areas of highest demand in Minnesota at this time. However, the same risk principles can be applied to domestic wastewater, industrial process wastewater, subsurface water, or other sources. In addition, while potable use (for drinking water) should also be examined at some time, it is not within the scope of this paper.

In this paper, we first give an overview of stormwater reuse risk and define terminology around risk. We then describe a microbial risk assessment specifically for Minnesota and compare it to the health benchmarks and risk-based targets in the WE&RF Report. Finally, we provide options for managing risk.

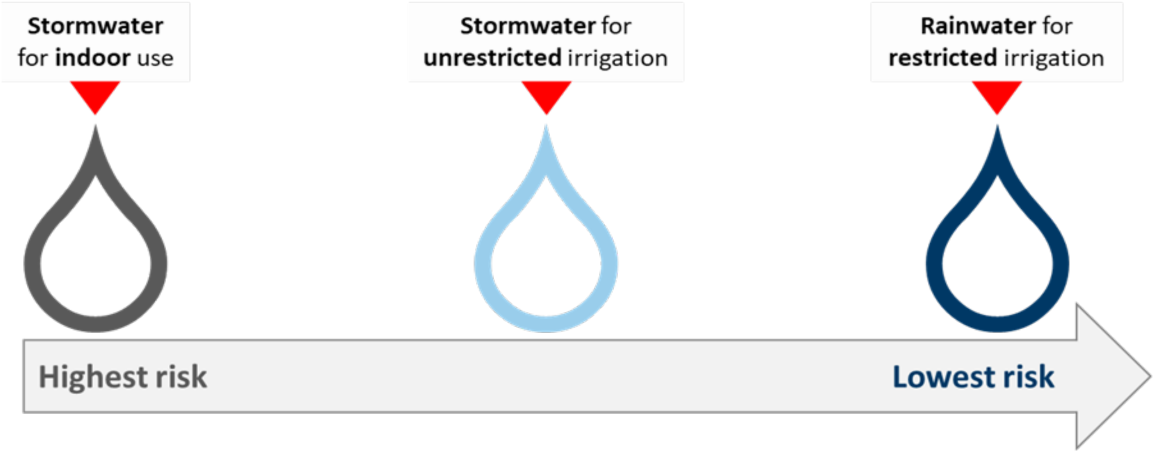
Ultimately, the decision to implement or regulate stormwater reuse will depend on the public's interest in reusing water and willingness to accept some uncertainty and risk. This decision will need to be weighed with the costs and benefits of implementation. Regardless, success is dependent on well-maintained stormwater reuse systems that operate efficiently and deliver dependable water quality and quantity. Any recommendations in this paper are not mandatory and have no formal legal status.

An overview of the health risk for nonpotable reuse of rainwater and stormwater

Water reuse can pose human health risks. The level of risk can vary depending on where the water comes from and how it will be used (Figure 1). Water that is reused for drinking water, called potable reuse, is required to meet United States Environmental Protection Agency (U.S. EPA) drinking water standards outlined in the Safe Drinking Water Act (SDWA). Unlike the standards for drinking water, there are currently no clear U.S. guidelines on the water quality needed for nonpotable reuse purposes such as watering lawns (irrigation), washing cars, or flushing toilets.

Therefore, we needed to consider the potential human health risks that nonpotable stormwater reuse could pose, such as for people who may contact or pass by reuse systems during or shortly after operation. We conducted a focused literature review on stormwater and rainwater quality, contaminants, and potential risk related to reuse. While most of the studies were from areas outside of Minnesota, the literature provided a good foundation for understanding potential health risks of stormwater reuse in Minnesota. This information is summarized in Appendix A.

Figure 1. Graphic demonstrating stormwater reuse risk



The main human health concern in most stormwater reuse scenarios is currently understood to be pathogens. Pathogens can cause acute illness (short-term onset) even when people are exposed to very small amounts of water. This paper is therefore focused on microbial risk.[1]

Microbial risk

Human exposure to water that contains pathogens (bacteria, viruses, or protozoa) could occur with some types of stormwater reuse. For example, mist or airborne droplets from watering lawns or golf courses (i.e., irrigation), or toilet flushing, can contain microbes. People could accidentally swallow or breathe in the mist or droplets and get sick. Reused water could also be accidentally consumed if it were used for irrigating food crops. Finally, people could swallow the water through hand-to-mouth contact when watering an athletic field, park, yard, or golf course. This could happen if someone were to touch the grass, and then eat food or touch their mouth without washing their hands.

Chemical risk

Currently, there is limited information on chemical risks in water reuse systems in general, particularly for nonpotable water reuse systems with rainwater or stormwater sources. Chemicals in rainwater and stormwater might come from the air, roofing materials, pesticide runoff, or contamination from other sources (e.g., roadway runoff, agricultural, municipal, or industrial wastes). While more research is needed in this area, we estimate there is low public health risk from manmade chemicals for most nonpotable water uses, based on the available information.

---

[1] This paper was written before SARS-CoV-2/COVID became prevalent globally. Research and study about human health risks of SARS-CoV-2 in water is ongoing. When more information is available, this paper will be updated appropriately.

In addition to manmade chemicals, some naturally produced chemicals, such as toxins from cyanobacteria, might be found in water collected for reuse. These could pose a threat if a dog or other pet entered a stormwater pond and drank the water because these toxins can harm animals if there are high amounts of the toxins. These naturally produced chemicals may be of higher concern than manmade chemicals, but again more research is needed.

Operational risk

As stated in Appendix C of the Interagency Report, there are potential concerns about the liability related to operating a water reuse system. Liabilities could include health risk, drowning hazard, or inadequate supply or quality of water. These concerns should be considered by owners of water reuse systems. As more water reuse systems become active, others, such as insurance agencies or underwriters, might recommend additional practices to reduce liability.

A water reuse system typically adds complexity to a building or operation. The reuse system will usually require storage, pumps, piping, controls and possibly some form of treatment. All of these things take time and money to maintain and operate. Neglecting system maintenance might increase potential health threats of the system, make the system an eyesore or nuisance, or decrease public acceptance. Operational risks are further discussed later in this report.

Risk-based framework

In this paper, a risk-based framework for stormwater reuse is defined as a structured process, not a prescribed list, used to identify potential risks from implementing reuse and to define a strategy for minimizing the risks. A framework incorporates the concepts of risk, risk perception, acceptable risk, risk assessment and risk management. Before we talk about a risk-based framework for public health and stormwater reuse systems, we will first describe all of these concepts.

Risk, risk perception, and acceptable risk

The Centers for Disease Control and Prevention (CDC), U.S. EPA, and the National Research Council (NRC) all have different definitions of risk, which generally incorporate three main ideas (Irias, 2019):

- A hazard that has the potential to create a harmful effect or consequence.
- The probability of the hazard or event occurring.
- The vulnerability of a person or system to the hazard or event should it occur.

Most people would choose to accept zero risk for any adverse outcome (illness, injury, loss, death, or other negative outcomes). However, zero risk is unattainable. Even decreasing risk to very low levels is very difficult and/or expensive to do. Therefore, we are forced to choose a level of risk that is considered acceptable by people who are exposed to the hazard. The perception of risk can be highly personalized; based on a person’s life experiences and frame of reference (Brown, 2014). However, the decisions we make based on our perceptions of a risk are not always in line with the actual magnitude of the risk.

Sometimes the level of risk that is accepted will change over time. U.S. EPA made determinations about the level of acceptable risk for several environmentally-related threats. Some of these include the risk of becoming sick after recreational contact with water (U.S. EPA, 2012a); the risk of getting an infection from drinking water (National Primary Drinking Water Regulations, 1989); or the risk of developing cancer (Hunter & Fewtrell, 2001). The level of risk that is "acceptable" for each of these outcomes has been developed independently, and each is very different. A brief history of these determinations is described in Appendix B.

As described above, the concept of acceptable risk is subjective, but it seems that when the public trusts a water authority, they generally perceive lower risk and are willing to accept more risk (Ross & Louis, 2014). A standard accepted risk level for drinking water is 1/10,000 (or 10^{-4}) per person per year. At this level, one infection per every ten thousand people drinking the water is expected per year. In the context of water reuse, this drinking water risk level has been used for indoor exposures and involuntary outdoor exposures such as exposures from flushing toilets, washing clothes, or entering an unrestricted area irrigated with reused water (Sharvelle et al., 2017).

For voluntary outdoor exposures of reused water, experts have applied a standard of approximately one illness for every 100 people exposed (or 10^{-2}) (Sharvelle et al., 2017). That standard is similar to U.S. EPA's recreational standard, where there is an expectation of about three illnesses for every 100 people exposed per recreational event (e.g., swimming). This level of risk might be acceptable in some communities where there is knowledge about the risk of reuse and the practice has been voluntarily accepted.

While these risk levels of 10^{-4} and 10^{-2} have been cited in the literature and applied in practice, the acceptable risk levels could be lower, depending on the perspective of the people involved and the degree of exposure anticipated. For example, if a water reuse system is in a location that could include a population with several immunocompromised people or those in otherwise fragile health status, a lower risk level might be appropriate. Studies completed on public perception and acceptance of water reuse systems have found if people perceive there to be lower risk, they are more accepting of water reuse systems, especially for wastewater reuse (Ross et al., 2014). Then again, researchers have found the acceptance of water reuse may be higher if people think reuse is very important to protecting water resources (Liu, He, Fu, Chen, Wang, & Wang, 2018).

The discussion about acceptable risk for water reuse should continue with the expanded stakeholder group, and the risk management recommendations can be adjusted as needed.

Risk assessment

Risk assessments objectively study hazards and exposure factors in a process that involves hazard identification, hazard characterization, exposure assessment, and risk characterization. The understanding of how hazards and exposure factors interact is used to calculate a likelihood, or probability, that an unwanted outcome will occur. An unwanted outcome in a water reuse scenario could be someone getting sick from exposure to the water. For this paper, we performed a risk assessment to objectively look at the risks associated with stormwater reuse.

Risk management

For the context of this paper, we consider risk management to be the process of deciding whether and how to manage the risks identified through risk assessment. A risk management approach is proactive, rather than simply reacting when problems arise. Risk management identifies preventive measures to control hazards and establishes a monitoring program to ensure that any preventive measures operate effectively (Natural Resource Management Ministerial Council [NRMMC], Environmental Protection and Heritage Council [EPHC], & Australian Health Ministers Conference [NHMRC], 2006).

Risk management could also consider other factors such as legal, economic, social, and behavioral factors and ask questions such as:

- What are the relative health or environmental benefits of the proposed activity?
- How do other factors (available technologies, costs, etc.) affect the activity?
- What are the recommendations, and the justifications, in light of benefits, costs and uncertainties?
- How is the effectiveness of the recommendations evaluated?

These risk management questions are beyond the scope of this paper, but we recommend that they be considered as part of the ongoing work with the expanded stakeholder group.

WE&RF's risk-based framework and Minnesota

After deciding what is acceptable risk, completing a risk assessment, and identifying preventive measures, a risk-based framework that guides water reuse system program administrators, design engineers, owners, operators, and regulators in designing, implementing, operating, and monitoring a water reuse system can be developed. Risk-based frameworks for water reuse systems should allow some flexibility in the design and operations of the system while maintaining safety.

For this paper, we evaluated the WE&RF Report as the primary risk-based framework currently available for stormwater and rainwater reuse in the U.S. We were a member of the Stakeholder Advisory Committee for the report. We wanted to capitalize on this available work, while critically evaluating its appropriateness for Minnesota. Since there are currently no federal reuse standards, we see value in aligning our approach with an existing framework and/or coming to consensus with other states. Our goal is to provide clarity to those trying to implement or provide service to water reuse systems in multiple jurisdictions.

Minnesota quantitative microbial risk assessment

Quantitative microbial risk assessment (QMRA) is a relatively new discipline. QMRA was developed to fill the need for assessing potential threats to human health from pathogens. To date, comparisons of the predictive ability of QMRA to epidemiology data (i.e. data from past human disease outbreaks), have shown that QMRA is a reasonably accurate and useful tool (Burch, 2019; Soller et al., 2016).

QMRA often predicts *infection* with a pathogen, but not necessarily an *illness*. In an infection, a part of a person's body, such as the gastrointestinal tract, has been invaded by the pathogen and the pathogen might be reproducing. However, the infection might not cause noticeable symptoms. Sometimes a person's body can stop the infection and remove the pathogen before a person feels sick. If the body cannot fight off the infection, symptoms may occur (e.g., diarrhea or vomiting). The infection is now called an illness. There are many factors involved in developing symptoms. More research is needed to understand when an infection will progress to an illness.

People are more convinced of the need to act on a potential risk when we can see illness or infection. However, we need to consider potential reasons why illnesses or infections are not always reported. Some of these reasons are:

1. People have been infected, but the infection is subclinical (i.e., there are no symptoms).
2. People have been infected and show symptoms (i.e., become ill), but the affected person or family does not seek treatment.
3. A few people have been infected and show symptoms, but the public health surveillance system is not robust enough to detect these illnesses as being related.

We will now describe a QMRA specifically for Minnesota data and compare it to the health benchmarks and risk-based targets in the WE&RF Report. The WE&RF Report relied heavily on a QMRA conducted by Schoen, Ashbolt, Jahne, & Garland, (2017). We used that work and recent advances as the basis for our QMRA methodology.

Components of QMRA

QMRA includes many of the classic risk assessment components (Haas, Rose, & Gerba, 1999; U.S. EPA, 2012b). These include:

1. **Hazard identification** (Which pathogens pose a potential hazard?)
2. **Dose response models** (How many pathogens will cause an infection or illness?)
3. **Exposure assessment** (What types of pathogens and how many are present in the scenario studied?)
4. **Risk characterization** (Using the data from the first three steps, what is the health risk?)

Each of these four risk assessment components require data and analysis of the data. Each component is broken down into more detail in the following four sections. In each section we will first discuss the QMRA component generally, then describe the analysis used for the Minnesota QMRA, and finally compare to methodology from the WE&RF Report.

1. Hazard identification

Hazard identification answers such questions as:

- What types of pathogens might be found in a stormwater reuse system?
- How do they infect people?
- What types of illnesses are possible (Haas, et al., 1999; Medema & Ashbolt, 2006)?

To answer these questions, we turned to other researchers and scientists. Ahmed, Hamilton, Toze, Cook, and Page (2019) provide a thorough review of pathogens detected in stormwater runoff and outfalls and the associated human health risks. This review is focused on pathogens in the source water that make people sick when ingested (swallowed). They affect the intestine (enteric pathogens); symptoms of illnesses may include diarrhea or vomiting.

Legionella bacteria could also be found in stormwater reuse systems. *Legionella* poses a risk when the water is aerosolized (as in a mist or spray) and the small droplets are inhaled. Inhalation (breathing in) of the bacteria can cause Legionellosis. Legionellosis includes two diseases, Legionnaires' disease and Pontiac fever.

Reference pathogens

Reference pathogens are a tool used in hazard identification. Because the list of pathogens that could be found is long and they are difficult and expensive to measure, typically a subset of microbes, called reference pathogens, are chosen for risk assessment. Reference pathogens are chosen based on their occurrence frequency, disease severity, survival in the environment, and ability to be measured. Reference pathogens typically represent the three major categories of pathogenic microbes in water: virus, protozoa, and bacteria. Not only do these groups vary in frequency of occurrence, but they differ in size, survivability, infectivity, and resistance to treatment. Therefore, it is necessary to look at them as separate groups. It is understood that if reference pathogens are under control, risk from the many other waterborne pathogens in each group should be low.

Reference pathogens for the Minnesota QMRA included:

- Virus: norovirus, enterovirus
- Protozoa: *Giardia*, *Cryptosporidium*
- Bacteria: *Salmonella,* pathogenic *E. coli* and *Shigella*

These were all detected in Minnesota reuse systems. All of these pathogens commonly cause gastrointestinal illness.

WE&RF Report

Reference pathogens for the WE&RF report included:

- Virus: norovirus (primary target virion); also rotavirus and adenovirus
- Protozoa: *Cryptosporidium*; also considered *Giardia*
- Bacteria: *Campylobacter* and *Salmonella* (both zoonotic); also pathogenic *E. coli*

2. Dose response models

Dose-response models are equations that provide information about the amount of pathogen that usually causes an infection in a person. Dose-response models are often based on controlled laboratory experiments, but sometimes they are developed or validated using data from disease outbreaks (Burch, 2018; Haas et al., 1999; Haas, 2015; Soller et al., 2016). Selecting an appropriate dose-response model is important in estimating the potential for an unwanted effect to occur.

Several variables are involved in dose-response, such as:

- A person's susceptibility to infection from a particular pathogen.
- The pathogen's infection-causing ability.
- How a person can come in contact with the pathogens.
- The general health status of the person.

Unfortunately, getting health data that can be applied across the entire human population is difficult. Scientists have created statistical models that can be broadly applied, but there are known shortcomings in the models. In addition, the number of dose-response models available for pathogens is limited. Risk assessors sometimes cannot make a risk prediction, or they must make their best estimates using the models available.

In recent years, numerous researchers have been working to find the most accurate dose-response model for various microbes. The task is difficult because there are many unknown factors that could contribute to the accuracy of the dose-response model, such as the infectiousness of the microbe strain or the immunity or resistance of the host. As researchers learn more about microbes, their ability to infect a host, environmental and immune factors that allow or prevent infections, and other factors, the dose-response models continue to be refined.

Currently several dose-response models are available for some microbes, and no dose-response models exist for others. For example, norovirus has numerous dose-response models, and we considered three of the models for our Minnesota QMRA (Messner, 2014; Teunis, 2008; Schmidt, 2015). Some of the population is believed to be immune to certain strains of norovirus. The three models account for the potential for immunity through different approaches. A full discussion of the differences is beyond the scope of this paper. In general, it has been suggested that the Teunis model, though widely used, may over-predict risk, especially at low doses.

A similar case of differing dose-response models also exists for other pathogens. We ran some of the more widely used models to compare the risk. We expect that more research will continue on this topic and the models will continue to be refined over time.

WE&RF Report

The dose-response model used for each microbe for the WE&RF Report can be found in Table B-1 of the WE&RF Report (Sharvelle et al., 2017, Table B-1).

3. Exposure assessment

Exposure assessment involves first determining the type and concentration of microbes present. We can determine those concentrations either by sampling from a system or by estimating the amount of microbes.

Next, we consider the ways people could be exposed to the microbe. If the water will be sprayed, for example, there is potential for contact with pathogens in the water via inhalation (breathing in), ingestion (swallowing), or skin contact. However, if no one is in the area when the water is being sprayed, then there is low likelihood that someone would be exposed. There is still the possibility of indirect ingestion through hand-to-mouth contact (e.g. a soccer player touches the turf that has been sprayed and then eats without washing hands). Therefore, for each planned use of the water (e.g., irrigation), the range of operating conditions (e.g., wind speed and direction), the location, and the exposure routes must be considered.

Pathogen characterizations

Pathogen concentrations can be characterized through direct observation or by estimations. Determining pathogen concentrations through direct observation is difficult because we need to account for variability in pathogen density over time and the possibility of sporadic pathogen occurrence (Sharvelle et al., 2017). For stormwater and rainwater, both variability and sporadic occurrence can be caused by environmental conditions such as precipitation events, temperature differences, exposure to light, or sewer overflows. To obtain accurate pathogen observations, there needs to be frequent sampling. Large sample volumes are also often required, meaning sampling can be time-consuming.

Methods of analysis are also expensive. Standard methods for some organisms involve observation by microscopy, a relatively complex process requiring an expert analyst. Viruses are very small and difficult to capture. Some are also very hard to grow. Finally, to identify specific pathogens, genetic testing methods are often required. Genetic methods are again expensive and require expert analysts. Additionally, these genetic and microscopy methods do not tell you if a pathogen is viable and able to make someone sick. Therefore, while direct pathogen observations are ideal for characterizations, they are difficult and expensive to obtain and therefore relatively sparse for any type of water source.

Since pathogens can be difficult to measure directly in water systems, fecal indictor bacteria (FIB) are often used as substitutes for pathogens. FIB are bacteria that do not cause waterborne disease in humans, are easy to measure, and indicate fecal contamination. Indicator data are much more available as well. Historically, there has been heavy reliance on indictor organisms, although there is ample evidence showing that indicators are relatively poor predictors of pathogens in many settings (Boehm, Silverman, Schriewer, & Goodwin, 2019). For example, a stormwater pond sample in a Minnesota study showed indicator concentrations of 3 *E.coli* and 6.3 enterococcus per 100 ml. These concentrations are acceptable for human contact per the 2012 U.S. EPA recreational water quality criteria. However, in the same sample, *Giardia* (a pathogen) was found at 3100 genetic copies (or about 190 cysts) per liter, which could indicate a human health hazard. More recently, indicators specific to a particular host (e.g., dog or human) have been used to determine the source of fecal contamination in environmental waters through a process called microbial source tracking.

To get more data for Minnesota reuse systems, MDH is working with the University of Minnesota and other partners to conduct studies. These studies will add to data on microbial and chemical contaminant profiles of reuse sources in Minnesota. They will focus on rainwater and stormwater because these are where the largest data gaps exist, and where there would conceivably be the largest regional differences. Ongoing studies by other researchers in Minnesota and the Midwest will also help to contribute to the data in the future. Study descriptions, design, and summarized data are provided in Appendix C.

As can be seen from this discussion, source pathogen characterization is not straightforward and much uncertainty remains in these estimations. This type of uncertainly is common across water disciplines, and the solution has been to start with what we know and to continuously improve and expand over time.

WE&RF Report

For stormwater, WE&RF compared two approaches to pathogen characterization, one based on distributions derived from actual observations, and one based on dilutions of wastewater. The literature indicates stormwater typically contains some component of human sewage, and this component could be described by a dilution factor (e.g. there is one part sewage to every 1000 parts stormwater). There is evidence that microbes from sewage will dominate the risk (Schoen & Ashbolt, 2010).

WE&RF used an animal fecal approach for rainwater, because of the limited human presence on most rooftops and the zoonotic bacteria concerns. This approach assumes FIB present in rainwater are from animals and uses data for pathogens in animal feces to estimate pathogens in rainwater.

Exposure volumes

In addition to characterizing the pathogens in reuse water, there also needs to be an estimate of exposure volume and frequency. For drinking water, data from the U.S. EPA Exposure Factors Handbook estimates an average intake of 1.1 liters per day (L/day) in the U.S. for all ages (U.S. EPA, 2019). When water is used for purposes other than drinking water, such as for watering lawns, the amount people swallow is much lower. Exposures can be through direct ingestion of mouthfuls or droplets of water, indirect ingestion through hand-to-mouth (touching a surface or object that has been sprayed and then touching the mouth), or inhalation.

The Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1) contain a table listing estimated exposures for a variety of nonpotable uses (NRMMC et al., 2006, Table 3.3). The guidelines note that the examples of exposure volumes are often based on limited information, and that further research is required. Typical exposure volumes for nonpotable uses range from 1 mL/year for washing machine use to 1000 mL/year for firefighting. Looking at Table 3.3 in the Australian Guidelines can help assess the relative exposure volumes from different uses. The largest volume exposure is assumed to be ingestion due to accidental cross-connection with the potable water supply. This exposure is unlikely if proper precautions are taken (such as annual cross-connection testing) and would not likely affect the entire population.

It is understood that different individuals will have different annual exposures. For example, one person might golf once a year, and another person golfs every week; they will be exposed to different amounts of irrigation water. Just as variability in pathogen concentrations makes assessment difficult, so does variability in exposure volume. There is inherently some uncertainty in the risk estimations.

A common reuse application in Minnesota is municipal irrigation of parks, commercial landscaping, golf courses, and athletic fields. The Australian Guidelines assume that people are unlikely to be directly exposed to large amounts of water spray. Instead they suggest exposure is more likely from hand-to-mouth contact, which occurs when people touch the grass and then touch their mouth. Table 3.3 in the Australian Guidelines says exposure is likely to be higher when irrigating sports fields and golf courses for this reason. We questioned these assumptions for Minnesota for two reasons. First, data on hand-to-mouth exposures is limited. Second, some Minnesota reuse systems use spray guns that send the spray a considerable distance and closer to head height, making exposure to spray more likely.

For the Minnesota QMRA, we used the same exposures as the WE&RF Report for comparison, but have the ability to adjust our analysis based on site-specific information if it were available. For example, if the irrigation schedule at a given location were known, the number of possible exposures could be plugged in to the assessment to give guidance specific to that site.

WE&RF Report

The WE&RF Report made use of the exposure table from the Australian Guidelines to make assessments for two broad categories of reuse: unrestricted irrigation and indoor use. Unrestricted irrigation included ornamental plant (non-food) irrigation and dust suppression. Indoor use included exposures for toilet flushing, clothes washing, and rare accidental cross connection with drinking water.

4. Risk characterization

Using all of the information collected in the hazard identification, dose response, and exposure assessment steps, the potential risk can be calculated. Major decision points in risk characterization include whether to calculate a point estimate (single value) for risk or use a risk range to try to account for variability in exposure, and what timeframe of risk to consider.

For our Minnesota QMRA, risk is calculated as the annual probability of infection for various source types, uses, and reference pathogens. To account for variable concentrations of microbes in the water and potential uncertainty about the water's pathogen content, we used a technique called Monte Carlo simulation. The simulation builds a range, from Minnesota data, of possible concentrations for each reference pathogen. Using randomly selected values (including nondetects) from that range and an estimated amount of water that a person could be exposed to during each event (e.g., one toilet flush), the simulation calculates a risk estimate for a given number of concentration and exposure combinations. The resulting event risk estimates are used to calculate a risk estimate for one year (e.g., 1,100 toilet flushes per year).

To get an overall estimate of yearly risk under a wide range of different scenarios, the simulation is repeated a large number of times (e.g., 10,000 times) and a final estimated yearly risk is derived from all of the yearly risk estimates produced (10,000 estimates in this example). This helps to answer the question of how likely it is that a person could be infected with a pathogen from flushing a toilet that uses reused water. Estimated yearly risks for other activities like irrigation and clothes washing can be calculated in a similar way.

The characterized risk can then be compared to the acceptable risk to determine what, if any, safeguards need to be in place to reduce the risk. This comparison and options for safeguards are discussed in the risk management section.

WE&RF Report

The WE&RF Report used probability distributions to describe pathogen concentrations in their Monte Carlo simulation. Since their stormwater pathogen characterizations were based on the sewage dilution approach, the probability distributions for stormwater came from actual pathogen observations in sewage. For rainwater, probability distributions were based on pathogen observations in animal fecal matter.

Risk management implementation

Once the microbial risk has been characterized, we can determine the amount (if any) of safeguards to consider to meet the target acceptable risk level. That is, if the amount of pathogens in the reuse source water and the amount of potential exposure is enough to make someone sick, then the amount must be reduced to make the water safe for a specific use. This is a balance - if the use involves minimal exposure to the water, then a higher level of microbes can remain.

The WE&RF Report used two risk standards in their characterization: The U.S. EPA acceptable risk for drinking water of 1/10,000 (10^{-4}) infections per person per year and the U.S. EPA health risk assumption for illness for water recreation of 10^{-2} infections per person per event. The report suggested that the more stringent standard (10^{-4}) be used for involuntary exposures, and 10^{-2} for voluntary exposures. While we agree in concept with the WE&RF Report goals of keeping the risk below a benchmark of 1/10,000 infections per year for the people exposed involuntarily, and 1/100 for people who have more choice about being near the water reuse system, it is difficult to say what would really constitute a voluntary exposure. For instance, golfing might be considered a voluntary activity, but presumably, the golfers would need to be informed of the increased risk from reused irrigation water. Therefore, this assessment will focus on meeting the 10^{-4} risk goal.

The expanded stakeholder group should continue the discussion about voluntary exposures and informed risk.

In addition to microbial risk, chemical and operational risks should be considered. Chemical risks have not yet been quantified like the microbial risk, and operational risk is hard to quantify. Possible management strategies for these risks are included in the following section.

Measures to minimize risk

Most reuse scenarios will represent unacceptable risks if there is unrestricted exposure to untreated water or if the systems are not managed properly. Strategies to minimize the risk include:

- Source control
- Exposure control
- Treatment
- Management plan
- Regulation and/or guidance

Source control

We do not currently have enough data to determine how much control we can have over pathogen or chemical concentrations in the source based on system design, but we know that design choices can have an impact on water quality in general.

For rainwater, choices can be made about roofing materials, tree cover over the roof, and who is allowed to access the roof. Shingle roofs have been shown to produce higher bacterial loads, while green roofs result in higher dissolved organic carbon content (Mendez, Klenzendorf, Afshar, Simmons, Barrett, Kinney, & Kirisits, 2011). Dissolved organic carbon can interfere with UV disinfection or cause disinfection byproducts with chlorine disinfection.

For stormwater, land use and/or activities in the drainage area can affect pathogen concentrations. For example, bacteria levels were significantly higher in stormwater from developed compared to undeveloped watersheds (Tiefenthaler et al., 2008).

Further research is recommended to explore system design options for reducing source loading.

Exposure control

The type of use for reused water determines how effectively exposure to the water can be controlled.

For example, watering a golf course or an athletic field at night can control direct ingestion of irrigation spray if spray does not leave the boundaries of the property and property access at night is restricted. Exposure could still happen through hand-to-mouth ingestion by touching a golf ball or turf and then touching one’s mouth or not washing hands before eating. As discussed in the exposure assessment section, the Australian Guidelines assume that exposure from municipal irrigation is more likely from indirect ingestion through contact with lawns than direct ingestion through exposure to spray. The guidelines also indicate exposure is likely to be higher when irrigating facilities like golf courses and athletic fields. The Australian Guidelines suggest that exposure could be reduced by implementing withholding periods after irrigation (i.e. people could not enter the area for a certain number of hours). However, the many variables that control pathogen die-off on turf including temperature, moisture, and sunlight, cannot be controlled so it would be hard to determine a standard withholding time.

Hand-to-mouth exposures seem much more unlikely for irrigation of a commercial landscape. Drip irrigation rather than spray should also minimize exposure.

When reused water is piped into a housing development for irrigation of residential lawns, there is limited control over the exposure. We can either make carefully considered assumptions around exposure or solicit more research in this area.

It is also important to reduce vulnerable populations’ (children, the elderly and immunocompromised individuals) exposure to reused water. More work is needed to fully assess the risk to these populations.

Institutional controls (deed restrictions or other limitations on land use that come with the property), physical controls (fencing or other restrictions on access) and proper signage and awareness can also be considered to limit exposure.

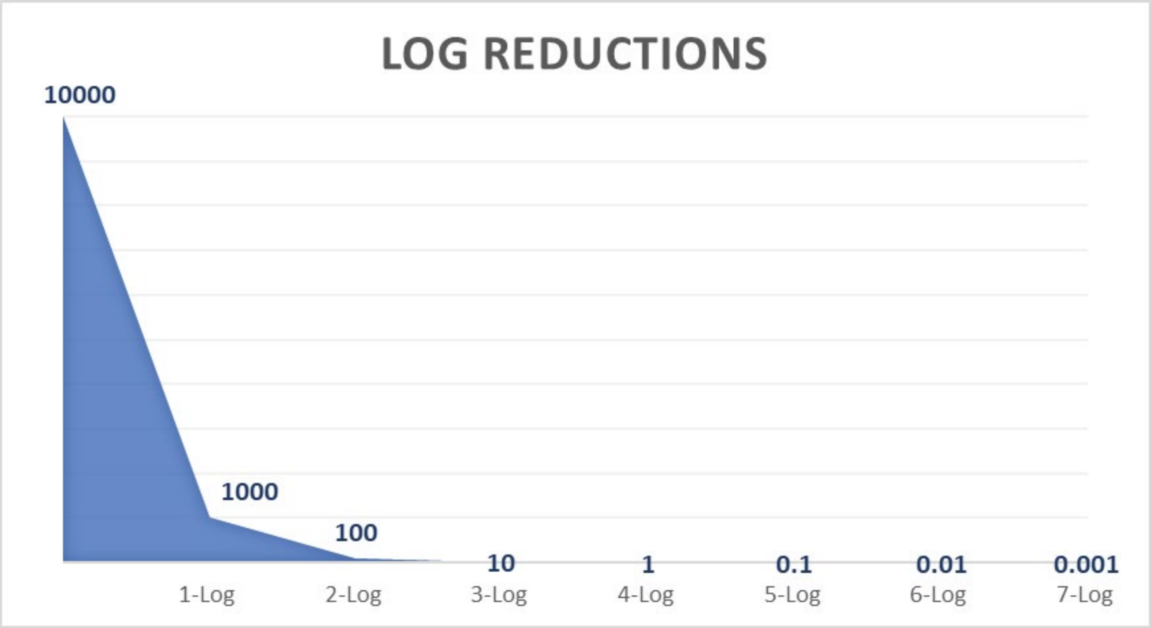
Treatment

Treatment may be required for most indoor or unrestricted outdoor uses to meet the 10^{-4} risk level. Treatment provides a barrier between the source and use, and removes or inactivates microbes.

Log_{10} reduction targets (LRTs) are one way to set a level of treatment needed to meet risk targets. The Interagency Report recommended developing water quality criteria based on the LRT approach.

LRTs are numbers that represent the difference between the level of microbes in the water before and after treatment on a Log_{10} scale (Schoen et al., 2017; Sharvelle et al., 2017). Figure 2 illustrates the impact log reductions have on a source harboring 10,000 microbes. For example, meeting an LRT of 3 (3-log reduction) would leave 10 microbes, which equates to a 99.9% reduction in potentially harmful microorganisms. An LRT is the treatment goal to meet. Since each pathogen group (bacteria, protozoa, virus) responds differently to treatment, potential health risks are controlled by using LRTs specific to each group.

Figure 2. Log Reductions



Meeting LRTs can be accomplished through water treatment options like chlorination, ultraviolet light, or filtration. A full discussion of the treatment options is beyond the scope of this paper. However, the WE&RF Report gives a good introduction to selecting and evaluating treatment technologies to meet LRTs (Sharvelle et al., 2017, Chapter 4).

In a simple scenario where risk is characterized for a single pathogen concentration, the LRT for a given application is calculated using this formula:

$$Log\ reduction\ target = \log[\frac{characterized\ risk}{acceptable\ risk}]$$

When using a distribution rather than a single value for any of the risk variables, such as in the WE&RF Report, the formula gets more complicated. The details of LRT calculations in this case can be found in Schoen et al. (2017). For the Minnesota QMRA, we replicated the process used by Schoen et al. (2017) for calculating LRTs but used our Minnesota data for pathogens in rainwater and stormwater sources.

LRTs are treatment goals. Bigger numbers mean that more treatment is needed. A higher LRT could be because there are a lot of pathogens in the water, only a small number of pathogens are needed to make someone sick, or there is a high exposure volume to the water. Table 1 shows a comparison of LRTs from the Minnesota QMRA and the WE&RF Report for stormwater used for unrestricted irrigation and indoor use. For the WE&RF Report, we are listing the values for the 10^{-4} acceptable risk level with 10^{-3} sewage dilution representing stormwater from Table 3-3 (Sharvelle et al., 2017, Table 3-3). For the Minnesota QMRA, we present a range of LRTs for each pathogen group, based on evaluation of multiple dose responses and reference pathogens (see Tables 3 through 7 in Appendix C for complete tables of LRTs).

Table 1. LRTs for pathogens in stormwater for 10^{-4} acceptable risk level

	Water Use Scenario	Virus	Protozoa	Bacteria
WE&RF Stormwater (10^{-3} dilution)	Unrestricted irrigation	3	2.5	2
	Indoor use	3.5	3.5	3
Minnesota QMRA Stormwater	Unrestricted irrigation	NA – 5.6	1 – 3.1	1 – 4.5
	Indoor use	0.1 – 5.5	1.6 – 4.3	0 – 4.5

Table 2. LRTs for pathogens in rainwater for 10^{-4} acceptable risk level

	Water Use Scenario	Virus	Protozoa	Bacteria
WE&RF Rainwater	Unrestricted irrigation	Not applicable	No data	3.5
	Indoor use	Not applicable	No data	3.5
Minnesota QMRA Rainwater	Unrestricted irrigation	NA – 0.3	No data	0 – 3.7
	Indoor use	NA – 0.9	No data	0 – 5.2

We can see that the LRTs for each pathogen group from the WE&RF Report are contained within the range of Minnesota QMRA LRTs for each type of use (unrestricted irrigation and indoor use). This shows that the LRTs used in the WE&RF Report are within a reasonable range for Minnesota.

Management Plan

Planning and Asset Management

An important aspect of implementing safe and sustainable reuse is proper planning and asset management. Planning and management should involve asking questions such as:

- How does the reuse system fit in with existing drinking water, stormwater, and wastewater infrastructure?
- Is there a consistent need for the reused water or is it variable?
- What is the lifespan of the system components? Who will cover replacement costs?
- Who will run the system and how will they be trained?
- What are the annual equipment (e.g. filter) and maintenance costs? Is this accounted for in the budget?
- Are any neighborhood residents or potentially exposed individuals aware of and accepting of the system?
- For stormwater ponds, is there a plan to control harmful algal blooms or minimize contaminant input?
- For tanks, is there a plan to clean and control microbial growth?
- Have possible odor issues been addressed?

Thinking carefully about these questions on the front end can maximize the best use of resources.

Operation, Maintenance, and Monitoring

While designing and installing a system that meets the LRTs is a significant step toward protecting public health, the responsibility does not stop there. Proper operation, maintenance, and monitoring are ongoing requirements to maintain the safety and success of the system. Table 8-3 of the WE&RF Report lists elements of an Operation and Maintenance Plan (Sharvelle et al., 2017, Table 8-3). The Minnesota Plumbing Code currently regulates nonpotable rainwater catchment systems for indoor use or combined indoor/outdoor use and has minimum requirements for inspection.

Fortunately, in many cases, stormwater reuse system operators may already be responsible for maintenance of other water, wastewater, or similar facilities, and accustomed to the requirements of maintaining and monitoring a system. In other cases, however, more training or instruction could be needed. In either case, best practices such as availability of standard operating procedures and back-up operators are recommended.

Responsible Management Entity

The WE&RF Report discusses the need for a Responsible Management Entity (RME) who will ensure the system provides safe, affordable, and dependable service to end users. The RME can be a person, corporation, or governmental body with ultimate legal responsibility for the system. The WE&RF Report relates the term RME to the historical use by the decentralized wastewater industry as “a term used to describe an array of possible regulatory, oversight, and management structures that divide roles and responsibilities appropriately between the local regulator, owner, and operator of smaller systems”. The Interagency Report also uses this term. Table 5 in the Interagency Report lists potential reuse scenarios by risk category and roles for both agencies and RMEs. The Minnesota Plumbing Code for rainwater catchment systems requires operation, maintenance, monitoring, testing, and inspection of the systems be the responsibility of the property owner.

Monitoring

To ensure the LRTs are met on an ongoing basis, the treatment processes require monitoring, as discussed in Chapter 6 of WE&RF (Sharvelle et al., 2017, Chapter 6). Monitoring may also be in the form of visual checks on the system, such as verifying the condition of the collection area or if access restrictions are in place.

Proper storage and distribution

The Interagency Report describes how proper storage and distribution of reuse water are also important to maintaining water quality and protecting public health and the environment, especially in relation to control of opportunistic pathogens like *Legionella* bacteria.

Waterborne pathogens are considered opportunistic when they are adapted to survive and persist in manmade water systems. While *Legionella* is a concern in any water system, warmer source water temperatures and dissolved organic matter content in reuse sources may increase the potential for *Legionella* growth if not managed. As shown in Appendix C, evidence of *Legionella* was found in 67 percent of rainwater source samples and 73 percent of stormwater samples. Since *Legionella* is also prevalent in drinking water sources, reuse systems with city water back up may have *Legionella* enter the system from the back up supply and then proliferate under the conditions of the reuse system.

A documented outbreak in New Zealand was associated with several private rainwater reuse systems (Simmons et al., 2008). The outbreak involved a marina in New Zealand that stored groundwater in a tank for use in a “marine blaster” that allowed high-pressure spray cleaning of boats. An outbreak of Legionnaire’s disease occurred in an area downwind from where the marine blaster was used. Based on testing of bacteria in both locations, it is suspected that the water from the marine blaster settled in the rainwater tanks and subsequently exposed residents to *Legionella* when they used their private reuse systems for showering. This incident indicates that rainwater storage tanks provided favorable conditions for *Legionella* survival.

Meeting the log reduction requirements suggested in the previous section would be a first step to maintaining appropriate water quality all the way to the end user. General water quality such as organic content should also be taken into consideration as many sources of reuse can contain organics that provide food and habitable conditions for biofilms. A reuse system needs to be managed to prevent deterioration of water quality due to stagnation, high temperature and other factors. Some Best Management Practices (BMPs) for storage and distribution can be found in the WE&RF Report Chapter 7 (Sharvelle et al., 2017, Chapter 7) or in other standards such as ANSI/ASHRAE (The American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 188 Legionellosis: Risk Management for Building Water Systems.

The reuse distribution system also needs to be managed to prevent cross-connection with the potable water supply. The Minnesota Plumbing Code currently requires cross-connection testing for nonpotable rainwater catchment systems and marking of nonpotable water system components. Irrigating from a stormwater pond typically falls outside the authority of the plumbing code, but caution is still needed to ensure no connections are made to the potable water system.

Regulation and guidance

The Interagency Report recommends developing a risk-based management system to determine if oversight and monitoring can be governed by guidance or regulation. We support the continued effort to explore and develop this framework as a way to reduce possible health risks. Proper guidance and oversight will help keep reuse safe, provide public assurance and make it more successful.

Conclusions

This paper serves to lay the groundwork for creating a flexible approach for managing risks for a variety of water reuse sources and uses. Our Minnesota QMRA shows that the health benchmarks and risk-based targets in the WE&RF Report could be appropriate for Minnesota stormwater reuse systems, and gives us the ability to adjust existing targets and develop targets for other uses as new Minnesota-specific information is available.

We have secured funding through the Clean Water Fund to hire a facilitator to create an expanded workgroup to move the Interagency Report recommendations forward and to prioritize and implement research needs. We recommend that the WE&RF Report serve as a resource for this ongoing effort.

We will continue our participation with the National Blue Ribbon Commission for Onsite Non-potable Water Systems. The Commission continues to develop resources and conduct research for decentralized reuse of rainwater, stormwater, graywater and wastewater. Resources to support implementation of onsite nonpotable water reuse programs are located at Resources for Onsite Non-Potable Water Programs.

Areas for further research include:

- Data on the viability of pathogens found in stormwater reuse systems.
- Impacts of design choices on pathogen concentrations.
- Factors affecting pathogen survival in reuse systems and the environment (e.g. on athletic fields).
- Exposure volumes for various uses.

Topics that may require further discussion include:

- Acceptable risk for voluntary and involuntary exposures
- Cost/benefit analysis

Interim Recommendations

While recognizing the value of stormwater reuse systems, we have also learned that there are potential public health risks associated with these systems. Managing and operating a system properly also requires training and attention. It is important to understand there are limitations to current knowledge and data availability on some sources of reuse. It is also important to protect the public's health when we have evidence of risk.

Since stormwater reuse is happening in the absence of comprehensive statewide guidance or policy, we recommend an interim framework that draws heavily on the WE&RF Report and includes:

Management Plan:

- Make sure the reuse system meets a specific purpose and that it will be funded and managed throughout its lifetime.
- Specify a responsible management entity (RME) who has ultimate responsibility for the performance of the reuse system.
- Designate roles and responsibilities based on the level of potential health risk.

Design:

- Include early planning components (see Planning and Asset Management Section).
- Control contaminants through choice and management of source water.
- Consider design and control features that enhance the reliability of the system.
- Use a licensed Professional Engineer who is familiar with advanced water treatment to design systems if intending to meet the Log_{10} Pathogen Reduction Targets (LRTs) in Table 3-3 of the WE&RF Report and access to the water is not restricted.
- Allow for the option of restricted access and signage to minimize risk under certain scenarios.
- Adjust exposure levels based on frequency of irrigation at a given site.
- Allow for monitoring requirements based on the number of people exposed to a reuse system (e.g., reduced monitoring frequency when serving a small population).
- Avoid uses like irrigation of edible crops including community gardens until more is known about chemical content.

Operations and maintenance:

- Provide training and education to system operators.
- Provide assurance of reliability via an operations and maintenance plan (See Table 8-3 of WE&RF). Responsibilities may include:
    - Conduct initial and periodic tests of microbial water quality.
    - Monitor and change filters, UV bulbs, disinfectant additives, or other treatment components.
    - Clean system tanks and flush lines when needed.
    - Provide standard operating procedures for the system.
    - Record site-specific notes in a designated location.

Managing storage and distribution:

- Control microbial growth in the distribution system (Table 7-1 of WE&RF).
- Review published guidelines for the management of *Legionella* in distribution systems.

Monitoring:

- Monitor process performance via operational parameters correlated to the LRTs.
- Monitor water quality in the distribution system.
- Have a back-up plan when water quality goals are not met.

Reporting:

- Report anything required by the plumbing authority or other regulatory entity.
- Share data and experiences with the broader reuse community.

Resources

Australian Guidelines for Water Recycling:

Managing Health and Environmental Risks (Phase 1) (PDF) (https://www.waterquality.gov.au/sites/default/files/documents/water-recycling-guidelines-full-21.pdf)

Managing Health and Environmental Risks (Phase 2): Augmentation of Drinking Water Supplies (PDF) (https://www.waterquality.gov.au/sites/default/files/documents/water-recycling-guidelines-augmentation-drinking-22.pdf)

Interagency Report:

Advancing Safe and Sustainable Water Reuse in Minnesota (PDF) (https://www.health.state.mn.us/communities/environment/water/docs/cwf/2018report.pdf)

WE&RF Report:

Final Report: Risk Based Framework for the Development of Public Health Guidance for Decentralized Non-Potable Water Systems (PDF) (https://watereuse.org/wp-content/uploads/2019/11/Risk-Based-Framework-for-DNWS-Report_FINAL.pdf)

Additional Resources:

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2017 LCCMR Work Plan (PDF) (https://www.lccmr.leg.mn/projects/2017/work_plans_june/_2017_04f.pdf)

Pathogen Project (https://www.health.state.mn.us/communities/environment/water/cwf/virus.html)

Resources for Onsite Non-Potable Water Programs (http://www.uswateralliance.org/initiatives/commission/resources)

Temporal Dynamics of Pathogens and Antibiotic Resistance in Raw and Treated Stormwater (https://www.wrc.umn.edu/temporal-dynamics-pathogens-and-antibiotic-resistance-raw-and-treated-stormwater)

Water Reuse System Sampling Results Summary (PDF) (https://www.health.state.mn.us/communities/environment/risk/docs/guidance/dwec/qmra/umresults.pdf)

Appendices

Appendix A: Focused literature review

The summary below focuses on literature related to rainwater and stormwater reuse and risk.

Water quality and risk estimates

There are few studies available on rainwater and stormwater contaminants, especially for the Midwest area of the United States. Several studies conducted in locations outside of the United States, especially in Australia, provide some information, but the climate and ecology of these locations could differ from Minnesota's climate and ecology.

In general, rainwater (water collected from a roof) has been found to be a relatively clean source of water for water reuse (Jiang, et al., 2015; Ahmed, et al., 2011). However, rainwater is still subject to contamination from trees, birds, atmospheric deposition, roofing materials and other sources (Hamilton, et al., 2018; Jiang et al., 2015; Mendez et al., 2011).

Rainwater collected from the beginning of the rainfall is often the most contaminated because the water runs over surfaces that might have collected contaminants (e.g., bird droppings, dirt, and other debris) since the last rainfall. One approach to reducing contamination from rainwater is a "first flush" mechanism that will allow the most contaminated water from the start of the rainfall to be discarded. The water collected after the first flush is generally cleaner, but more research is needed (Despins, et al., 2009; Dobrowsky, et al, 2014; Martinson & Thomas, 2009).

Stormwater often picks up contaminants as it runs over the ground and other structures (Bichai & Ashbolt, 2017; Jiang et al., 2015; Lim, et al., 2015), and therefore can be more contaminated than rainwater. Often, stormwater contains chemicals, metals, waste material from humans (i.e., sewage), and fecal material from animals (Ahmed et al., 2019; Sidhu, Ahmed et al., 2013). Several authors have noted that stormwater tends to have human-specific chemical and microbial components that are found in sewage (Ahmed, 2019; Cities et al., 2012; Jiang et al., 2015; Schoen et al., 2017; Sidhu, et al,. 2012). Some of these components might come from leaking sewage pipes (Jiang et al., 2015; Lim et al., 2015; Sidhu et al., 2013) or chemical or fecal materials on the ground.

Microbial contaminants

Studies of rainwater and stormwater microbial water quality have often reported the presence of microbes, including pathogens. Risk estimates have been calculated based on the current understanding of pathogen occurrence.

Rainwater

A study by Ahmed et al. (2010) found that the rainwater tested in Australia had the presence of *Salmonella* and *Giardia*. If the water were consumed, the number of expected cases of salmonellosis ranged from 9.8 to 54 cases per 10,000 people per year, while the number of expected cases of giardiasis ranged from 10 to 65 cases per 10,000 people per year (Ahmed et al., 2010). The authors recommend disinfecting rainwater that will be consumed.

In a later study, researchers evaluated the risks related to *Legionella* and *Mycobacterium avium* complex (MAC) for potable and nonpotable uses of roof-harvested water (Hamilton et al., 2017). In this study, drinking, showering, and garden hosing were found to present unacceptable risks related to aerosol exposure to *Legionella* and MAC, which are primarily respiratory and skin pathogens, respectively. For immune-compromised people, toilet flushing and eating lettuce irrigated with roof-harvested rainwater were also not recommended because of annual predicted risks of more than 1 infection in 10,000 exposures.

In a study of rainwater harvesting systems in Texas by Kim, et al. (2016). researchers collected samples from six stormwater reuse systems collecting water from roofs with different types of roofing material and different treatment systems. The samples contained human pathogens such as *Mycobacterium* species (spp.), *Aspergillus* spp., and *Legionella* spp., including *Legionella pneumophila* (often involved in outbreaks). The authors state that the treatment systems did not always reduce the bacterial concentrations by the amount expected, and suggest filtration and UV treatment effectiveness deficiencies (Kim et al., 2016).

Hamilton et al. (2018) evaluated the water quality of roof-harvested water captured in rain barrels in Philadelphia. In this study, the presence of opportunistic and gastrointestinal pathogens were found such as species of *Mycobacteria*, amoeba and *Legionella*, and *Campylobacter*. The microbes could pose a health risk if the water is aerosolized or if produce irrigated with the water is eaten raw.

In a similar study on rain barrels in residential areas in the United Kingdom, Steeg and Moore (2018) found *Legionella* spp. in 107 of 113 (95 percent) of samples. Only two of the 113 samples (two percent) showed the presence of *Legionella pneumophila*, however. Tests with cyclone air samples showed that the *Legionella* was aerosolized when the hose nozzle was set to produce a fine mist. The authors recommend using courser droplet settings to avoid exposure to airborne Legionella spp. (Steeg & Moore, 2018).

A rain barrel study in Minneapolis, MN reported that *E. coli* concentrations in 32 percent (twelve) of the samples were above the monthly geometric mean standard of 126 CFU/100 mL for recreational water quality, and eight percent (three) of the samples were above the not-to-exceed standard of 1,260 CFU/100mL. The study concluded that wildlife is likely the main source of *E. coli* in rooftop runoff (City of Minneapolis, 2008).

Stormwater

Jiang et al. (2015) described the uses of toilet-flushing, garden hosing (irrigation of food crops), and showering, using data and risk reported in other journal articles. After reviewing the data, the authors concluded that toilet flushing poses low, acceptable risk, but garden hosing and showering have risks that are higher than acceptable levels. The risk for garden hosing was related to consuming produce that contacted the irrigation water rather than exposure to spray from the watering system. Sprays for showering were evaluated, but showering involved a larger water volume intake (1.9 ml) than water intake assumed for spray inhalation/ingestion in other papers (1 ml), resulting in part in higher risk. Further, because of lower microbial concentration, Jiang el al. (2015), found that rooftop rainwater could be used for more purposes than stormwater while staying under the acceptable risk benchmarks.

Ahmed et al. (2019) summarized literature on stormwater microbial contaminants and risk. Often specific microbes have been targeted in the few studies that have been completed. Several of the studies identified *Campylobacter*, human adenovirus, *Legionella*, norovirus, and *Salmonella* in tested stormwater. The authors note that risk assessment methods have included epidemiological and QMRA models. The predicted risks varied widely and depended on the target pathogen and exposure routes. In many cases, the predicted risk was greater than levels of accepted risk for drinking water and/or recreation (Ahmed, 2019). Based on the predicted risks, the authors stated that treatments may be required to address human and environmental risks, depending on the exposure potential from the system.

Chemical contaminants

There are some studies about the chemical contaminants in rainwater and stormwater. Common contaminants in stormwater include hydrocarbons (i.e., gas and oil from vehicles), heavy metals, and grease (Jiang et al., 2015). Some contaminants of emerging concern have been found in stormwater runoff, including Bisphenol A, caffeine, and salicylic acid (Boyd, et al., 2004; Masoner et al., 2019; Napier et al., 2018; Sidhu et al., 2013). A study of Minnesota rainwater showed detections of N,N-diethyl-meta-toluamide (DEET) and cocaine in rain samples (Ferrey, et al., 2018). These contaminants are all from human impact. Additionally, reusing water many times might allow these chemicals to concentrate.

In the rain barrel sampling study by Hamilton et al. (2018) described in the rainwater section above, tests for the metals lead and zinc were also conducted. Lead was detected in 88.5% of the 26 samples, with concentrations ranging from 3 µg/L to 1,282 µg/L. The U.S. EPA irrigation standard for lead is 5,000 µg/L, making these detections within the acceptable range for irrigation. Zinc was detected in 88.5 percent of the 26 samples. Concentrations ranged from 29 µg/L to 2660 µg/L. The U.S. EPA irrigation standard for zinc is 2000 µg/L, indicating that one sample is over this level (Hamilton et al., 2018). In the Minneapolis rain barrel study, described above, tests showed elevated levels of copper, lead and zinc (City of Minneapolis, 2008).

A study of urban stormwater in Minneapolis-St. Paul, MN found 123 chemical contaminants in 36 stormwater samples (Fairbairn, et al., 2018). Categories of compounds detected included commercial-consumer compounds, pharmaceuticals, personal care products, pesticides, and others. Concentrations varied, but the median concentrations were more than 10 ng/L for 25 of the chemicals analyzed and more than 100 ng/L for nine of the chemicals. Some chemicals, like atrazine, 2,4-D, and cotinine were detected in 100% of the samples. Carbazole, found in 28% of the samples, was detected the least often (Fairbairn et al., 2018). Human health and risk implications were not explored in this study.

Outbreaks

The literature provides reports of human disease outbreaks related to stormwater reuse systems. Most of the outbreaks reported are related to direct ingestion of collected water, especially in countries other than the U.S. (Franklin, et al., 2009; Heyworth, et al., 2006; Koplan, et al., 1978; Simmons et al, 2008). There have also been outbreaks reported in association with use of wastewater for irrigation (Barrimah, et al., 1998) and with recycled process water in a sugar beet processing plant (Castor, et al., 2005).

To date, we found only one report in the literature of potential outbreaks related to inhalation of aerosols related to rainwater or stormwater reuse. This outbreak was associated with several private rainwater reuse systems in New Zealand (Simmons et al., 2008). The outbreak related to aerosols involved a groundwater storage tank in New Zealand that became contaminated with *Legionella*. The groundwater was used in a "marine blaster" that allowed high pressure spray cleaning of boats. In an area downwind from where the marine blaster was used in February 2006, a summer month in New Zealand, an outbreak of Legionnaire's disease was reported. In this outbreak, 11 potential cases were identified, with four confirmed. One person with a confirmed case died. Sampling showed that allele patterns of the *Legionella* identified in patients and in the water system were similar, which may indicate they originated from a common source. These data suggest that the marine blaster water was the cause of Legionnaire's disease cases. It is suspected that the water from the marine blaster settled in the rainwater reuse systems and subsequently exposed residents to *Legionella* when they used their private rainwater reuse systems for showering (Simmons et al., 2008).

Instances of gastrointestinal illness related to ingestion of water from rainwater harvest systems have also been reported. For example, an outbreak was reported from Trinidad, the West Indies, when a group of children and adults at a church camp ingested rainwater from a roof-collected rainwater system. A group of 48 children and adults became ill with gastrointestinal symptoms from infection with *Salmonella arechevalata.* This *Salmonella* species was found in bird droppings on the roof and entered the water source during rainfall (Koplan et al., 1978).

Risk reduction through treatment

The number of human pathogens in stormwater can vary by source and other factors, but most authors have generally reported that treatment of stormwater is recommended when there is possibility that humans will be exposed to the water. As stated by Sidhu et al., 2012,

> *"Since stormwater runoff routinely contains high numbers of [fecal indicator bacteria] FIB and other enteric pathogens, some degree of treatment of captured stormwater would be required if it were to be used for non-potable purposes."*

Another paper by Murphy et al. (2017) used data from Australia to focus on potential treatment options and estimated risk of exposure to *Campylobacter* in stormwater. In this evaluation, *Campylobacter* was monitored at the inlet and outlet of a stormwater catchment wetland system over 18 months. The log reduction (pathogen reduction) of seven different types of water treatment were evaluated either through direct measurements of *Campylobacter* or using literature values. The treatment options were 1) no treatment, 2) wetland treatment, 3) biofilter, 4) biofilter plus ultraviolet, 5) Australian recommended treatment for municipal irrigation, 6) Australian recommended treatment for indoor and outdoor use, and 7) the treatment installed at the stormwater catchment studied (direct filtration (coagulation/filtration through sand and granular activated carbon), UV disinfection and chlorination). The log reductions ranged from zero for no treatment to a range of 5.37 to 13.36 for treatment number seven.

Using the dose-response model from Schmidt et al. (2016), Murphy et al. (2017) found that none of the treatment scenarios met the annual goal of 10^{-4}-annual risk of *Campylobacter* infection for all uses, except for the stormwater pond treatment with filtration, UV and chlorination.

Bichai and Ashbolt (2017) note many stormwater treatment systems have not been tested “in situ” or in real-life application. Questions remain about the effectiveness of the treatment systems, and how often they need to be monitored and serviced. In addition, a way to check for treatment effectiveness is needed. The authors acknowledge that direct monitoring for pathogens is not practical, and suggest other options, such as monitoring for the traditional fecal indicator bacteria (such as *E. coli*) and a second surrogate, such as Human bacteroides. Schoen et al. (2017) provide suggestions for $\log_{10}$ reduction targets (LRTs) and continuous process monitoring.

Appendix B: Development of acceptable risk levels

Microbial risk

Recreational water contact

The first recreational water quality criteria were proposed in 1968 by the National Technical Advisory Committee (NTAC) (National Technical Advisory Committee, 1968). The recommendations were based on studies of swimmers conducted in 1940s and 1950s by the U.S. Public Health Service. Beaches were located in Chicago, IL; Dayton, KY; Long Island Sound, NY; and New Rochelle, NY. Participants used a calendar system to record when they went swimming and when they experienced gastrointestinal illnesses, respiratory and skin infections (U.S. EPA, 1986).

In the 1960s, the NTAC determined that the level at which swimmers experienced a "significant" increase in illnesses was 400 fecal coliform colony forming units (CFU) per 100 milliliters (about 3.5 fluid ounces) of water. To set a standard, 400 CFU level was cut in half, resulting in a standard of 200 fecal coliform CFU per 100 ml of water. The researchers later assumed that this level of fecal coliform concentration was appropriate, basing their assumption on the swimmers' willingness to return to the recreational areas (U.S. EPA, 1986).

After some criticism of the studies from the 1940s and 1950s, U.S. EPA commissioned a new epidemiological study of illnesses associated with recreational swimming in the 1970s. This study examined more beaches, including areas known to be "clean," along with water known to be in the path of sewage effluents (U.S. EPA, 2012a). In this study, the measured parameters were better defined than in the previous study. In addition, the definition of a gastrointestinal (GI) illness was more strictly defined. A GI illness was defined as symptoms of vomiting; diarrhea with a fever or diarrhea that required staying home, remaining in bed, or seeking medical advice; or a stomachache or nausea with a fever. This information was collected by phone survey.

In 1986, U.S. EPA used the 1970 epidemiological data and associated water quality measures to update the water quality standard for recreational waters. To derive the standard, EPA first determined the background level of illness within the population of people who went to the beach but did not swim (nonswimmers). U.S. EPA observers then compared nonswimmers to swimmers (people who visited the beach and did swim). U.S. EPA calculated that the nonswimmer rate of illness was approximately 14 illnesses per 1000 people. For swimmers, U.S. EPA calculated that there were an *excess* of 8 people with GI illness per 1,000 swimmers by subtracting the nonswimmers' rate of illness from the swimmers' rate of illnesses (U.S. EPA, 1986). (The swimmers' rate of illness was 22 per 1,000 swimmers.) In marine waters, U.S. EPA calculated that there was an excess of 19 people with GI illnesses per 1,000 swimmers, using the same evaluation technique (U.S. EPA, 1986).

Within the water quality standard, there is a tacit implication that the level of illness associated with swimming is acceptable, because people continued to go to the beach to swim.

Beginning in 2002, U.S. EPA made an attempt to get a better understanding of water quality and health effects after recreational use of water. Under the National Epidemiological and Environmental Assessment of Recreational Water (NEEAR) study, there were seven studies completed by 2007. The definition of GI illness was updated under this study to exclude the fever requirement. The updated definition required diarrhea within a 24 hour period after swimming; vomiting; nausea and stomachache; or nausea and stomachache that required missing time from work or school or other regular activities.

Using data from the NEEAR studies, U.S. EPA released updated criteria in 2012. For marine waters, the criteria are a geometric mean concentration of 35 enterococcus/100 ml or 30 enterococcus/100 ml over 30 days. For freshwater, the criteria are a geometric mean concentration of 35 enterococcus/100 ml and 126 E. coli/100 ml or 30 enterococcus /100 ml and 100 E. coli /100 ml over 30 days (U.S. EPA, 2012c). These concentrations are expected to result in 36 or 33 illnesses per 1000 swimmers per event, respectively. U.S. EPA maintains that these levels are comparable to background levels of illness, which implies that the level is "acceptable."

Drinking water

A goal of 1/10,000 infections per year from drinking water is widely accepted in the U.S. water community. This benchmark was developed based on the probability of infection with *Giardia*, a protozoan that causes gastrointestinal symptoms, after ingesting water. *Giardia* was chosen as the target pathogen because it has a cyst stage that is more difficult to inactivate with disinfection techniques (National Research Council (NRC), 2006).

Note that unlike the recreational standard, which uses illnesses as the endpoint, this drinking water acceptable risk goal concerns *infection*. During an infection, the microbe has invaded the tissue and has possibly begun reproduction, but symptoms of illness might not necessarily occur. In practice, given that about 50-67% of *Giardia* infections are thought to progress to illness, the benchmark effectively limits *illnesses* (i.e., infection with symptoms) to 1/20,000 per year (Hunter & Fewtrell, 2001). In other words, in a population of 20,000 people, one person would become ill during the year using the goal of one *Giardia* infection per 10,000 consumers of water (National Primary Drinking Water Regulations, 1989)

Cancer risk

In 1960s, U.S. federal agencies determined that 1/1 million risk (or probability) of developing cancer over a lifetime of exposures is considered "essentially zero" risk (Hunter and Fewtrell, 2001). In the early 1970s, U.S. Food and Drug Administration adopted 1/100 million cases in a lifetime as a "virtually safe" standard, based on risk of residues of carcinogenic drugs in animals used for food, but reverted to 1/1 million in 1977 (Hunter and Fewtrell, 2001). U.S. EPA now has target range of 1/10,000 to 1/1 million cases of cancer over a lifetime from exposure to carcinogens. The World Health Organization has also used this range for drinking water quality and risk of cancer. MDH has followed this range in its calculations for Health Risk Limits and other health-based guidance for groundwater, with water guidance values calculated for a lifetime risk of cancer of 1/100,000.

Appendix C: Research in Minnesota

We used data from three out of the following four studies in our Minnesota QMRA[2]. The data used in QMRA came from samples analyzed in laboratories using techniques called quantitative polymerase chain reaction (qPCR) and microfluidic qPCR. Both methods provide information about the presence of microbes in the sample by counting the number of the microbe's genetic copies per liter (gc/L) in the sampled water.

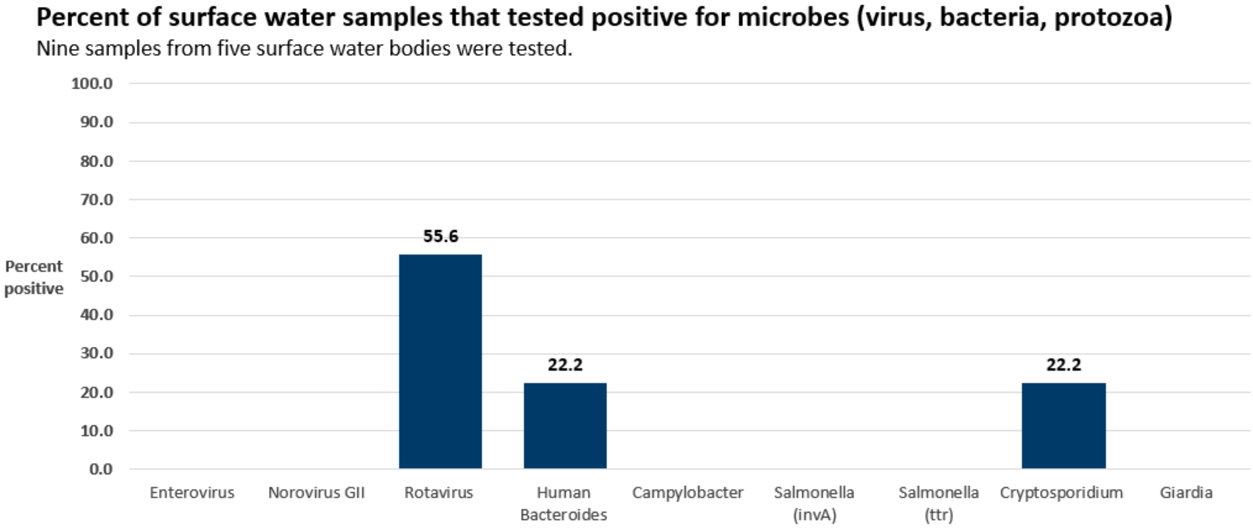
Project descriptions

Groundwater and surface water

At the request of the Minnesota Legislature, we conducted a study of viruses and other pathogens in Minnesota groundwater Pathogen Project. During the study, we sampled untreated source water from 145 public drinking water supply wells. Five surface water bodies (lakes and rivers) were also sampled to determine if they could be a potential source of pathogens (Figures 3 and 4). Here, these results can be used to offer some comparison to the results for stormwater in the other studies. There were fewer types of microbes detected in surface water, and maximum concentrations were lower than stormwater for two out of three microbes detected.

Figure 3. Percent of surface water samples that tested positive for microbes

Nine samples from five surface water bodies were tested.

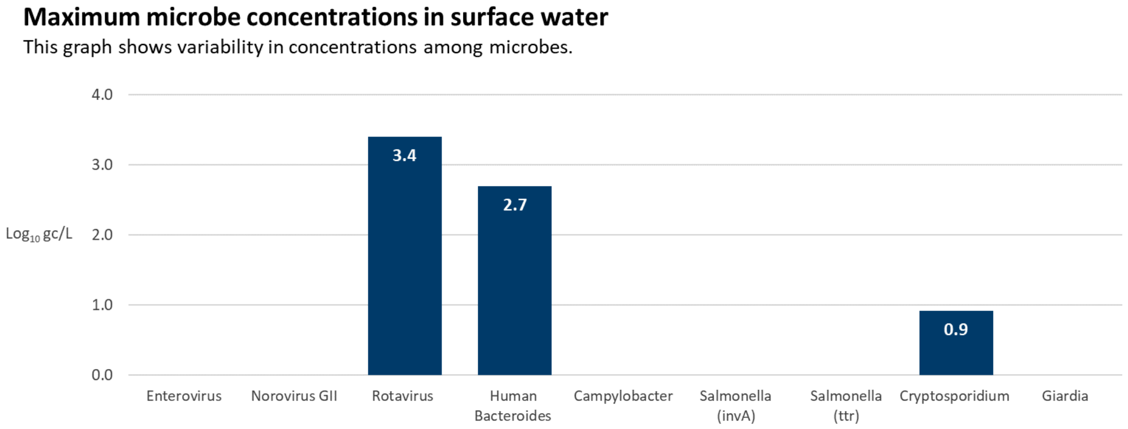


---

[2] Data used in these analyses are owned by the University of Minnesota. Inquiries about access to the data can be directed to MDH at health.water.reuse.mn@state.mn.us for further information.

Figure 4. Maximum microbe concentrations in surface water

This graph shows variability in concentrations among microbes.



Two systems, repeated sampling

In June 2015, we contracted with the University of Minnesota (U of M) to complete a study, supported by the Clean Water Fund, which focused on potential human health risks related to exposures from stormwater reuse systems. The study goal was to identify potential pathogens in the water.

A series of water samples were collected from two systems:

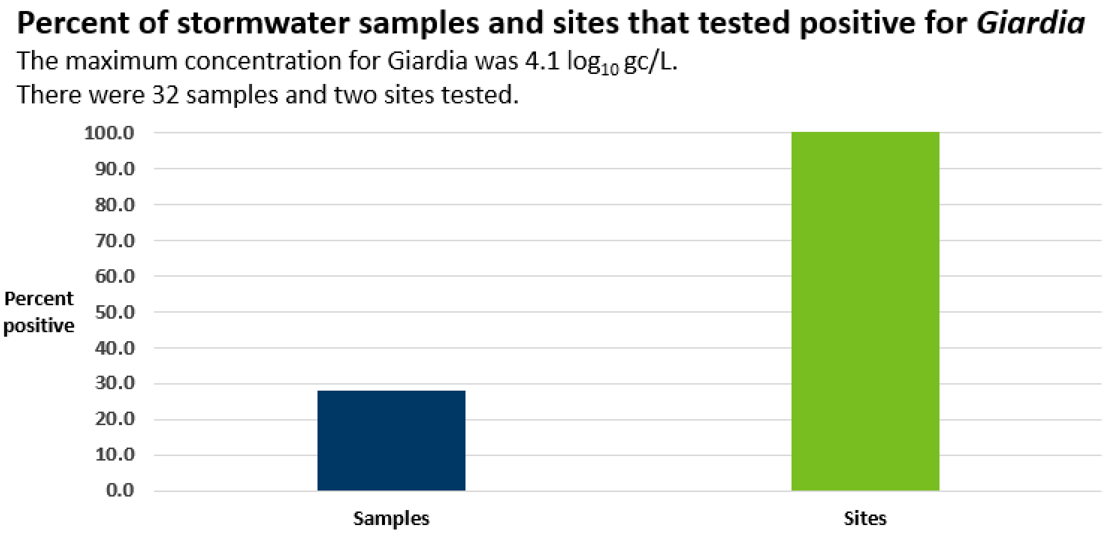
1) collected stormwater feeding a toilet flushing system in a building and 2) a stormwater pond used to irrigate fields in a city park.

Water quality in both systems was compared to other sources of water. Water in the stormwater toilet flushing system was compared to municipal tap water. Water in the stormwater irrigation system was compared to groundwater and lake water.

For both systems, the water to be reused contained higher levels of pathogens than the water tested for comparison. Overall, the concentrations of pathogens in the stormwater reuse systems were relatively low, but still at concentrations that could make people sick. More information about the results of this study can be found at Water Reuse System Sampling Results Summary (PDF). This was the only study that analyzed for *Giardia* in stormwater and we used that data in our QMRA (Figure 5).

Figure 5. Percent of stormwater samples and sites that tested positive for *Giardia*

The maximum concentration for Giardia was 4.1 log$_{10}$ gc/L. There were 32 samples and two sites tested.



Stormwater infiltration study site

There is a study site at Upper Villa Park in Roseville where stormwater is collected in a cistern and from there either infiltrated into the ground or used to irrigate an athletic field. Lysimeters were installed at the site in order to monitor groundwater quality below the infiltration gallery. A monitoring well was also installed between the infiltration system and the receiving wetland. The Minnesota Pollution Control Agency (MPCA) is studying groundwater quality at this site. MDH also had an interest in monitoring for microbial pathogens as part of the Pathogen Project (see groundwater and surface water section above), to see if stormwater was a possible source of microbial contamination to groundwater. Eight rounds of samples were collected at various sample points between November 2016 and November 2017 and analyzed for microbial pathogens and indicators along with a suite of pharmaceutical compounds, artificial sweeteners and personal care products. Two studies analyzed for *Cryptosporidium* in stormwater, but the only detection for source water was in this study (de Lambert, et al., 2021). We used that data point from this study, a *Cryptosporidium* detection of -0.1 log$_{10}$ gc/L in the cistern, in our Minnesota QMRA (Table 7).

Multiple systems (LCCMR study)

The first U of M study focused on repeated sampling in two systems, but there are many different types of water reuse systems already being used in Minnesota. To get a better understanding about microbial populations in different types of systems, we partnered again with the U of M. This study, funded by the Legislative-Citizens Commission on Minnesota Resources (LCCMR), analyzed the microbial population in several kinds of systems. In addition, some samples were analyzed for chemical contaminants. This study ran until June 2019. More information about this study can be found at Environment and Natural Resources Trust Fund (ENRTF) M.L. 2017 LCCMR Work Plan (PDF).

For chemical contaminants, we also asked our Minnesota Public Health Laboratory to use a recently acquired instrument to screen the water from some of the systems sampled. They used both non-targeted analysis (looking at a broad range of many chemicals based on no prior knowledge or expectations) and suspect screening (looking for certain contaminants we would expect to find) (Backe, 2021). The instrument provides a way to look for many chemicals at once using sophisticated mass spectrometry methods and generates a lot of data quickly.

The analysis indicated the compounds detected are often a reflection of the source water (i.e., wastewater indicators like pharmaceuticals are frequently detected in wastewater, pesticides are detected in stormwater runoff, and municipal drinking water is fairly free of detected compounds). Stormwater sources showed some detections of wastewater indicators, but at lower frequencies than wastewater sources. Further analysis may show how and if this instrument could be used to categorize sources of reuse.

A subsequent study funded by the Minnesota Stormwater Research Council (MSRC) will build on the LCCMR project. This project sampled frequently from a small number of systems to establish Temporal Dynamics of Pathogens and Antibiotic Resistance in Raw and Treated Stormwater. A publication on the study is in process.

The LCCMR project aimed to determine the number and types of pathogens and their concentrations present in currently operational water reuse systems in Minnesota. Systems were sampled from the source, after treatment (as applicable), and in the distribution system at or near where water is used. Eighty-three samples were collected from 25 systems and 15 bacterial and nine viral genes were detected through microfluidic quantitative polymerase chain reaction (qPCR).

While qPCR offers the advantages of high accuracy and shorter analysis time as compared to culture (growth) based methods, it does not indicate if a microbe is viable and able to make someone sick. It is also not yet a standardized method, and there is not a laboratory certification process for it, meaning that data can be interpreted in different ways by different researchers. For example, we found it challenging to interpret results from replicate analyses. Each of the samples was analyzed in triplicate. In many cases, the triplicates gave very different results. The most likely explanation was that the sample was not homogeneous (e.g. microbes were clumped together). We therefore decided to include any results even if not replicated, while the U of M researcher censored (did not include) these data. There are also many interpretations of limits of detection (LODs) and limits of quantification (LOQs) (Stokdyk et al., 2016). The U of M researcher calculated LOQs based on analysis of laboratory standards and blanks for each microbe, resulting in LOQs ranging from 0.3 to 4.19 $\log_{10}$ gene copies per liter ($\log_{10}$ gc/L), and excluded data that were below quantification. For our analysis, we included a result for any sample that showed a signal and was quantified, even if it was below the quantification limit. While our approach was more conservative in that it allowed us to assess risk for a larger number of microbes, we did not feel comfortable excluding more data, in part based on discussion from Chik, et al. (2018).

Source Data

A summary of data for rainwater and stormwater source waters is shown in Figures 6 through 13. For most microbes, the maximum concentrations were higher for stormwater than rainwater (Figures 7, 9, 11, 13). In both sources (rainwater and stormwater), the concentrations of pathogens were highly variable, ranging from non-detectable to several million gene copies per liter of water. The highest concentrations were for microbes that are indicators of human or animal fecal contamination (*E. coli* (ftsZ) and *E. coli* (uidA)), but all of the samples had at least one human pathogen detection.

The patterns of widespread but variable pathogen detections seen here are common to most studies of environmental microbes. There were several microbes that are not typically studied in environmental samples such as aichivirus and sapovirus, and so we do not have a baseline for those detections.

Figure 6. Percent of rainwater samples and sites that tested positive for viruses

Four viruses were detected in rainwater. There were six samples and four sites tested. Bars for the samples are on the left in blue and the sites are on the right in green above the virus name below.

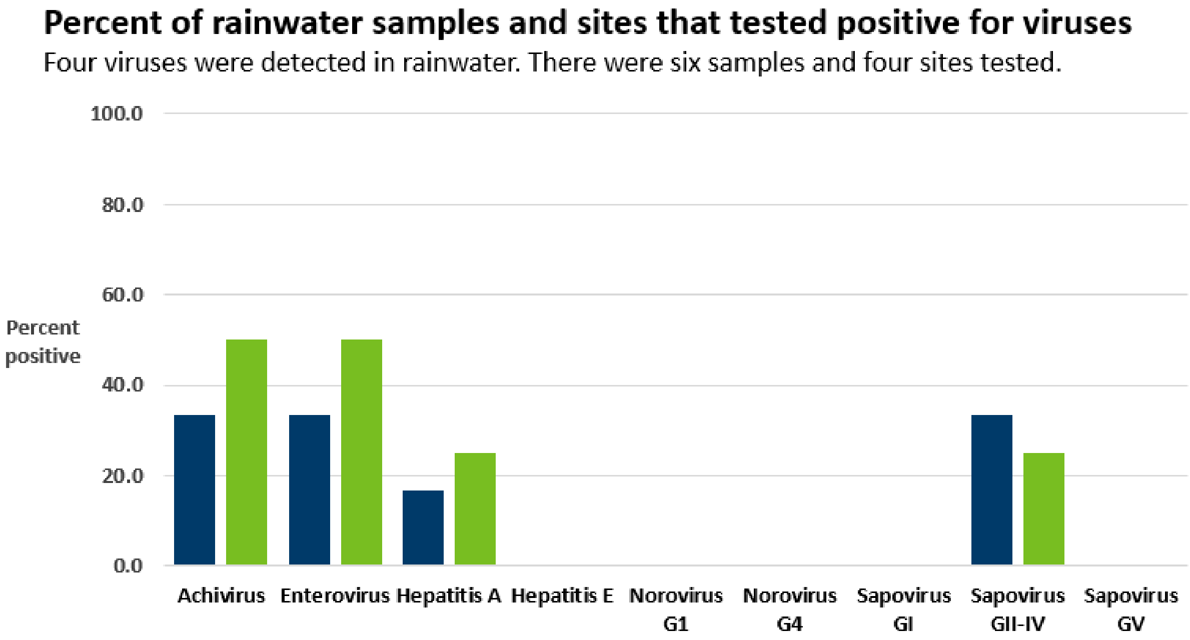


Figure 7. Maximum virus concentrations in rainwater

This graph shows variability in concentrations among viruses

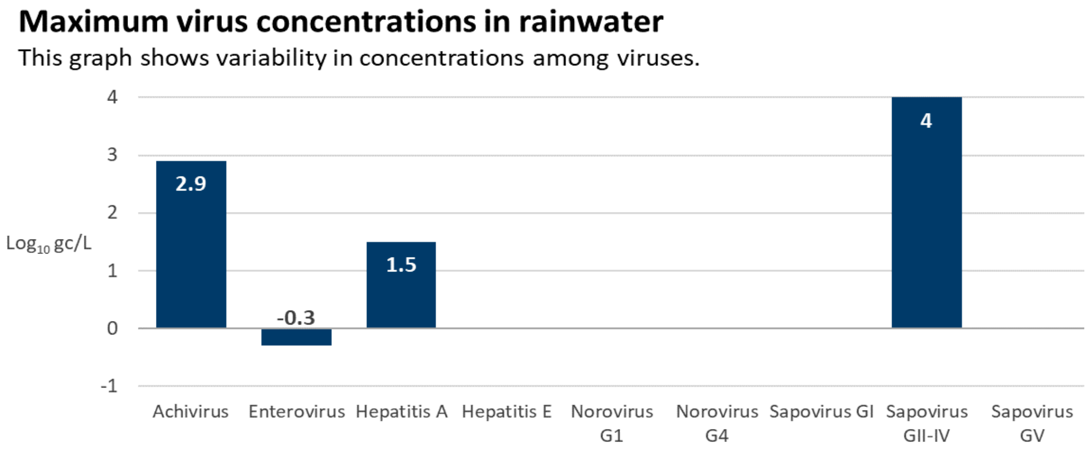


Figure 8. Percent of rainwater samples and sites that tested positive for bacteria

Thirteen bacterial targets were detected in rainwater. There was a 100 percent detection rate for two generic E. coli targets and Salmonella ttrC genes. There were six samples and four sites tested. Samples are in blue on the left and sites are in green on the right above the bacteria name below.

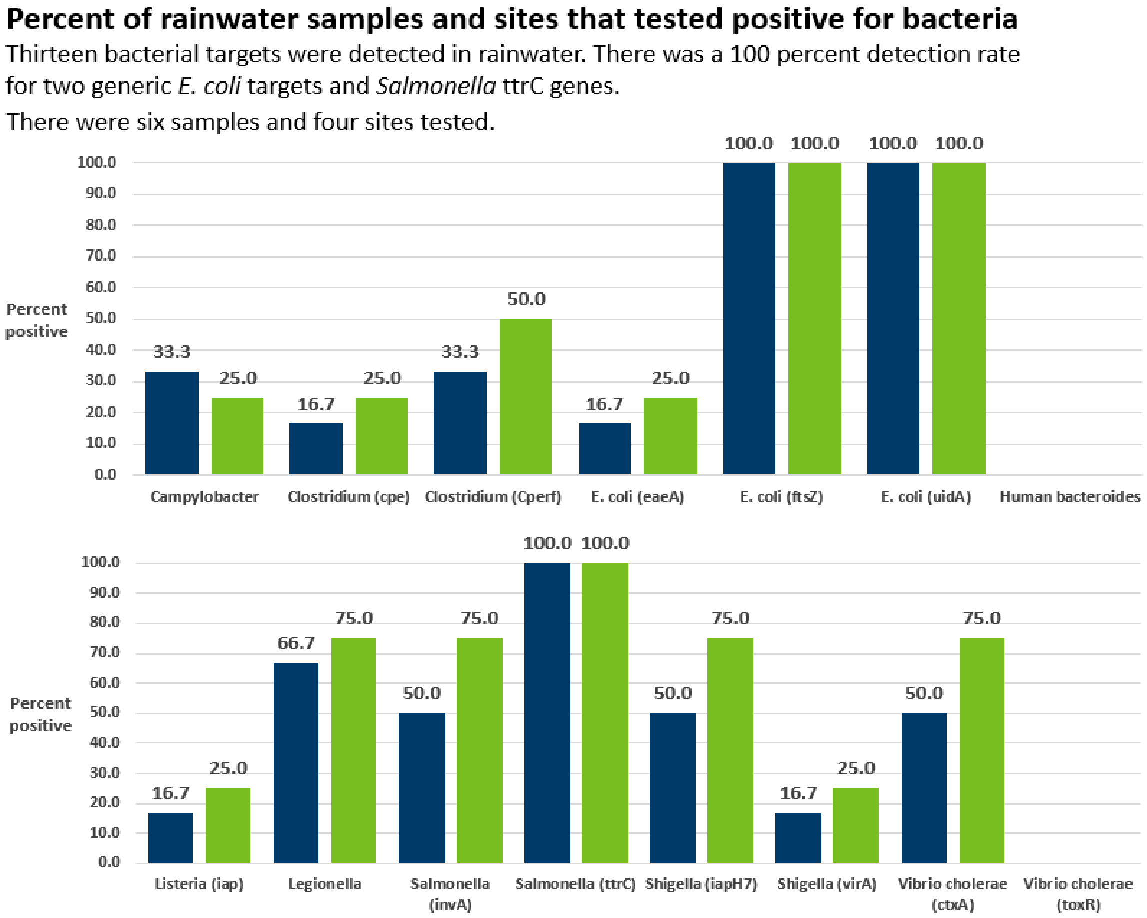


Figure 9. Maximum bacteria concentrations in rainwater

This graph shows variability in concentrations among bacteria.

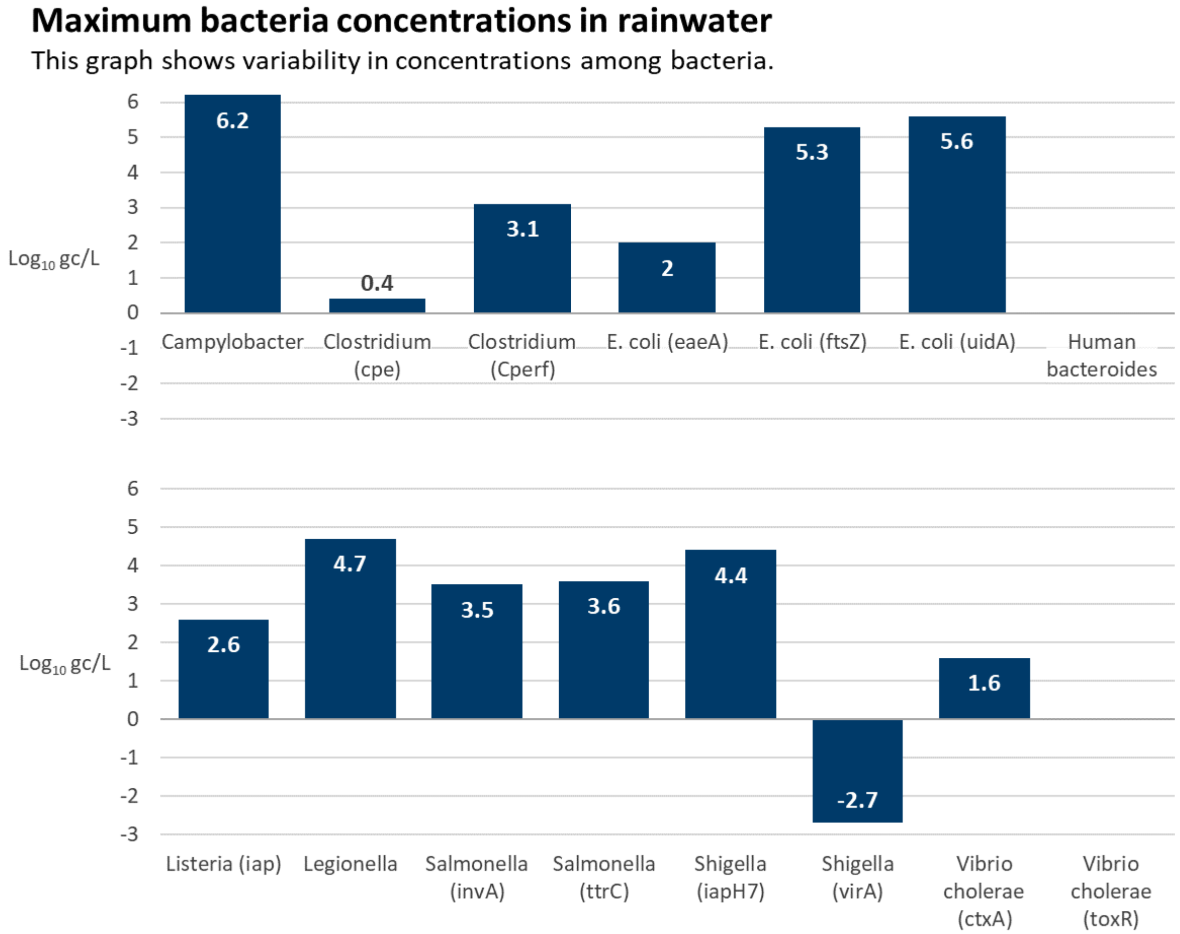


Figure 10. Percent of stormwater samples and sites that tested positive for viruses

Nine viruses were detected in stormwater. There were 22 samples and 16 sites tested. Samples are in blue on the left and sites are in green on the right above the virus name below.

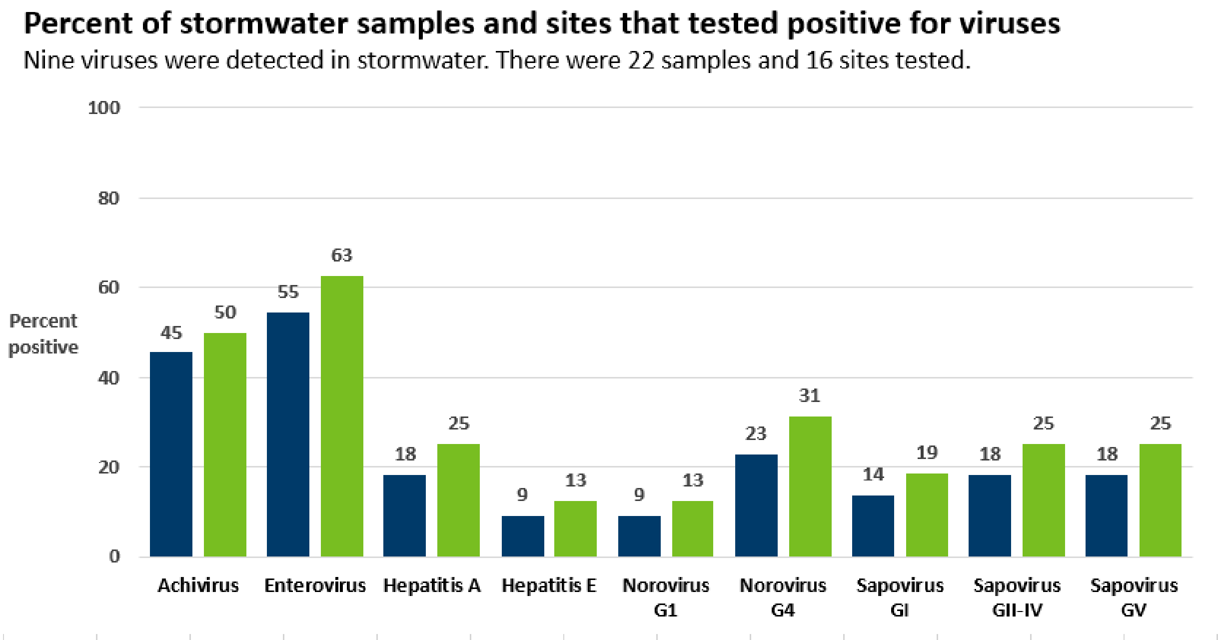


Figure 11. Maximum virus concentrations in stormwater

This graph shows variability in concentrations among viruses.

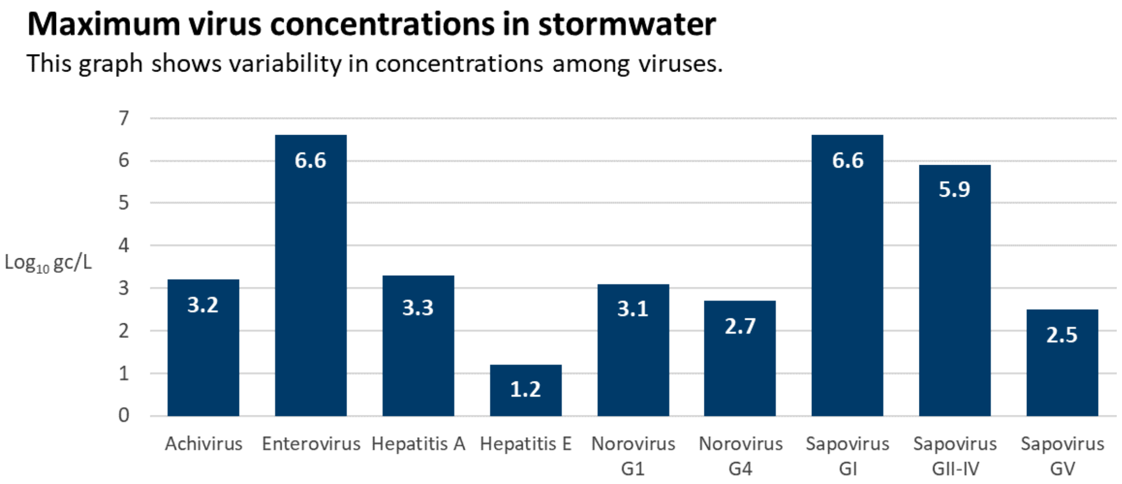


Figure 12. Percent of stormwater samples and sites that tested positive for bacteria

Fifteen bacterial targets were detected in stormwater. There was a 100 percent detection rate for one generic E. coli target. There were 22 samples and 16 sites tested. Samples are on the left in blue and sites are on the right in green above the bacteria name below.

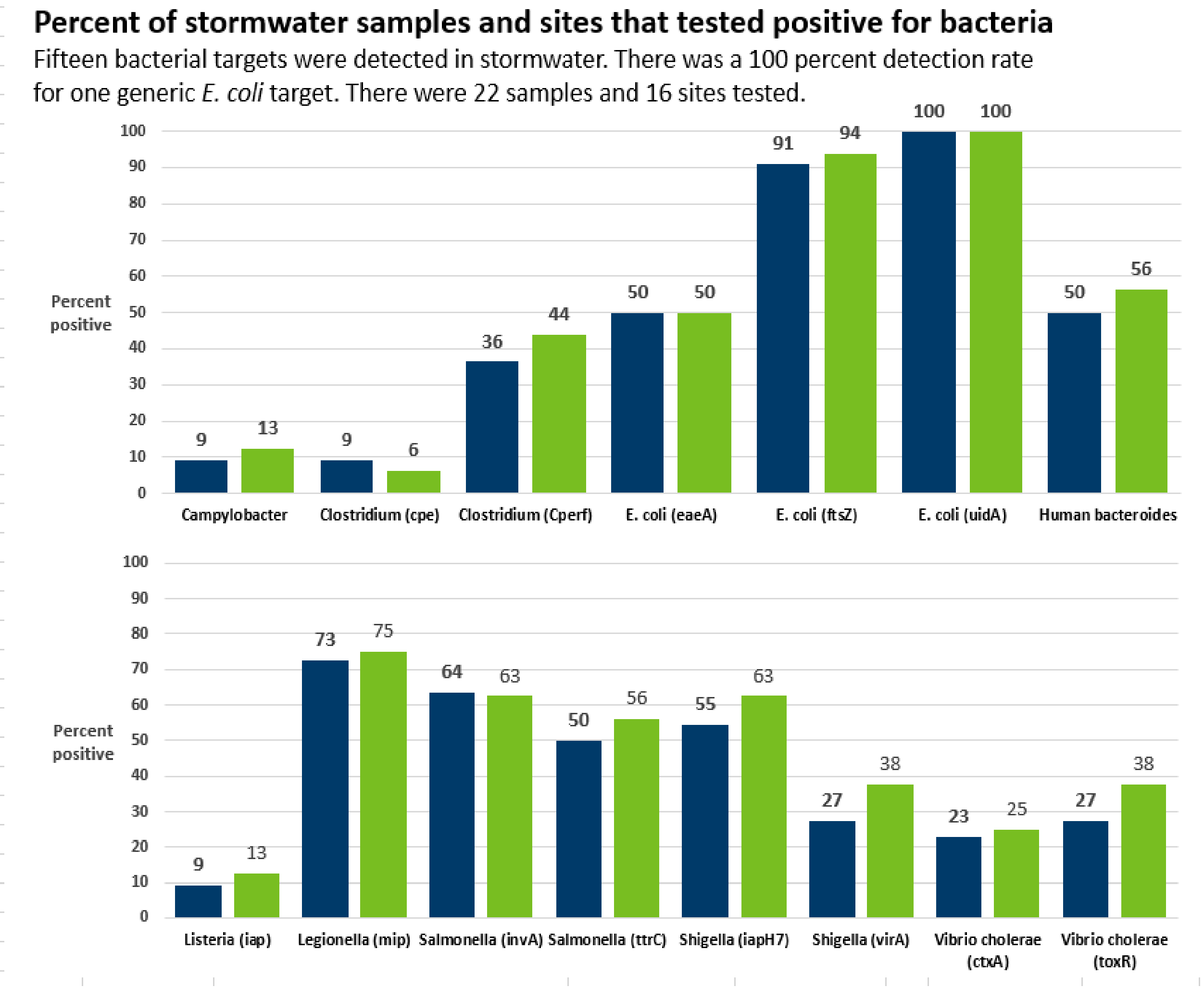
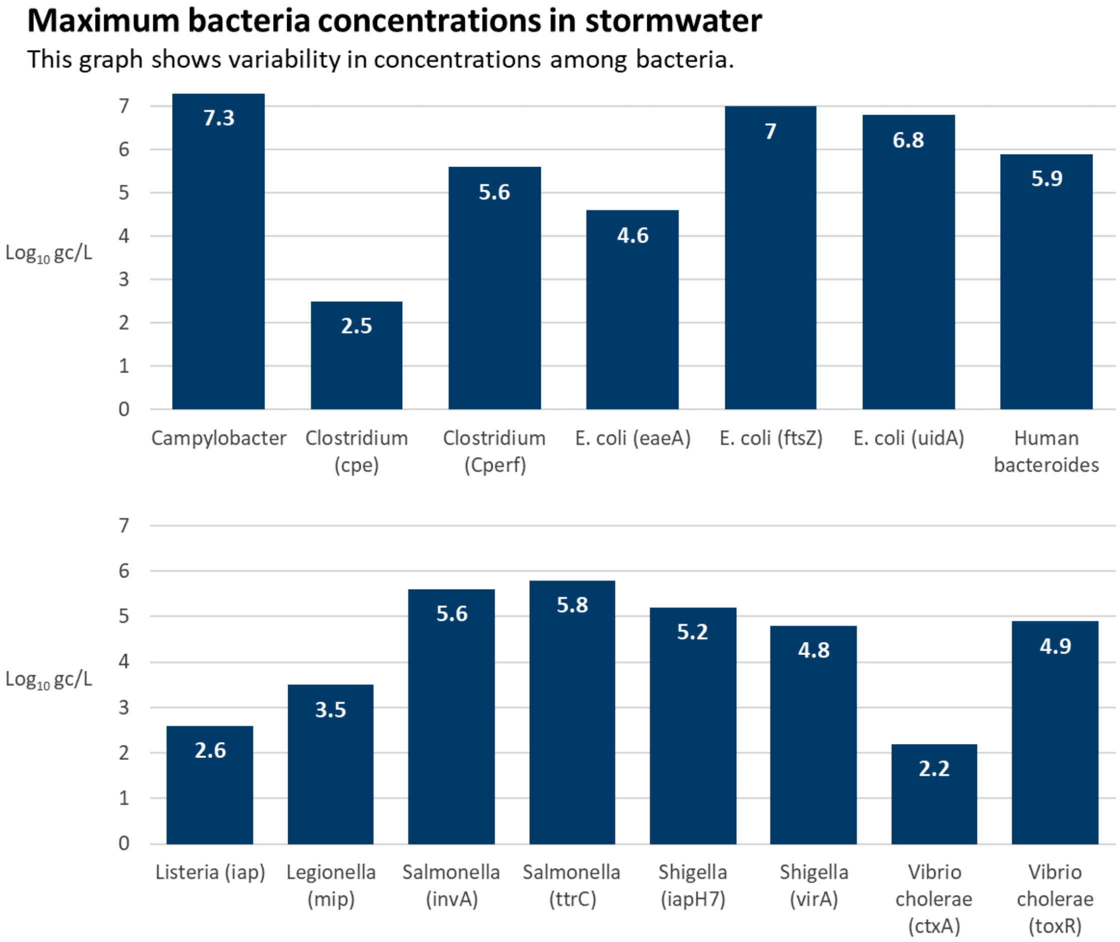


Figure 13. Maximum bacteria concentrations in stormwater

This graph shows variability in concentrations among bacteria.



Our analysis focused on source water quality, because most systems did not have treatment that was designed to remove or inactivate microbes. Further analysis of treatment and distribution will continue with ongoing projects.

Source samples were also analyzed for *E. coli* using a culture based method. Eighty-five percent of 26 samples analyzed were positive for *E. coli* by culture. So, while we don't know the viability of microbes tested by genetic methods, we have evidence of viability for FIB.

Log$_{10}$ reduction targets (LRTs)

As discussed previously in the risk management implementation section, once the risk was characterized using the source water data, log$_{10}$ reduction targets (LRTs) were calculated for several combinations of source type and use and are shown here for Minnesota data in Tables 3-7. An LRT was calculated for any microbe that had both detections and an available dose-response equation. Water uses were chosen to match the WE&RF Report Table 3-3 to allow for comparison.

Table 3. LRTs for bacteria in rainwater

Bacteria (Dose-response)	Irrigation[1]	Toilet flush[2]	Cross connection[3]	Clothes washing[4]	Combined indoor uses[5]
Pathogenic *E. coli* (Haas, 1999)	0	0	0	0	0
Pathogenic *E. coli* (Center for Advancing Microbial Risk Assessment [CAMRA], 2020b)	0	0	0	0	0
***Salmonella* (invA)** (Hass, 1999)	1.3	0.5	2.9	0	2.9
***Salmonella* (invA)** (CAMRA, 2020d)	2.7	1.9	3.4	0.9	3.4
***Salmonella* (ttrc)** (Haas, 1999)	1.5	0.7	2.7	0	2.7
***Salmonella* (ttrc)** (CAMRA, 2020d)	2.9	2.1	4.1	1.1	4.1
***Shigella flexerni* (virA)** (CAMRA, 2020e)	0.1	0	0.7	0	0.7
***Shigella flexerni* (ipaH7)** (CAMRA, 2020e)	3.7	3.0	5.2	2.0	5.2

Table 4. LRTs for bacteria in stormwater

Bacteria (Dose-response)	Irrigation[1]	Toilet flush[2]	Cross connection[3]	Clothes washing[4]	Combined indoor uses[5]
Pathogenic *E. coli* (Haas, 1999)	0	0	0	0	0
Pathogenic *E. coli* (CAMRA, 2020b)	1.0	0.1	1.3	0	1.3
***Salmonella* (invA)** (Haas, 1999)	3.0	2.0	3.2	1.1	3.2
***Salmonella* (invA)** (CAMRA, 2020d)	4.3	3.4	4.5	2.5	4.5
***Salmonella* (ttrc)** (Haas, 1999)s)	3.1	2.2	2.8	1.3	2.8
***Salmonella* (ttrc)** (CAMRA, 2020d)	4.5	4.2	3.6	2.7	4.2
***Shigella flexerni* (virA)** (CAMRA, 2020e)	3.6	2.8	3.4	1.9	3.4
***Shigella flexerni* (ipaH7)** (CAMRA, 2020e)	4.0	3.1	4.4	2.2	4.4

Table 5. LRTs for viruses in rainwater

Virus (Dose-response)	Irrigation[1]	Toilet flush[2]	Cross connection[3]	Clothes washing[4]	Combined indoor uses[5]
Norovirus G1 (Teunis et al., 2008)	NA	NA	NA	NA	NA
Norovirus G1 (Schmidt, 2015)	NA	NA	NA	NA	NA
Norovirus G1 (Messner et al.,2014)	NA	NA	NA	NA	NA
Norovirus G4 (Teunis et al., 2008)	NA	NA	NA	NA	NA
Norovirus G4 (Schmidt, 2015)	NA	NA	NA	NA	NA
Norovirus G4 (Messner et al., 2014)	NA	NA	NA	NA	NA
Enterovirus (CAMRA, 2020a)	0.3	0	0.9	0	0.9

Table 6. LRTs for viruses in stormwater

Virus (Dose-response)	Irrigation[1]	Toilet flush[2]	Cross connection[3]	Clothes washing[4]	Combined indoor uses[5]
Norovirus G1 (Teunis et al., 2008)	4.1	3.2	3.2	2.3	3.2
Norovirus G1 (Schmidt, 2015)	1.2	0.2	0.2	0	0.2
Norovirus G1 (Messner et al., 2014)	1.1	0.2	0.1	0	0.2
Norovirus G4 (Teunis et al., 2008)	4.0	3.1	3.2	2.2	3.2
Norovirus G4 (Schmidt, 2015)	1.0	0.2	0.2	0	0.2
Norovirus G4 (Messner et al., 2014)	1.0	0.1	0.1	0	0.1
Enterovirus (CAMRA, 2020a)	5.6	4.7	5.5	3.8	5.5

Table 7. LRTs for protozoa in stormwater

Protozoa (Dose-response) *Harmonization*	Irrigation[3]	Toilet flush[4]	Cross connection[5]	Clothes washing[6]	Combined indoor uses[7]
Giardia (Rose, 1991) *16 gc/cysts*	3.1	2.3	4.3	1.4	4.3
Cryptosporidium (U.S. EPA 2005) 4 gc/oocyst	1.0	0.3	1.6	0	1.6

Given the difficulties of pathogen monitoring, we thought a fecal indicator specific to humans, such as the human-specific HF183 *Bacteroides* marker, would be useful to help estimate the level of human health concern in a given source water. For example, if we use the sewage dilution approach from the WE&RF Report, the HF183 marker could be used to give an estimate of sewage dilution. However, HF183 levels in sewage are variable and this microbe does not live as long as some pathogens under environmental conditions. Understanding these limitations, we used the HF183 data from the Minnesota studies, along with literature values for HF183 concentrations in sewage, to estimate the range of sewage dilution for Minnesota stormwater and it ranged from 3.7×10^{-7} to 3.6×10^{-2} with a median of 5.3×10^{-6}. Only 50 percent of pathogen positive samples were positive for HF183, however, and based on pathogen results we are currently recommending using the LRTs for 10^{-3} dilution from the WE&RF Report.

Recommendations for Future Studies

There were several study limitations that we recommend researchers try to address within future projects:

- Develop standard procedures to address heterogeneity of stormwater samples.
- Plan and document standardized quality assurance and quality control procedures for both in the field and in the lab.
- Sample sites multiple times to provide a good picture of seasonality or general variability.
- Make special planning efforts to sample systems when in normal operation (e.g. systems are often programmed to irrigate at night, while sampling is more convenient during the day but operators are hesitant to override the programming).
- Use qPCR in combination with culture-based methods for more complete analysis. Knowing microbe viability will reduce uncertainty and will allow for analysis of treatment effectiveness. We do not know for sure if microbes that have been inactivated by UV disinfection or chlorination will still be detected by qPCR.

---

[3] 50 exposures/year at 1ml/exposure

[4] 1100 exposures/year at 0.01 ml/exposure

[5] 1 exposure/year for 10% of population at 2L/exposure

[6] 100 exposures/year at .01 ml/exposure

[7] Combined toilet flushing, clothes washing and cross-connection

References

Ahmed, W., Vieritz, A., Goonetilleke, A., & Gardner, T. (2010). Health risk from the use of roof-harvested rainwater in Southeast Queensland, Australia, as potable or nonpotable water, determined using quantitative microbial risk assessment. *Appl. Environ. Microbiol.*, *76*(22), 7382-7391.

Ahmed, W., Gardner, T., & Toze, S. (2011). Microbiological quality of roof-harvested rainwater and health risks: a review. *Journal of environmental quality*, *40*(1), 13-21.

Ahmed, W., Hamilton, K., Toze, S., Cook, S., & Page, D. (2019). A review on microbial contaminants in stormwater runoff and outfalls: Potential health risks and mitigation strategies. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2019.07.055

Backe, W. J. (2021). Suspect and non-target screening of reuse water by large-volume injection liquid chromatography and quadrupole time-of-flight mass spectrometry. *Chemosphere*, 266, 128961.

Barrimah, E., Salem, K. A., & Gabal, M. S. (1998). An outbreak of hepatitis A associated with treated waste water used for irrigation. The Journal of the Egyptian Public Health Association, 74(3-4), 227-239.

Bichai, F., & Ashbolt, N. (2017). Public health and water quality management in low-exposure stormwater schemes: A critical review of regulatory frameworks and path forward. Sustainable cities and society, 28, 453-465.

Boehm, A. B., Silverman, A. I., Schriewer, A., & Goodwin, K. (2019). Systematic review and meta-analysis of decay rates of waterborne mammalian viruses and coliphages in surface waters. *Water research*, *164*, 114898. https://doi.org/10.1016/j.watres.2019.114898

Boyd, G. R., Palmeri, J. M., Zhang, S., & Grimm, D. A. (2004). Pharmaceuticals and personal care products (PPCPs) and endocrine disrupting chemicals (EDCs) in stormwater canals and Bayou St. John in New Orleans, Louisiana, USA. Science of the Total Environment, 333(1-3), 137-148. https://doi.org/10.1016/j.scitotenv.2004.03.018

Brown, V. J. (2014). Risk perception: it’s personal. *Environmental Health Perspectives,* 122(10), A276. https://doi.org/10.1289/ehp.122-A276

Burch, T. (2019). Validation of Quantitative Microbial Risk Assessment Using Epidemiological Data from Outbreaks of Waterborne Gastrointestinal Disease. Risk Analysis, 39(3), 599-615. https://doi.org/10.1111/risa.13189

Castor, M. L., Wagstrom, E. A., Danila, R. N., Smith, K. E., Naimi, T. S., Besser, J. M., & Kirkhorn, S. R. (2005). An outbreak of Pontiac fever with respiratory distress among workers performing high-pressure cleaning at a sugar-beet processing plant. The Journal of infectious diseases, 191(9), 1530-1537. https://doi.org/10.1086/428776

Center for Advancing Microbial Risk Assessment. (2020a). Completed Dose Response Model for Enterovirus. http://qmrawiki.org/experiments/enterovirus/113.

Center for Advancing Microbial Risk Assessment. (2020b). Completed Dose Response Model for Pathogenic E. coli. http://qmrawiki.org/experiments/escherichia-coli.

Center for Advancing Microbial Risk Assessment. (2020c), Completed Dose Response Model for Giardia. http://qmrawiki.org/experiments/giardia-duodenalis

Center for Advancing Microbial Risk Assessment. (2020d.) Completed Dose Response Model for Salmonella. http://qmrawiki.org/experiments/salmonella-nontyphoid

Center for Advancing Microbial Risk Assessment. (2020e), Completed Dose Response Model for Shigella flexerni. http://qmrawiki.org/experiments/shigella-flexneri

Chik, A. H. S., Schmidt, P. J., & Emelko, M. B. (2018). Learning something from nothing: the critical importance of rethinking microbial non-detects. *Frontiers in microbiology*, *9*, 2304.

Cities, W. S. (2011). Blueprint 2011 stormwater management in a water sensitive city. *The Centre for Water Sensitive Cities. Monash University, Clayton*

City of Minneapolis, Department of Public Works Division of Surface water & Sewers. (2008.) U.S. EPA Region 5 Great Cities Program Neighborhood Rain Barrel Partnership Final Project Report.

de Lambert, J. R., Walsh, J. F., Scher, D. P., Firnstahl, A. D., & Borchardt, M. A. (2021). Microbial pathogens and contaminants of emerging concern in groundwater at an urban subsurface stormwater infiltration site. *Science of The Total Environment*, *775*, 145738.

Despins, C., Farahbakhsh, K., & Leidl, C. (2009). Assessment of rainwater quality from rainwater harvesting systems in Ontario, Canada. Journal of Water Supply: Research and Technology—AQUA, 58(2), 117-134. https://doi.org/10.2166/aqua.2009.013

Dobrowsky, P. H., De Kwaadsteniet, M., Cloete, T. E., & Khan, W. (2014). Distribution of indigenous bacterial pathogens and potential pathogens associated with roof-harvested rainwater. Appl. Environ. Microbiol., 80(7), 2307-2316.

Fairbairn, D. J., Elliott, S. M., Kiesling, R. L., Schoenfuss, H. L., Ferrey, M. L., & Westerhoff, B. M. (2018). Contaminants of emerging concern in urban stormwater: Spatiotemporal patterns and removal by iron-enhanced sand filters (IESFs). *Water Research*, *145*, 332-345.

Ferrey, M. L., Hamilton, M. C., Backe, W. J., & Anderson, K. E. (2018). Pharmaceuticals and other anthropogenic chemicals in atmospheric particulates and precipitation. Science of The Total Environment, 612, 1488–1497. doi: 10.1016/j.scitotenv.2017.06.201

Franklin, L. J., Fielding, J. E., Gregory, J., Gullan, L., Lightfoot, D., Poznanski, S. Y., & Vally, H. (2009). An outbreak of Salmonella Typhimurium 9 at a school camp linked to contamination of rainwater tanks. *Epidemiology & Infection*, *137*(3), 434-440.

Haas, C. N. (2015). Microbial dose response modeling: past, present, and future. Environmental Science & Technology, 49(3), 1245-1259.

Haas, C. N., Rose, J. B., & Gerba, C. P. (1999). Quantitative microbial risk assessment. John Wiley & Sons. https://doi.org/10.1017/S095026880800109X

Hamilton, K. A., Ahmed, W., Toze, S., & Haas, C. N. (2017). Human health risks for Legionella and Mycobacterium avium complex (MAC) from potable and non-potable uses of roof-harvested rainwater. Water research, 119, 288-303.

Hamilton, K., Parrish, K., Ahmed, W., & Haas, C. (2018). Assessment of Water Quality in Roof-Harvested Rainwater Barrels in Greater Philadelphia. Water, 10(2), 92.

Heyworth, J. S., Glonek, G., Maynard, E. J., Baghurst, P. A., & Finlay-Jones, J. (2006). Consumption of untreated tank rainwater and gastroenteritis among young children in South Australia. International Journal of Epidemiology, 35(4), 1051-1058. https://doi.org/10.1093/ije/dyl105

Hunter, P. R., & Fewtrell, L. (2001). Acceptable risk. Water Quality: Guidelines, Standards and Health. Risk assessment and management for water-related infectious disease. London: IWA Publishing, 207-227. http://www.who.int/water_sanitation_health/dwq/iwachap10.pdf.

Irias, X. (2019). The Three Rs of Risk Management. *Journal-American Water Works Association*, *111*(8), 56-64. https://doi.org/10.1002/awwa.1343

Jiang, S. C., Lim, K. Y., Huang, X., McCarthy, D., & Hamilton, A. J. (2015). Human and environmental health risks and benefits associated with use of urban stormwater. Wiley Interdisciplinary Reviews: Water, 2(6), 683-699.

Kim, T., Lye, D., Donohue, M., Mistry, J. H., Pfaller, S., Vesper, S., & Kirisits, M. J. (2016). Harvested rainwater quality before and after treatment and distribution in residential systems. Journal-American Water Works Association, 108(11), E571-E584.

Koplan, J. P., Deen, R. D., Swanston, W. H., & Tota, B. (1978). Contaminated roof-collected rainwater as a possible cause of an outbreak of salmonellosis. *Epidemiology & Infection*, *81*(2), 303-309. https://doi.org/10.1017/S0022172400025146

Lim, K. Y., Hamilton, A. J., & Jiang, S. C. (2015). Assessment of public health risk associated with viral contamination in harvested urban stormwater for domestic applications. *Science of the Total Environment*, *523*, 95-108.

Liu, X., He, Y., Fu, H., Chen, B., Wang, M., & Wang, Z. (2018). How environmental protection motivation influences on residents' recycled water reuse behaviors: A case study in Xi'an city. *Water*, *10*(9), 1282. https://www.mdpi.com/2073-4441/10/9/1282

Martinson, B., & Thomas, T. (2009). Quantifying the first-flush phenomenon: effects of first-flush on water yield and quality. In *14th International Rainwater Catchment Systems Conference*. https://researchportal.port.ac.uk/portal/files/33154/Quantifying_the_First-Flush_phenomenon.pdf

Masoner, J. R., Kolpin, D. W., Cozzarelli, I. M., Barber, L. B., Burden, D. S., Foreman, W. T., Forshay, K. J., Furlong, E. T., Groves, J. F., Hladik, M. L., Hopton, M. E., Jaeschke, J. B., Keefe, S. H., Krabbenhoft, D. P., Lowrance, R., Romanok, K. M., Rus, D. L., Selbig, W. R., Williams, B. H., & Bradley, P. M. (2019). Urban stormwater: An overlooked pathway of extensive mixed contaminants to surface and groundwaters in the United States. *Environmental Science & Technology*, 53(17), 10070-10081. https://doi.org/10.1021/acs.est.9b02867

Medema, G., & Ashbolt, N. (2006). QMRA: its value for risk management. *Comunidade Europeia*. http://www.camra.msu.edu/documents/QMRA_framework.pdf

Mendez, C. B., Klenzendorf, J. B., Afshar, B. R., Simmons, M. T., Barrett, M. E., Kinney, K. A., & Kirisits, M. J. (2011). The effect of roofing material on the quality of harvested rainwater. *Water Research*, *45*(5), 2049-2059. https://doi.org/10.1016/j.watres.2010.12.015

Messner, M. J., Berger, P., & Nappier, S. P. (2014). Fractional Poisson—A simple dose-response model for human norovirus. *Risk Analysis*, *34*(10), 1820-1829.

Minnesota Water Reuse Interagency Workgroup. 2018. Advancing Safe and Sustainable Water Reuse in Minnesota. https://www.health.state.mn.us/communities/environment/water/docs/cwf/2018report.pdf. Retrieved on May 9, 2019.

Murphy, H. M., Meng, Z., Henry, R., Deletic, A., & McCarthy, D. T. (2017). Current stormwater harvesting guidelines are inadequate for mitigating risk from Campylobacter during nonpotable reuse activities. *Environmental Science & Technology*, *51*(21), 12498-12507.

Napier, M. D., Poole, C., Stewart, J. R., Weber, D. J., Glassmeyer, S. T., Kolpin, D. W., Furlong, E.T., Doufour, A.P. & Wade, T. J. (2018). Exposure to Human-Associated Chemical Markers of Fecal Contamination and Self-Reported Illness among Swimmers at Recreational Beaches. *Environmental Science & Technology*, *52*(13), 7513-7523. https://doi.org/10.1021/acs.est.8b00639

National Primary Drinking Water Regulations, 54 Fed. Reg. 27490, Jun 29, 1989.

National Research Council. 2006. Drinking Water Distribution Systems: Assessing and Reducing Risks. Washington, DC: The National Academies Press. doi: 10.17226/11728. Available from http://www.nap.edu/read/11728/chapter/5#90. Accessed April 21, 2016.

National Technical Advisory Committee. 1968. Water Quality Criteria. Report of the National Technical Advisory Committee to the Secretary of the Interior. https://files.eric.ed.gov/fulltext/ED046708.pdf

Natural Resource Management Ministerial Council, Environmental Protection and Heritage Council, & Australian Health Ministers Conference. (2006). Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1). *National Water Quality Management Strategy, Canberra, Australia*. https://www.waterquality.gov.au/sites/default/files/documents/water-recycling-guidelines-full-21.pdf

Ross, V. L., Fielding, K. S., & Louis, W. R. (2014). Social trust, risk perceptions and public acceptance of recycled water: Testing a social-psychological model. Journal of environmental management, 137, 61-68.

Schmidt, P. J. (2015). Norovirus dose–response: are currently available data informative enough to determine how susceptible humans are to infection from a single virus? *Risk Analysis*, *35*(7), 1364-1383.

Schoen, M. E., & Ashbolt, N.J. (2010). Assessing pathogen risk to swimmers at non-sewage impacted recreational beaches. *Environmental Science & Technology, 44(7), 2286-2291.*

Schoen, M. E., Ashbolt, N. J., Jahne, M. A., & Garland, J. (2017). Risk-based enteric pathogen reduction targets for non-potable and direct potable use of roof runoff, stormwater, and greywater. *Microbial Risk Analysis*, *5*, 32-43. https://doi.org/10.1016/j.mran.2017.01.002

Sharvelle, S., Ashbolt, N., Clerico, E., Holquist, R., Levernz, H., & Olivieri, A. (2017). Risk-Based Framework for the Development of Public Health Guidance for Decentralized Non-Potable Water Systems. *Proceedings of the Water Environment Federation*, *2017*(8), 3799-3809. https://watereuse.org/wp-content/uploads/2019/11/Risk-Based-Framework-for-DNWS-Report_FINAL.pdf

Sidhu, J. P. S., Hodgers, L., Ahmed, W., Chong, M. N., & Toze, S. (2012). Prevalence of human pathogens and indicators in stormwater runoff in Brisbane, Australia. *Water Research*, *46*(20), 6652-6660. https://doi.org/10.1016/j.watres.2012.03.012

Sidhu, J. P. S., Ahmed, W., Gernjak, W., Aryal, R., McCarthy, D., Palmer, A., Kolotelo, P., & Toze, S. (2013). Sewage pollution in urban stormwater runoff as evident from the widespread presence of multiple microbial and chemical source tracking markers. Science of the Total Environment, 463, 488-496. https://doi.org/10.1016/j.scitotenv.2013.06.020

Simmons, G., Jury, S., Thornley, C., Harte, D., Mohiuddin, J., & Taylor, M. (2008). A Legionnaires' disease outbreak: A water blaster and roof-collected rainwater systems. *Water Research*, *42*(6-7), 1449-1458. https://doi.org/10.1016/j.watres.2007.10.016

Soller, J. A., Eftim, S., Wade, T. J., Ichida, A. M., Clancy, J. L., Johnson, T. B., Schwab, K., Ramirez-Toro, G., Nappier, S. P., Ravenscroft, J. E. (2016). Use of quantitative microbial risk assessment to improve interpretation of a recreational water epidemiological study. *Microbial Risk Analysis*, 1, 2-11. https://doi.org/10.1016/j.mran.2015.04.001

Stokdyk, J. P., Firnstahl, A. D., Spencer, S. K., Burch, T. R., & Borchardt, M. A. (2016). Determining the 95% limit of detection for waterborne pathogen analyses from primary concentration to qPCR. *Water Research*, 96, 105-113. https://doi.org/10.1016/j.watres.2016.03.026

Teunis, P. F., Moe, C. L., Liu, P., E. Miller, S., Lindesmith, L., Baric, R. S., & Calderon, R. L. (2008). Norwalk virus: how infectious is it? *Journal of Medical Virology*, *80*(8), 1468-1476. https://doi.org/10.1002/jmv.21237

Tiefenthaler, L., Stein, E. D., & Schiff, K. (2008). Origins and mechanisms of watershed and land use based sources of fecal indicator bacteria in urban stormwater. Southern California Coastal Water Research Project 2008 Annual Report. Costa Mesa, CA, 153-161. ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/AnnualReports/2008AnnualReport/AR08_153_161.pdf

U.S. Environmental Protection Agency. 1986. Ambient Water Quality for Bacteria, 1986. Retrieved from https://www.regulations.gov/document?D=EPA-HQ-OW-2007-0808-0001.

U.S. Environmental Protection Agency. 2012a. Appendix A; Recreational Water Quality Standard. Available from https://www.epa.gov/sites/default/files/2015-09/documents/rwqc2012_appendixa.pdf.

U.S. Environmental Protection Agency. 2012b. Microbial Risk Assessment Guideline: Pathogenic Microorganisms with Focus on Food and Water. https://www.epa.gov/risk/microbial-risk-assessment-guideline-pathogenic-microorganisms-focus-food-and-water.

U.S. Environmental Protection Agency. 2012c. Guidelines for Water Reuse. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100FS7K.PDF?Dockey=P100FS7K.PDF.

U.S. Environmental Protection Agency. 2019. Update for Chapter 3 of the Exposure Factors Handbook Ingestion of Water and Other Select Liquids, Table 3-1. Retrieved from https://cfpub.epa.gov/ncea/efp/recordisplay.cfm?deid=34366.