PROJECT NO.
5034

Assessing the Microbial Risks and Impacts from Stormwater Capture and Use to Establish Appropriate Best Management Practices

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Abstract and Benefits

Abstract: Stormwater capture and use (SCU) offers a wide range of benefits including enhancement of local water supplies, combined sewer overflow reductions, and stormwater runoff volume and pollutant load reductions. However, lack of regulatory frameworks and consistent water quality targets serve as a barrier to implementation of stormwater use projects. The guidance presented here includes selection of appropriate log reduction targets based on quality of stormwater and intended end use, methodology for monitoring stormwater microbial quality, and approaches for continuous monitoring of operational systems to ensure safe water is reliably delivered. The authors of this guidance recommend use of pathogen log reduction targets (LRTs) to inform treatment levels for varying source water end use combinations to meet acceptable risk levels. Two options are suggested in this guidance for SCU projects: Option 1: Conservative Treatment (selection of LRTS consistent with 10% sewage in stormwater), and Option 2: Low Treatment Category. The conservative treatment category is recommended as the suggested default and the low treatment category is considered a voluntary category to reduce treatment required with the tradeoff of additional monitoring of human MST markers. Example treatment process trains are provided for varying LRTs.

Benefits:

- Guidance is provided on selection of appropriate LRTs for treatment of microbial contaminants in stormwater to an acceptable level of risk.
- Example treatment process trains at varying LRTs are summarized and could be applied for prescriptive stormwater treatment standards.
- A Low Treatment Category is identified where treatment of stormwater is pragmatic, requiring membrane disinfection and ultraviolet (no chemical disinfectant dosing).
- Guidance is provided for stormwater treatment for industrial purposes that is based on distance of exposure to sprayed water.
- Dry weather flow collection and use is garnering interest and treatment requirements for removal of microbial contaminants are similar to those for wet weather flows.
- Stormwater can be treated for use to irrigate edible crops, for example in urban gardens.

Keywords: stormwater microbial quality, stormwater treatment, human microbial source trackers, pathogens, indicators, water quality, stormwater capture and use

Contents

Tables

Figures

Acronyms and Abbreviations

BIP	Bogue inlet pier
BLEST	Bacteria Load Estimator Spreadsheet Tool
BMP	Best management practice(s)
CCPs	Critical control points
CLASIC	Community-enabled Lifecycle Analysis of Stormwater Infrastructure Costs
CSI-MST	Collection system investigation microbial source tracking
CSA	Community supported agriculture
CST	Chemical source tracking
DNA	Deoxyribonucleic acid
DNQ	Detected not quantified
DNWS	Decentralized Non-Potable Water Systems
EMC	Event mean concentration
FIB	Fecal indicator bacteria
FRNA	Male-specific (F+) ribonucleic acid
GC	Gene copies
HERC	Hennepin Energy Recovery Center
HFCA	Human fecal contamination analog
HRSD	Hampton Roads Sanitation District
HSPF	Hydrologic Simulation Program – Fortran
HVAC	Heating, ventilation, and air conditioning
I&I	Inflow and infiltration
IAC	Internal amplification control
LID	Low impact development
LRCs	Log_{10} reduction credit
LRTs	Log_{10} reduction targets
LRVs	Log_{10} reduction values
MCE	Maximum environmental concentration
MIQE	Minimum information for publication of quantitative real-time PCR experiments
MLE	Maximum likelihood estimation
MRL	Method reporting limits
MS4	Municipal separate storm sewer system
MST	Microbial source tracking
NOAA	National Oceanic and Atmospheric Administration
NSQD	National stormwater quality database
NWRI	National Water Research Institute
PCPs	Pathogen control points
PCR	Polymerase chain reaction
ppy	per persons per year
PE	Polyethylene
QA/QC	Quality assurance / quality control

QMRA	Quantitative microbial risk assessment
qPCR	Quantitative polymerase chain reaction
RME	Responsible management entity
RMGC	Royal Melbourne golf club
ROS	Robust regression on order statistics
RT-qPCR	Reverse transcriptase quantitative polymerase chain reaction
SCU	Stormwater capture and use
SFPCU	San Francisco Public Utilities Commission
SPC	Standard plate counts
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
SWMM	Stormwater Management Model
TCM	Town creek marina
TMDL	Total maximum daily load(s)
TSP	Triple S pier
TSS	Total suspended solids
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UV	Ultraviolet
UVT	Ultraviolet transmittance
VDHSS	Virginia Department of Health Division of Shellfish Safety
WinSLAMM	Source Loading and Management Model
WRF	The Water Research Foundation

Terminology

General Terms	
Stormwater	Precipitation runoff from rain events or snowmelt which flows over pervious and/or impervious surfaces such as parking lots, roof tops, and streets.
Stormwater capture and use	The practice of harvesting stormwater runoff and treating the water for beneficial use as a water supply source (Smith et al., 2022).
Wet weather flows	Precipitation runoff from rain events or snowmelt which flows over pervious and/or impervious surfaces such as parking lots, roof tops, and streets synonymous with stormwater).
Dry weather flows	Runoff that is not from precipitation events that enters the separate stormwater network from activities such as over-irrigation, illegal discharges, lawn watering, groundwater seepage, and car washing.
Unrestricted access irrigation	Irrigated areas where there are no restrictions on access during or after irrigation events.
Restricted access irrigation	Irrigated areas where there is no access to the area during irrigation events, and consequently no hand to mouth ingestion through contact when access to the irrigated areas is restricted.

Terms for Microorganisms	
Human-infectious pathogens	Pathogenic organisms that may infect humans.
Potentially human-infectious pathogens	Human-infectious pathogens measured by polymerase chain reaction (PCR). PCR provides total concentrations of organisms and assessment of pathogenicity cannot be done using PCR. Thus, pathogens measured by this approach are considered potentially human-infectious.
Microbial Source Tracking (MST) markers	Microorganisms specific to fecal matter of a particular source used to determine the source of contamination (e.g., human or zoonotic) in environmental waters.

Terms for Treatment	
CT	The product of residual disinfectant concentration and time (mg-min/L).

Log_{10} reduction	The removal of a pathogen or surrogate in a unit process expressed in log_{10} units. A 1-log_{10} reduction equates to 90-percent removal, 2-log_{10} reduction to 99-percent removal, 3-log_{10} reduction to 99.9-percent removal, and so on.
Log_{10} Reduction Target (LRT)	The log_{10} reduction target for the specified pathogen group (i.e., viruses, bacteria, or protozoa) to achieve the agreed level of risk to the exposed population (e.g., 10^{-4} infection per year or 10^{-6} disability adjusted life years per person, per year).
Log_{10} Reduction Value (LRV)	The observed log_{10} pathogen reduction performance for a unit process. The LRV is equal to the difference in concentration of an added or indigenous pathogen or surrogate (reported in log_{10} units) between paired influent and effluent samples.
Log_{10} Reduction Credit (LRC)	A pathogen or surrogate log_{10} reduction value that is given/credited to a unit treatment process according to validation test results of the process. Typically, LRCs are conditional on process operation within limits of one or a number of performance monitoring surrogate parameters, e.g., maintaining filter effluent turbidity less than 0.15 NTU or maintaining a minimum ultraviolet (UV) dose delivery and remaining under a maximum flow for a validated UV system (US Water Alliance et al. 2017)
Surrogate Parameter	Parameters that can be continuously monitored correlated with performance of a unit process, and are typically parameters that can be readily monitored continuously, e.g., turbidity, UV transmittance (UVT), electrical conductivity.
Human Fecal Contamination Analog	An estimate of human fecal contamination in stormwater that is based on the estimated amount of wastewater present in stormwater. For the purposes of this report, human fecal contamination analog replaces sewage dilution.
Challenge testing	The evaluation of a treatment process for its performance expressed as pathogen log_{10} reduction using either indigenous or selected surrogate constituents (US Water Alliance et al. 2017). Generally, a surrogate is spiked into the process influent, and both the influent and effluent are monitored for the surrogate's concentration (US Water Alliance et al. 2017).
Pathogen crediting framework	A crediting structure consisting of requirements for treatment performance validation, field verification, and continuous monitoring.
Multiple barrier design	The use of treatment barriers in series such that the malfunction of one process does not compromise the performance of the entire treatment train.
Validated Log_{10} reduction value	The log_{10} reduction value for a unit process determined through validation testing over the range of anticipated operational conditions and taken to be representative of the lower bound of performance (typically, at the lower 5- or 10-percent value).

Executive Summary

ES.1 Introduction

Stormwater capture and use (SCU) is the practice of harvesting stormwater runoff and treating the water for beneficial use as a water supply source (Smith et al., 2022). SCU offers a wide range of benefits, including enhancement of local water supplies, combined sewer overflow reductions, and stormwater runoff volume and pollutant load reductions. Lack of regulatory frameworks and consistent water quality targets serve as a barrier to implementation of stormwater use projects (NRC, 2016). The goal of this guidance is to inform the design and operation of SCU systems for removal of microbial constituents. This guidance focuses on urban stormwater and refers to precipitation runoff from rain events or snowmelt, which flows over pervious and/or impervious surfaces such as parking lots, roof tops, and streets (Sharvelle et al., 2017). Guidance presented here includes selection of appropriate log reduction targets based on quality of stormwater and intended end use, methodology for monitoring stormwater microbial quality, and approaches for continuous monitoring of operational systems to ensure safe water is reliably delivered.

ES.2 Pathogen Log Reduction Targets for SCU Projects

The authors of this guidance recommend use of pathogen log reduction targets (LRTs) to inform treatment levels for varying source water end use combinations to meet acceptable risk levels. LRTs are pathogen treatment targets and are defined as the difference between the $\log_{10}$-transformed concentrations of pathogens before treatment and after treatment (Schoen et al., 2017). Risk-based pathogen reduction targets are estimated using quantitative microbial risk assessment (QMRA) to attain a certain level of health protection for end users (Schoen et al., 2017). In this report, human fecal contamination analog (HFCA) is used to serve as an estimate of human fecal contamination in stormwater to inform selection of LRTs. The HFCA can be estimated based on human microbial source tracking (MST) markers (e.g., HF183 and BacHum) and potentially human-infectious pathogens (e.g., adenoviruses, norovirus, *Cryptosporidium parvum*, and *Giardia lamblia*) in stormwater compared to municipal wastewater. Because data collected and analyzed for the literature synthesis conducted in support of this guidance (Alja'fari et al., 2023) did not support use of collection area characteristics to estimate HFCA, it is recommended to achieve conservative treatment of stormwater that an HFCA of 10^{-1} (10% sewage content) be assumed to select LRTs. Based on current analysis, selection of LRTs associated with lower HFCA should require monitoring to confirm human fecal contamination.

ES.3 Example Treatment Process Trains to Meet Stormwater Log Reduction Targets

The impacts of LRT selection on treatment requirements are assessed through identifying potential treatment process trains associated with those LRTs. Several example treatment process trains for SCU are provided for LRTs associated with HFCA ranging from 10^{-5} – 10^{-1} (0.001% - 10% sewage content). Treatment requirements to meet LRTs for HFCA from 10^{-1} – 10^{-3} (10% - 0.1% sewage) require chemical disinfection in addition to ultraviolet (UV), unless multiple UV reactors are used in series. Chemical disinfectant dosing of stormwater adds substantial complexity to projects, and the treatment requirements for HFCA 10^{-1} – 10^{-3} (10% - 0.1% sewage) are not viewed to be substantially different. However, stormwater HFCA 10^{-4} (0.01% sewage) results in more pragmatic treatment process trains where stormwater can be treated to be protective of human health through filtration and UV disinfection with no additional chemical dosing. The example treatment process trains could be used to inform prescriptive SCU treatment standards.

ES.4 Guidance for Sampling and Analysis of Stormwater Microbial Quality

Criteria considered important to assess microbial quality of stormwater are as follows:

- Human rather than general or animal source pathogens or source tracking markers should be measured
- Specify the recovery method, recovery rate, and limit of detection (Schoen et al., 2017)
- Estimate and report percent detection, concentration, and number of collected samples
- Analyze fresh rather than stored samples (Schoen et al., 2017)
- Collect composite or event mean concentration (EMC) samples (Schoen et al., 2017)
- Monitor multiple locations over time (Schoen et al., 2017)

Most appropriate references for sample collection and analysis for microbial quality of stormwater are summarized in Chapter 4.

ES.5 Monitoring for SCU Projects to Assure Pathogen Reduction

Two options are suggested in this guidance for SCU projects—Option 1: Conservative Treatment, Option 2: Low Treatment Category (Figure ES-1). The conservative treatment category (selection of LRTs to meet 10^{-1} HFCA) is recommended as the suggested default and the low treatment category is considered a voluntary category (Figure ES-1, Option 2) to reduce treatment required with the tradeoff of additional monitoring of human MST markers. The low treatment category allows selection of LRTs based on 10^{-4} HFCA (0.01% sewage), but quarterly monitoring of human MST markers is recommended to ensure that human fecal matter in stormwater is low enough to maintain Low Treatment Category status. For all SCU projects where humans are exposed to treated water, routine monitoring of surrogate parameters is recommended that are readily measured using commercially available water quality monitoring technology. Surrogates specific to stormwater treatment using various unit treatment processes are recommended in Chapter 5.

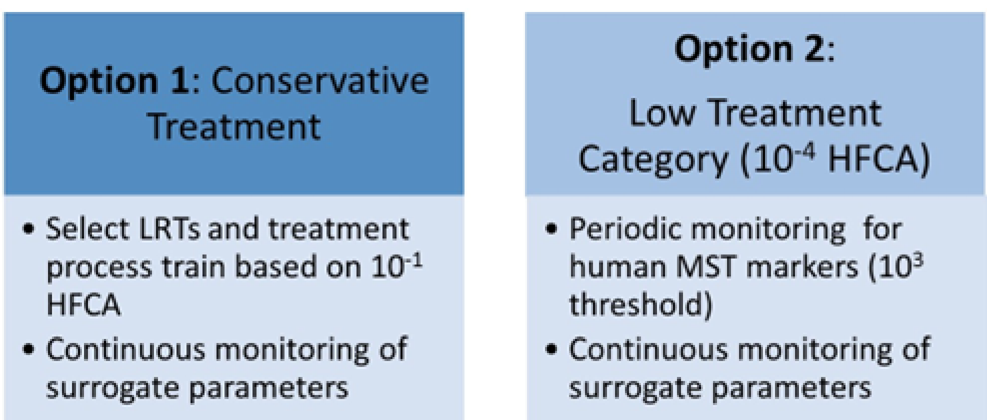

Figure ES-1. Option 1 (Conservative) and Option 2 (Low) Treatment Categories for SCU.

ES.6 Guidance for Treatment of Microbial Constituents in Stormwater for Industrial Use

Guidance for LRTs for industrial exposure is limited. In addition, industrial water exposures are highly variable depending on the specific industrial water use. It is not possible to capture every potential industrial water use that may exist to provide recommendations for each of those uses. Here, it is suggested that type of exposure to non-potable water source is considered to determine the appropriate management or treatment approach. Industrial exposures to water are described by three categories:

- No mist/spray or potential for aerosolization (water not heated above room temperature)
- No mist/spray, but potential for aerosolization exists (e.g., cooling tower)
- Water mist or spray exists in vicinity of human exposure

Management and/or treatment strategies are suggested based on these three possible exposures (Figure ES-2).

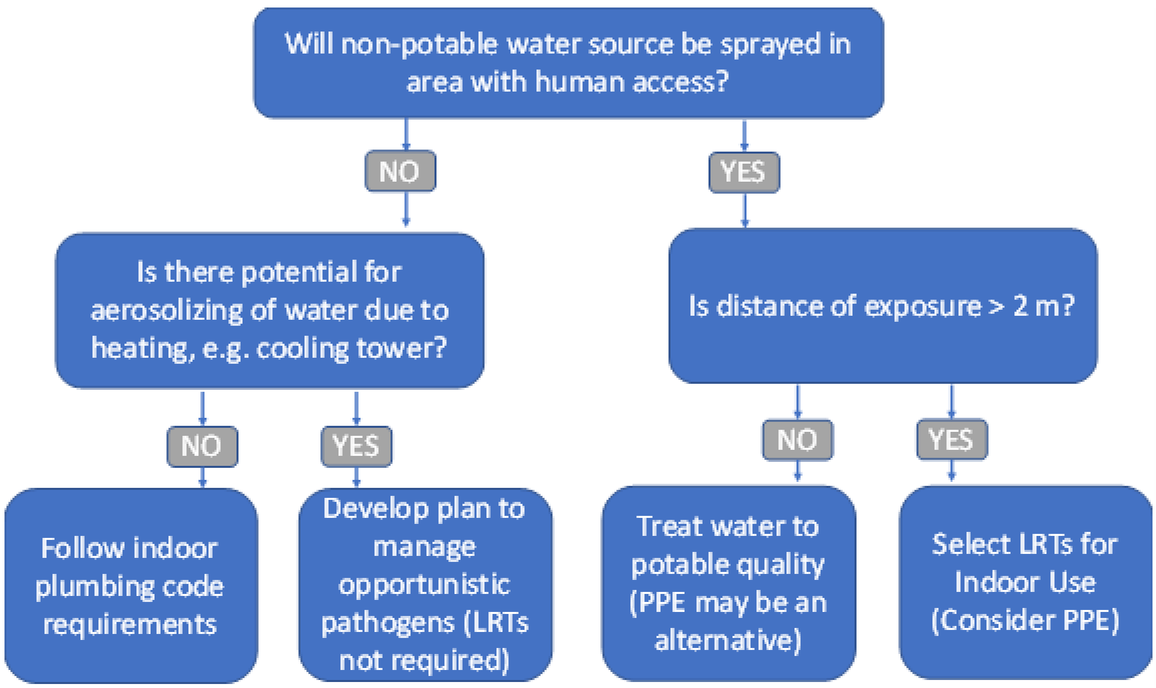

Figure ES-2. Management and Treatment Strategies for Categories of Non-Potable Water Uses for Industrial Applications

ES.7 Guidance for Treatment of Microbial Constituents in to Irrigate Edible Crops

To provide some context on the interpretation of the stormwater log reduction value (LRV) estimates a relative comparison was made against LRV estimates for accepted level of treatment of wastewater based on California Title 22 Recycled Waters for Unrestricted Irrigation of Food Crops (State of California, 2000). When stormwater is assumed to have a HFCA of 10^{-1} (10% wastewater), treatment to meet LRTs for indoor use should be consistent with or more conservative than requirements for Title 22 treatment for food crop irrigation.

ES.8 Guidance for Dry Weather Flow Capture and Use Projects

Descriptive statistics show that the median concentration of human MST markers in dry weather flows is approximately three orders of magnitude less than that in wet weather flows, on a national scale. However, due to the large uncertainty in dry weather flows and the low relative difference for treatment requirements for HFCA 10^{-2} compared to HFCA 10^{-1}, it may be recommended that treatment requirements and characterization of Low Treatment Category projects for dry weather flows be the same as those for wet weather flows (Figure ES-1). Limited examples of dry weather SCU exist in the United States. In existing projects, variability in water quantity and quality are a challenge for design.

ES.9 Research Needs

Research needs identified through this project are:

- Data collection on pathogens and human MST markers in stormwater and wastewater from the same collection areas
- Explore use of certified unit treatment processes for SCU systems to reduce continuous monitoring requirements
- Estimation of pathogen reduction in nature-based treatment systems and recommendations on validation approaches
- Approaches to determine treatment requirements for new development SCU projects
- Review approach for QMRA to develop LRTs and select treatment process trains
- Consider inclusion of bacteria in crediting frameworks

ES.10 Related WRF Research

- Risk-Based Framework for the Development of Public Health Guidance for Decentralized Non-potable Water Systems (4632)
- Onsite Non-Potable Water System: Guidance Manual and Training Modules (4909)
- Assessing the State of Knowledge and Research Needs for Stormwater Harvesting (4841)
- Drivers, Hindrances, Planning and Benefits Quantification: Economic Pathways and Partners for Water Reuse and Stormwater Harvesting (1748)
- Community-enabled Lifecycle Analysis of Stormwater Infrastructure Costs (CLASIC) (4798 to 4804)

CHAPTER 1

Introduction

Stormwater capture and use (SCU) offers a wide range of benefits including enhancement of local water supplies, combined sewer overflow reductions, and stormwater runoff volume and pollutant load reductions. Despite the benefits of collection and use of stormwater, regulatory frameworks that promote use of this water source remain sparse (Luthy et al., 2019). Lack of regulatory frameworks and consistent water quality targets serve as a barrier to implementation of stormwater use projects (NRC, 2016).

The National Water Research Institute (NWRI), The Water Research Foundation (WRF), and San Francisco Public Utilities Commission (SFPUC) partnered to develop a risk-based framework for decentralized non-potable water systems using a quantitative risk methodology (Sharvelle et al., 2017) that included stormwater. However, guidance on treatment requirements of stormwater leaves flexibility and requires interpretation by regulators and designers to select from a range of pathogen reduction targets. In an interview with utilities and health departments on development of onsite non-potable water programs, participants noted a lack of willingness by the stormwater community to accept the treatment recommendations for pathogen reduction for stormwater use (Smith et al., 2022; Lackey et al., 2020). A lack of clarity for selection of appropriate pathogen reduction requirements for stormwater was also noted. There is a critical need for more specific guidance on appropriate treatment for non-potable and potable uses to ensure stormwater use projects are protective of public health.

The goal of this guidance is to inform the design and operation of stormwater capture and use (SCU) systems for removal of microbial constituents. SCU is the practice of harvesting stormwater runoff and treating the water for beneficial use as a water supply source (Smith et al., 2022). The guidance presented here includes selection of appropriate log reduction targets based on quality of stormwater and intended end use, methodology for monitoring stormwater microbial quality, and approaches for continuous monitoring of operational systems to ensure safe water is reliably delivered. A comprehensive literature review has been conducted to support the guidance presented herein (Alja'fari et al., 2023) and is referenced throughout this report.

1.1 Definition of Stormwater and Scope of Guidance

Urban stormwater is the focus of this guidance and refers to precipitation runoff from rain events or snowmelt which flows over pervious and/or impervious surfaces such as parking lots, roof tops, and streets (Sharvelle et al., 2017). Agricultural runoff is not included in this guidance. Stormwater either intercepted prior to a collection system and/or stormwater discharge conveyed by separate stormwater collection systems is the focus, while stormwater conveyed by natural flowing rivers and streams is not within the scope of this guidance. Urban runoff is generally classified into wet weather and dry weather flows. In this document, wet weather flows are synonymous with stormwater. Dry weather flows refer to runoff that enters the separate stormwater network from several activities such as over-irrigation, illegal discharges, lawn watering, groundwater seepage, and car washing (Engelhorn and Krish, 2018). The guidance presented here focuses on wet and dry weather flows in areas with separate stormwater collection networks, and combined sewer overflows are not included (Table 1-1).

Table 1-1: SCU Options Considered in this Guidance.

Design Scale	Stormwater Characteristics	End-Uses (Non-potable only)
• Neighborhood • District • Municipal	• Urban • Wet weather • Dry weather • Separate collection (pipe discharge) • Collection prior to interception	• Toilet flushing • Clothes washing • Unrestricted access irrigation • Cooling towers • Industrial • Edible food crops

The scale of SCU systems considered in this guidance range from neighborhood-scale to municipal scale (Table 1-1). Data on stormwater collected at the site-scale prior to interception is lacking (Alja'fari et al., 2023) and the data that served as the basis for this guidance primarily included microbial quality of stormwater gathered from collection system discharges. While guidance specific to site-scale surface collected stormwater could not be provided at this time, the guidance provided here serves as a conservative approach to handle such stormwater. Although stormwater encompasses roof runoff, i.e., precipitation collected directly from a roof surface, capture and use systems exclusively collecting roof runoff are outside the scope of this project. Roof runoff is not considered to be contaminated with human fecal matter (Sharvelle et al., 2017), and considerations for design of a roof runoff harvesting system are different from SCU systems. However, SCU systems collecting stormwater in addition to roof runoff are addressed in this guidance.

1.1.1 End Uses for SCU Systems Included in this Guidance

SCU projects can be categorized in two ways; SCU for direct use (Figure 1-1) and SCU for aquifer recharge (Figure 1-2). In direct SCU, stormwater is captured, stored, and treated for direct fit-for-purpose use. SCU projects that recharge local groundwater systems are also common (Escriva-Bou et al., 2019). SCU for aquifer recharge differs from direct SCU in that additional treatment is achieved via infiltration and within the aquifer. For SCU where water is directly used (Figure 1-1), continuous availability of stormwater will require extensive storage. Storage size is dependent on local precipitation characteristics and end use demand (NRC, 2016). Storage of stormwater can be costly and should be considered to assess feasibility for SCU projects. The focus of the guidance provided herein is SCU when water is directly treated and used (Figure 1-1) for the following purposes (see also Table 1-1):

- Unrestricted access irrigation: irrigated areas where there are no restrictions on access to irrigated areas (during or after irrigation events)
- Indoor non-potable use: examples include toilet flushing and laundry.
- Industrial use: examples include cooling towers, concrete plants, etc.
- Food crop irrigation: irrigation of edible food crops including community vegetable gardens and agricultural crops produced for human and non-human consumption.

When studying treatment of stormwater for microbial contaminants, it is important to consider whether human exposure to water via ingestion is a possibility. In scenarios where humans are not exposed to treated stormwater, e.g., restricted-access irrigation, treatment of stormwater to reduce microbial constituents may not be needed or required. Restricted-access irrigation is defined here as irrigated areas where there is no access to the area during irrigation events, and consequently no hand to mouth ingestion through contact when access to the irrigated areas is restricted. Examples could include subsurface application of stormwater or areas where stormwater is applied by spray irrigation where public access is not possible during irrigation and limited exposure to the irrigated area exists between irrigation events.

This guidance addresses treatment of stormwater to reduce microbial constituents. Chemical quality of stormwater is also important to consider for SCU projects but is outside the scope of this effort. The use of stormwater for potable demand is also outside the scope of this document and must consider both chemical and microbial contamination.

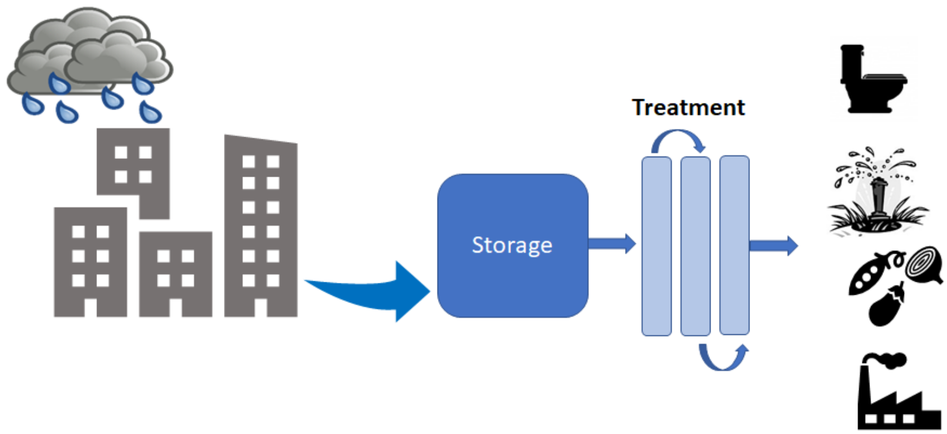

Figure 1-1. SCU for Direct Use.

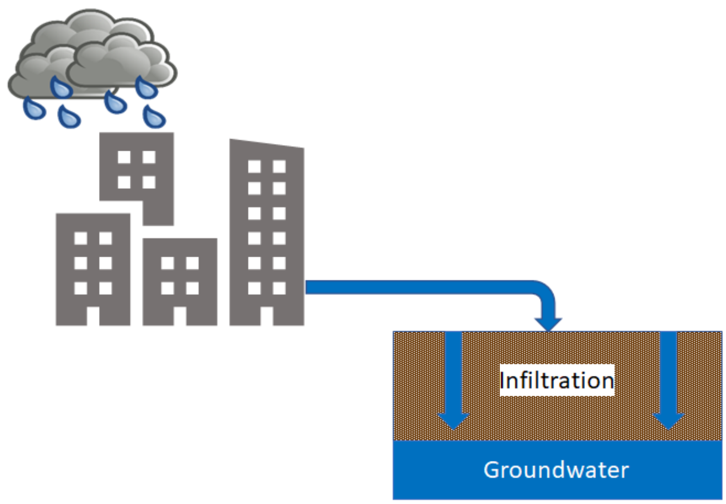

Figure 1-2. SCU for Managed Aquifer Recharge

1.2 Sources of Stormwater Microbial Contamination

Pathogens and indicator organisms in stormwater originate from human and animal sources (Clary et al., 2014). Human sources of pathogens and indicator organisms include improperly located or failing septic tanks, illicit sanitary sewer connections to stormwater collection networks, illegal discharges to stormwater manholes, and presence of human fecal matter in urban areas (Clary et al., 2014).

Several cities have identified homeless encampments as potential sources of human fecal contamination and, subsequently, as sources of human microbial contamination in stormwater. Approximately 116 homeless encampments were identified along the San Diego River mainstem according to a survey conducted in 2016 by the San Diego River Park Foundation (California Regional Water Quality Control Board, 2019). Assuming the individuals living in these encampments do not regularly use restroom facilities, outdoor defecation likely occurs which potentially results in human fecal matter discharge to the river during storm events (California Regional Water Quality Control Board, 2019). The Southern Nevada Water Authority is currently conducting a sampling campaign to examine the impact of homeless encampments on the microbial quality of stormwater under wet weather conditions; however, the results of this study are not yet available.

Animal sources of pathogens and indicator organisms include domestic pets, urban wildlife, and agriculture (Clary et al., 2014). In urban settings, agricultural sources such as animal feeding operations and grazing are not of primary importance. Indicator organisms have secondary sources such as biofilms attached to stormwater pipes and natural sources, e.g., soil and plants (Ishii and Sadowsky, 2008; McCarthy, 2009; Ran et al., 2013). A more comprehensive list of pathogens and indicator organism sources in stormwater generated from urban settings is provided in Table 1-2.

Table 1-2. Sources of Pathogens and Indicator Organisms in Urban Stormwater.

Category	Activity / Source
Piped Sanitary Infrastructure	Sanitary sewer overflows
	Illegal sanitary connections to stormwater networks
	Exfiltration of wastewater from sanitary sewer pipes to stormwater pipes
Human Sanitary Sources	Trash cans
	Garbage trucks
	Dumpsters / landfills (pet waste and diapers)
	Homeless encampments
	Failing or leaking septic tanks
	Porta-Potties
Domestic Animals	Cats, dogs, horses etc.
Urban Wildlife	Birds (swallows, pigeons, gulls, etc.)
	Rodents (racoons, rats, opossums, squirrels, etc.)
	Open space (foxes, coyotes, feral cats, beavers, etc.)
Other Urban Sources (including vector-attracting areas)	Food processing facilities
	Stairwells / bars (washdown areas)
	Restaurants grease bins
	Dining outdoors
Urban Non-Stormwater Discharges (possibly mobilizing surface depositions of indicators)	Excessive irrigation
	Hot tubs / pools
	Car washing
	Improperly managed greywater / reclaimed water
	Power washing

Stormwater Infrastructure	Illicit dumping
	Decaying plant matter, sediment, and litter in storm drains (sources of indicator organisms)
	Biofilms / regrowth (source of indicator organisms)
Recreational Sources	Mobile recreational vehicles
Open Space Areas	Wildlife populations
Naturalized Sources	Plants and soil (sources of naturalized indicator organisms)

Data Sources: Armand Ruby Consulting, 2011, Sercu et al. (2011), and Clary et al. (2014)

Environmental Incentives and EcoNorthwest (2017) reported best professional judgements pertaining to the relative contribution of each potential human fecal contamination source to the San Diego River and the level of uncertainty in these contributions (Table 1-3). Based on these best professional judgments and whether these sources are currently being monitored, the authors determined whether each source should be prioritized for study (Table 1-3). Homeless encampments, public sewer exfiltration, septic systems, and private sewer laterals were identified as potential sources of human fecal contamination to the San Diego River to be prioritized for further study (Table 1-3).

Table 1-3. Estimates of the Relative Proportions of Human Fecal Contamination to the San Diego River
Based on Best Professional Judgement, State of Monitoring of these Sources, Uncertainty Level Assigned to the Judgements, and Prioritization of these Sources for Future Studies.

Potential Source of Human Contamination	Relative contribution of contamination	Ongoing monitoring	Uncertainty level	Prioritized for investigation
Homeless encampments	High	Yes	High	Yes
Public sewer exfiltration	Medium	No	High	Yes
Private sewer exfiltration	Low – medium	No	High	Yes
Septic systems	Low	No	Medium	Yes
Sanitary sewer overflows	Low	Yes	Low	No
Illicit connections and illegal discharges	Low	Yes	Low	No

Data Source: Environmental Incentives and EcoNorthwest, 2017.

1.3 Guidance Provided in this Report

This report includes guidance for SCU related to microbial quality of stormwater. The basis of treatment recommendations is use of pathogen $\log_{10}$ reduction targets (LRTs) as recommended by Sharvelle et al. (2017). A description of content by chapter follows:

- Chapter 2 - Summary of existing LRTs for stormwater and new guidance for application of LRTs to treatment of stormwater
- Chapter 3 - Example treatment process trains to meet selected LRTs are provided
- Chapter 4 - Guidance for sampling and analysis of microbial quality of stormwater
- Chapter 5 - Monitoring of SCU projects to ensure that treatment processes achieve treatment levels in which they are designed
- Chapter 6 – SCU for industrial purposes
- Chapter 7 – SCU for edible food crop
- Chapter 8 - Considerations for use of dry weather flow (Chapter 7 through 9)
- Chapter 9 - Further research needs

CHAPTER 2

Pathogen Log Reduction Targets for SCU Projects

There are two approaches commonly used for establishing microbial treatment targets for water reuse and on-site water systems for establishing treatment regulatory requirements: end point water quality analysis for fecal indicator bacteria and use of human health risk based $\log_{10}$ reduction targets (LRTs).

2.1 Use of End Point Analysis of Fecal Indicator Bacteria in Regulations for SCU Systems

Use of end point water quality is most commonly used for regulatory requirements applied to publicly owned wastewater treatment works and have also been commonly applied to non-potable water systems. This approach provides target concentrations of water quality parameters and relies on routine monitoring of those parameters to ensure targets are met. This approach can be used with the goal to meet targets for either physicochemical parameters or fecal indicator bacteria.

2.2 Use of LRTs in Regulations for SCU Systems

A newer approach which is increasingly utilized is used is use of pathogen log reduction targets to inform treatment levels for varying source water end use combinations to meet acceptable risk levels. LRTs are pathogen treatment targets and are defined as the difference between the $\log_{10}$-transformed concentrations of pathogens before treatment and after treatment (Schoen et al., 2017). Risk-based pathogen reduction targets are estimated using quantitative microbial risk assessment (QMRA) to attain a certain level of health protection for end users (Schoen et al., 2017). QMRA relies on characterization of pathogenic organisms in the source water, estimation of exposure based on the end use, and selection of an acceptable level of risk to inform the development of LRTs for the source water-end use combination of interest (Figure 2-1; Haas et al., 1999; World Health Organization, 2016). An advantage of using LRTs to inform water treatment requirements is that the approach does not rely on correlation between fecal indicator bacteria and human-infectious pathogens, and design of systems to meet pathogen LRTs does not require regular monitoring of fecal indicator bacteria. Monitoring of fecal indicator bacteria is expensive and does not provide real time information on system performance due to time required for sample analysis (Sharvelle et al., 2017).

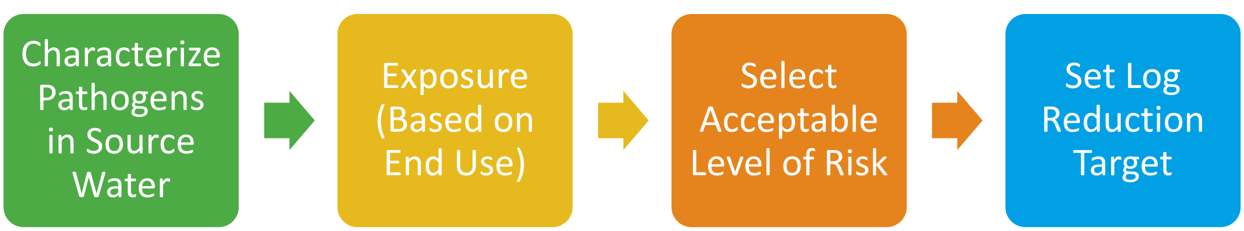

Figure 2-1. Steps to Estimate LRTs Based on QMRA.

2.3 Summary of Current Treatment Requirements for SCU Projects

A limited number of states and local agencies have published water quality requirements for SCU Projects (Table 2-1). Existing regulations include both the end point water quality and LRT approaches. The current regulations for the state of Minnesota and Los Angeles, CA include end point targets for fecal indicator bacteria while San Francisco, CA and the District of Columbia requirements include LRTs for bacterial, viral, and protozoa pathogens for both unrestricted irrigation and indoor use. Both Minnesota and the city of Los Angeles are in the process of modifying their regulatory process to include LRTs for stormwater treatment. In Minnesota, an interagency effort is underway to improve the sustainability and safety of water use (Minnesota Pollution Control Agency, 2021). In the state of California, Senate Bill 966 (State of CA, 2021) will require the state to adopt regulations for risk-based water quality standards for the onsite treatment and reuse of non-potable water in the near future. The state of Washington is also establishing treatment requirement that are planned to go into effect in 2023.

Table 2-1. Summary of Treatment Targets and Water Quality Requirements/Recommendations for Beneficial Use of Stormwater in the U.S.

Water Quality Parameter	Unrestricted Irrigation				Indoor Use (Toilet Flushing or Laundry)		
	State of MN[1]	Los Angeles, CA[2,3]	San Francisco, CA[4]	District of Columbia[5]	Los Angeles, CA[2,3]	San Francisco, CA[4]	District of Columbia[5,6]
BOD_5	NS	10 mg/L	NS	NS	10 mg/L	NS	NS
Turbidity	3 NTU	2 NTU	2 NTU	NS	2 NTU	2 NTU	NS
TSS	5 mg/L	10 mg/L	NS	NS	10 mg/L	NS	NS
pH	6 - 9	6 - 9	NS	NS	6 - 9	NS	NS
Chloride	500 mg/L	NS	NS	NS	NS	NS	NS
Zinc	2 mg/L (long term); 10 mg/L (short term)	NS	NS	NS	NS	NS	NS
Copper	0.2 mg/L (long term); 5mg/L (short term)	NS	NS	NS	NS	NS	NS
Pathogens/ Indicators	*E. coli*: 126 CFU/100mL	*E coli*: 2.2 CFU/100mL	*Virus*: 3.0-log_{10} reduction *Protozoa:* 2.5-log_{10} reduction	*Virus*: 3.0-log_{10} reduction *Protozoa:* 2.5-log_{10} reduction	*E coli*: 2.2 CFU/100mL	*Virus*: 3.5-log_{10} reduction *Protozoa:* 3.5-log_{10} reduction	*Virus*: 3.0-log_{10} reduction *Protozoa:* 2.5-log_{10} reduction

		Bacteria: 2.0-log_{10} reduction	*Bacteria:* 2.0-log_{10} reduction		*Bacteria:* 3.0-log_{10} reduction	*Bacteria:* 2.0-log_{10} reduction

Data Source: Revised from Luthy et al., 2019. NS – not specified; 1: Guidance (not regulation) provided in Minnesota Pollution Control Agency, 2017, 2: Can also treat to CA Title 22 water quality equivalence, 3: Los Angeles County Department of Public Health, 2016, 4: City and County of San Francisco, 2017, 5: District of Columbia, 2020, 6: also allows for use of stormwater for cooling towers and log10 reduction requirements are not in place and risk is managed for opportunistic pathogens instead.

2.4 Summary of LRTs for Stormwater

The authors of this guidance recommend the use of LRTs to determine treatment requirements for SCU projects. Pathogen LRTs for on-site (i.e., decentralized) water systems have been recommended by Sharvelle et al. (2017) and updated by Pecson et al. (2022) (Table 2-2). Stormwater has been included in guidance for decentralized and on-site systems because SCU projects at the site and neighborhood scale are common (Smith et al., 2022). Sharvelle et al. (2017) presented risk-based LRTs for fecal pathogens which would render stormwater suitable for unrestricted irrigation and indoor use. Their work was based on quantitative microbial risk assessment to develop pathogen reduction targets (Jahne et al., 2017; Schoen et al., 2017). Due to high variability of pathogen concentrations in stormwater (Alja'fari et al. 2023), LRTs for stormwater were estimated assuming two levels of wastewater (sewage) dilution: 10^{-1} (10% sewage) and 10^{-3} (0.1% sewage). These estimates of sewage content were based on concentrations of potentially human infectious pathogenic organisms observed in stormwater (Bambic et al., 2011) and an analysis conducted by Schoen et al. (2017). Rather than capturing the variability of stormwater microbial quality, the guidance by Sharvelle et al. (2017) recommended estimation of stormwater LRTs based on an expected level of stormwater contamination with sewage that may be caused by deteriorating infrastructure, homeless encampments, and other possible sources of human fecal contamination. Pecson et al. (2022) used the same estimates of sewage content as Sharvelle et al. (2017). However, for pathogen concentrations in untreated wastewater, Pecson et al. (2022) relied on a more recent monitoring effort conducted by Pecson et al. (2021) to serve as baseline pathogen concentrations which were diluted to determine treatment requirements. The wastewater LRTs used as the basis for estimation LRTs reported in Table 2-2 are reported in Schoen et al. (2017) and Pecson et al. (2022). Bacteria LRTs were not recommended by Pecson et al. (2022) due to lack of crediting frameworks for bacteria and the assumption that treatment to meet viral and protozoa LRTs would achieve treatment protective against bacterial pathogens. Pecson et al. (2022) note that UV and membrane filtration processes that meet credits for viral and protozoan pathogens also reduce bacteria to meet LRTs. While the LRTs recommended for stormwater by Sharvelle et al. (2017) and Pecson et al. (2022) were developed as part of guidance for on-site and decentralized systems, the approach applied for both use municipal wastewater pathogen concentrations as the baseline for estimating sewage content in stormwater. Therefore, the LRTs estimated in this literature are applicable across scales of SCU projects, including site, neighborhood, and municipal scales. This guidance seeks to build upon LRTs provided by Sharvelle et al. (2017) and Pecson et al. (2022) to guide selection of LRTs within the wide range of recommended LRTs reported.

Table 2-2. 95th Percentile Pathogen Log Reduction Targets for Nonpotable Uses of Stormwater
Based on 10^{-1} and 10^{-3} Wastewater Dilution in Stormwater.

Contamination Scenario	Bacteria		Protozoa		Virus	
	Sharvelle et al. (2017)	Pecson et al. (2022)	Sharvelle et al. (2017)	Pecson et al. (2022)	Sharvelle et al. (2017)	Pecson et al. (2022)
10% Sewage, HFCA = 10^{-1}						
Unrestricted Irrigation	4	NR	4.5	4.5	5.0	6.5
Indoor Use	5	NR	5.5	5.5	5.5	7.0
0.1% Sewage, HFCA = 10^{-3}						
Unrestricted Irrigation	2	NR	2.5	2.5	3.0	4.5
Indoor Use	3	NR	3.5	3.5	3.5	5.0

10^{-4} ppy Infection Risk; NR – no recommendation

2.4.1 Estimation of Sewage Content in Stormwater for Selection of LRTs

Both Sharvelle et al. (2017) and Pecson et al. (2022) used the term sewage dilution to reference the estimate of sewage content in stormwater. The authors of this report have recognized the term sewage dilution caused confusion among audiences intending to use the guidance (e.g., utilities and health departments). In this report, the term sewage dilution has been replaced with human fecal contamination analog (HFCA). HFCA refers to an estimate of human fecal contamination in stormwater that is based on the estimated amount of wastewater present in stormwater. The HFCA can be estimated based on human MST markers, e.g., HF183 and BacHum, and potentially human-infectious pathogens, e.g., adenoviruses, norovirus, *Cryptosporidium parvum*, and *Giardia lamblia* in stormwater compared to municipal wastewater. Table 2-3 is included to provide clarity on the HFCA and estimated sewage content.

Table 2-3. Forms of Expressing Estimated Sewage Content in Stormwater.

% Sewage	HFCA	Sewage Dilution	Fraction Sewage
10%	10^{-1}	10^{-1}	1/10
1%	10^{-2}	10^{-2}	1/100
0.1%	10^{-3}	10^{-3}	1/1000

2.5 Guidance for Selection of LRTs for SCU Projects

While the intent of guidance by Sharvelle et al. (2017) was to provide flexibility to select LRTs within the range of potential stormwater contamination with sewage (0.1% - 1% sewage) based on local characteristics, the regulatory community found the range of LRTs provided to create confusion on appropriate LRTs to include in regulatory frameworks (Lackey et al., 2020). In addition, there was a lack of understanding and trust in the range of stormwater contamination with sewage estimated that led to the range of recommended LRTS. Further analysis was conducted by Alja'fari et al. (2023) to address these concerns.

2.5.1 Use of Collection Area Characteristics to Select LRTs

The impact of land use characteristics, infrastructure condition, stormwater event characteristics, climate and stormwater collection area size on stormwater microbial quality were investigated (Alja'fari et al., 2023). The intent of analyzing the data was to provide guidance on estimation of HFCA (i.e., sewage content) to inform selection of LRTs. For example, a set of characteristics describing infrastructure age and land use type could be defined to categorize a SCU project into the 10^{-3} HFCA (0.1% sewage content) requiring less treatment. The current literature summarized in Alja'fari et al. (2023) does not point to specific trends between storm event characteristics, land use, or climate and associated microbial quality. It was determined that infrastructure condition impacts stormwater contamination with human fecal matter as detected by human MSTs (City of Santa Barbara, 2012, Sercu et al., 2011). The limited data set available at the time of this study did not support identification of characteristics to guide estimation of HFCAs for selection of LRTs.

2.5.2 Expanded Analysis of Human Fecal Contamination in Stormwater

To expand upon the analysis conducted by Schoen et al. (2017) that served as the basis for selection of the range of stormwater contamination with sewage, Alja'fari et al. (2023) estimated HFCA based on both potentially human-infectious pathogen concentrations (Bambic et al., 2011, Sauer et al., 2011, Steele et al., 2018) as well as human microbial source tracking (MST) markers (Bambic et al., 2011, Cao et al, 2017, Steele et al., 2018, Gonzalez et al., 2022) in stormwater and wastewater collected nationally. Potentially human-infectious pathogens are pathogens measured by polymerase chain reaction (PCR). PCR provides total concentrations of organisms and without assessment of pathogenicity. Thus, pathogens measured by this approach are considered potentially human-infectious. Human MST markers are microorganisms specific to fecal matter from a specific source measured to determine the source of contamination (e.g., human or zoonotic) in environmental waters. A statistical distribution was developed for a set of human MST markers and potentially human-infectious pathogens in both stormwater and wastewater from data collected across the United States. An unpaired data analysis was conducted using Monte Carlo simulation to generate 1000 combinations of data points from the distributions. The HFCA in wet and dry weather flows was then calculated by dividing data points in the stormwater distribution by data points in the wastewater distribution (Equation 1).

$$HFCA = C_{xi} / C_{xj} \qquad \text{(Equation 1)}$$

Where:
HFCA: Human fecal contamination analog in wet or dry weather flow based on microorganism *x*.
C_{xi}: concentration of microorganism x in wet or dry weather flow in GC/100 mL or (oo)cysts/L.
C_{xj}: concentration of microorganism x in influent wastewater in GC/100 mL or (oo)cysts/L.

Human MST markers were considered more reliable for estimation of HFCA compared to potentially human-infectious pathogens. Potentially human-Infectious pathogen datasets were limited by detection limits and subsequently the range of data observed within the distributions and number of available data points. The 95th percentile estimate of HFCA in stormwater using human MST markers was $10^{-1.5}$ (Table 2-4), suggesting that an HFCA of 10^{-1} (10 % sewage) in stormwater remains a conservative estimate to inform selection of treatment requirements. The median HFCA was $10^{-4.5}$, slightly lower than the upper end of sewage content (HFCA = 10^{-3}, 0.1% sewage) recommended by Sharvelle et al. (2017).

Table 2-4. Descriptive Statistics for HFCAs in Wet Weather Stormwater for 1000 Iterations of Combinations of Human MST Marker Concentrations in Stormwater and Wastewater.

Percentile	Human MST Marker Based HFCA
5th	$< 10^{-7.0}$
25th	$10^{-5.8}$
Median	$10^{-4.5}$
75th	$10^{-3.3}$
95th	$10^{-1.5}$

2.5.3 Recommendations for Selection of LRTs for SCU

Because this analysis could not identify variables that predict human fecal contamination of stormwater and the additional data analysis conducted confirmed high variability of stormwater microbial quality, it is recommended to achieve conservative treatment of stormwater that a HFCA of 10^{-1} (10% sewage content) be assumed to select LRTs. LRTs associated with HFCA 10^{-1} (10% sewage content) can be selected based on Table 2-2. Based on current analysis, selection of LRTs associated with lower HFCA should require monitoring to confirm human fecal contamination. Monitoring of human MSTs is suggested and described in Chapter 5. Methods for monitoring human MSTs are identified in Chapter 4.

CHAPTER 3

Example Treatment Process Trains to Meet Stormwater Log Reduction Targets

Implementation of SCU projects requires implementation of treatment process trains to ensure reduction of pathogens to deliver water meeting acceptable risk levels for protection of public health. This chapter provides examples of stormwater treatment process trains for non-potable uses including unrestricted landscape irrigation and indoor use (e.g., toilet flushing) that meet varying LRTs. Based on analysis of stormwater and wastewater human MST marker data (Section 2.5.2 and Alja'fari et al., 2023), the HFCA in wet weather flows was found to range from 10^{-1} to 10^{-6}. Consequently, treatment log reduction targets (LRTs) for SCU systems could be 1 to 6 – $\log_{10}$ units lower than equivalent schemes planning to treat wastewater for equivalent uses. Use of HFCAs in stormwater enables the selection and design of treatment process trains which comply with risk-based pathogen LRTs. The impacts of LRT selection on treatment requirements are assessed through identifying potential treatment process trains. Pathogen log reduction values (LRVs), pathogen LRTs, pathogen $\log_{10}$ reduction credits (LRCs), challenge testing, and regulatory frameworks for crediting are terms that are repeated throughout this document. Definitions of these terms are included in the glossary at the beginning of this report.

3.1 Pathogen LRTs Selected for SCU Treatment Train Examples

LRTs were selected to inform selection of treatment process trains for SCU projects (Table 3-1) based on the LRTs summarized in Chapter 2 (Table 2-2). Here, the more conservative LRTs of those summarized in the literature are selected. Pathogen LRTs for HFCA values of 10^{-1} and 10^{-3} are based on literature values (Schoen et al., 2017 adopted by Sharvelle et al., 2017; Pecson et al., 2022). Pathogen LRTs for 10^{-2}, 10^{-4}, and 10^{-5} HFCA were estimated assuming a linear relationship between HFCAs and pathogen LRTs. Because HFCAs and the LRTs are on a log scale, a linear increase in log HFCA results in a linear decrease in the required LRT.

Table 3-1. Stormwater Pathogen LRTs for Nonpotable Uses and HFCA Range of 10^{-5} to 10^{-1} Used to Select Treatment Process Trains

(10^{-4} ppy Infection Risk).

HFCA Scenario	Bacteria[a]	Protozoa[b]	Virus[b]
Estimated Based on QMRA[c]			
10^{-1}			
Unrestricted Irrigation	4	4.5	6.5
Indoor Use	5	5.5	7.0
10^{-3}			
Unrestricted Irrigation	2	2.5	4.5
Indoor Use	3	3.5	5.0
Estimated Based on Assumption of Linear Relationship Between HFCA and LRTs			
10^{-2}			
Unrestricted Irrigation	3	3.5	5.5
Indoor Use	4	4.5	6.0
10^{-4}			
Unrestricted Irrigation	1	1.5	3.5
Indoor Use	2	2.5	4.0
10^{-5}			
Unrestricted Irrigation	0	0.5	2.5
Indoor Use	1	1.5	3.0

a: Bacterial LRT is obtained from Sharvelle et al. (2017); b: protozoan and viral LRTs are obtained from Olivieri et al. (2021); c: Bacterial LRTs (Sharvelle et al., 2017) and viral & protozoan LRTs (Pecson et al., 2021) are estimated based on QMRA.

3.2 Pathogen LRVs for Unit Treatment Processes

Each treatment process in the treatment train is assigned an LRV for each pathogen class. LRV credits characterize the capacity of a unit process to remove pathogens (Sharvelle et al., 2017). While pathogen crediting frameworks in the U.S. include virus and protozoa, bacteria LRVs are not included in existing U.S. regulatory frameworks. Sharvelle et al. (2017) included bacteria LRTs as part of the guidance and bacteria LRTs are included in the analysis presented here for the sake of being thorough (see Appendix A and Table 3-2). Olivieri et al. (2021) conducted analysis to estimate bacteria LRTs for varying source water-end use combinations but recommended that regulations do not include bacteria LRTs due to the lack of crediting frameworks including bacteria. In addition, Olivieri et al. (2021) noted that meeting bacteria and virus LRTs would be protective of public health when residual chlorine is required. Achieving viral and protozoa LRTs has been considered acceptable for Direct Potable Reuse regulatory frameworks (Trussell et al., 2013).

To obtain validated LRVs, each treatment process should be tested under the full range of potential operating conditions which are specific to the application in question (Sharvelle et al., 2017). Influencing factors that affect treatment performance and reliability (e.g. turbidity, UVT, pH) and validation testing should be conducted to ensure performance is not compromised under the more challenging conditions. For example, UV disinfection performance would be validated at a minimum UV transmittance (UVT) and the maximum flow per reactor as these conditions would both result in the lowest likely delivered dose. Because validated technologies have primarily been applied for drinking water, many of the accepted crediting frameworks include LRVs developed using surface water as the source water. Thus, achieving water quality characteristics for each unit process as specified in crediting documentation is crucial to apply LRVs to stormwater treatment process. Examples of relevant water quality operating conditions for stormwater treatment include influent turbidity, temperature, UVT, ammonia concentration, pH, and pathogen concentration. It should also be noted that frequently the credits attributed to a process are more conservative, i.e., lower, than the actual performance of a system.

To assign LRVs to technologies in treatment process trains, a comprehensive review of the literature, e.g., peer-reviewed literature, challenge testing studies, official reports, and crediting frameworks, was conducted (see Appendix A). The intent of the review was to provide a summary of the ranges of the LRVs that could be achieved and potentially credited to different unit treatment process. A set of LRVs has been identified to guide selection of unit processes in the example treatment process trains summarized here (Table 3-2 and 3-3). Justification for selection of these LRVs in included in Appendix A. Important to note is that the referenced Australian Crediting Frameworks have gained traction for use in California for water reuse.

Table 3-2. Disinfection LRVs for Unit Treatment Processes Applied to Example Treatment Process Trains.

LRV Credit	Bacteria	Protozoa	Viruses	Crediting Framework or Pathogen Removal Studies
	Ultraviolet Disinfection Dose (mJ/cm^2)			
1 $\log_{10}$ reduction	3 - 6	2.5	58	Bacteria: Hinjen et al. (2006) – Peer Reviewed Literature Protozoa and Viruses: USEPA (2006) – US Crediting Framework
2 $\log_{10}$ reduction	7 - 12	5.8	100	
3 $\log_{10}$ reduction	10 - 17	12	143	
4 $\log_{10}$ reduction	14 - 51	22	186	
5 $\log_{10}$ reduction	NA	45	231	
6 $\log_{10}$ reduction	NA	85	276	
Free Chlorine CT Dose (mg-min/L)[a]				
1 $\log_{10}$ reduction	7	LRV cannot be claimed under WaterSecure (2017b) protocol	7	WaterSecure (2017b) – Australian Crediting Framework
2 $\log_{10}$ reduction	10[b]		10	
3 $\log_{10}$ reduction	13		13	
4 $\log_{10}$ reduction	16		16	
Chloramine CT Dose (mg-min/L)[c]				
1 $\log_{10}$ reduction	NA	615[d]	1482	Protozoa: USEPA (1999) – U.S. Crediting Framework Virus: Keegan et al. (2012) – Peer Reviewed Literature
2 $\log_{10}$ reduction	NA	1230[d]	2326	
3 $\log_{10}$ reduction	NA	1850[d]	3160	
4 $\log_{10}$ reduction	NA	NA	3949	
Ozone CT Dose (mg-min/L)[e]				
1 $\log_{10}$ reduction	0.85	9.9[f]	0.85	

2 log_{10} reduction	1.23[g]	20[f]	1.23	WaterSecure (2017c) - Australian Crediting Framework
3 log_{10} reduction	1.63	30[f]	1.63	
4 log_{10} reduction	2.01	NA	2.01	

***a**: bacterial and viral LRVs are for pH ≤ 8, turbidity ≤ 2 NTU, and temperature = 10°C, **b**: Hoff (1986) recommended a free chlorine CT dose of 0.034 to 0.05 (mg.min)/L to achieve 2 bacterial LRVs based on E. coli as the test microorganism, pH of 6 to 7, and a temperature of 5°C, **c**: the chloramine CT is for pH = 6-9, temp. = 10°C , **d:** These credits are for Giardia, **e:** CT values required to achieve pathogen LRV credits using ozone are obtained from WaterSecure (2017c) validation protocol at a temperature of 10°C, **f**: for protozoa, the CT values in WaterSecure (2017c) are based on USEPA (2006) guidance, **g**: Hoff (1986) recommended an ozone CT value of 0.02 (mg.min)/L to achieve 2 LRV for bacteria using E. coli as the test microorganism, pH of 6 to 7, and a temperature of 5°C.*

Table 3-3. Filtration Unit Process LRVs Applied to Example Treatment Process Trains.

Filtration Technology	Log Reduction Value			Crediting Framework or Pathogen Removal Studies
	Bacteria	Protozoa	Viruses	
Pretreatment plus bag or cartridge filter[a,b]	NA	2	0	USEPA (2019b) – U.S. Crediting Framework
Slow sand filtration[b, c]	2[d]	2	2	
Ultrafiltration[e]	3	4	0	Bacteria: Soller et al. (2019) – Peer Reviewed Literature Protozoa: California SWTR (2018) – U.S. Crediting Framework Virus: USEPA (2019b) – U.S. Crediting Framework
Microfiltration[e]	3[f]	4	0	

***a:** Prefiltration requirements for membrane cartridge filtration are strainers and/or bag filters with size ranging from 300 to 3000 µm, **b:** combined filter effluent turbidity (95% monthly/max) = 1/5 in NTU, max logs of credit (USEPA, 2019b), **c:** filter performance depends on presence of schmutzdecke, grain size, flow rate, operating conditions (mainly temperature, pH) (WHO, 2017), **d:** WHO (2017), **e:** combined filter effluent turbidity (95% monthly/max) = 0.1/0.5 in NTU, **f**: daily pressure decay test should be conducted.*

3.3 Example SCU Treatment Process Trains to Achieve Varying LRTs

Treatment process trains required to achieve pathogen LRTs for unrestricted irrigation and indoor use (Table 3-1) based on selected pathogen LRVs (Tables 3-2 and 3-3) are outlined in Table 3-4. The LRTs are lower for unrestricted irrigation than toilet flushing because the viral LRT for unrestricted irrigation is only 0.5 lower than for toilet flushing. Because the LRVs are rounded up, this results in the same LRVs achieved for treatment process trains across the two end uses. The example treatment process trains for HFCAs from 10^{-1} – 10^{-4} (10% - 0.01% sewage) are summarized in Figure 3-1. For each HFCA, several example treatment process trains are provided. While slow sand filtration was included in Table 3-3 and could be applied in SCU projects, it was not included in the examples due to highly specific operating conditions that may be difficult to achieve with stormwater as a source water.

Treatment requirements to meet LRTs for HFCA from 10^{-1} – 10^{-3} (10% - 0.1% sewage) require chemical disinfection in addition to UV, unless multiple UV reactors are used in series (Table 3-4 and Figure 3-1). Note that storage will be required prior to the example treatment process trains for continuous supply of water. In addition, many projects include diversion of first flush particularly after long dry periods, to reduce chemical and microbial loads to SCU storage and treatment systems.

Table 3-4. Example Treatment Process Trains Required to Achieve LRTs for Unrestricted Irrigation and/or Toilet Flushing.

Treatment Process	LRV		
	Virus	Protozoa	Bacteria
10^{-1} HFCA (10% Sewage): Examples 1 and 2			
Microfiltration	0	4	3
UV (186 mJ/cm^2)	4	6	>4
Free Cl_2 (13 mg-min/L)[a] (Chloramine 3160 mg-min/L)[b]	3	0	3
Total LRV	**7**	**10**	**>10**
Required LRT	**6.5**	**4.5**	**4**
10^{-1} HFCA (10% Sewage): Example 3			
Microfiltration	0	4	3
UV (186 mJ/cm^2)	4	6	>4
O_3 (1.63 mg-min/L)[c]	3	0	3
Total LRV	**7**	**10**	**>10**
Required LRT	**6.5**	**4.5**	**4**
10^{-2} HFCA (1% Sewage): Examples 1 and 2			
Microfiltration	0	4	3
UV (186 mJ/cm^2)	4	6	>4
Free Cl_2 (10 mg-min/L)[a] (Chloramine 2326 mg-min/L)[b]	2	0	3
Total LRV	**6**	**10**	**>10**
Required LRT	**5.5**	**3.5**	**3**
10^{-2} HFCA (1% Sewage): Example 3			
Microfiltration	0	4	3
UV (186 mJ/cm^2)	4	6	>4
O_3 (1.23 mg-min/L)[c]	2	0	3
Total LRV	**6**	**10**	**>10**
Required LRT	**5.5**	**3.5**	**3**
Treatment Process	**LRV**		
	Virus	**Protozoa**	**Bacteria**
10^{-2} HFCA (1% Sewage): Example 4			
Microfiltration	0	4	3
UV (276 mJ/cm^2)	6	6	>4
Total LRV	**6**	**10**	**>7**
Required LRT	**5.5**	**3.5**	**3**
10^{-3} HFCA (0.1% Sewage): Examples 1 and 2			
Microfiltration	0	4	3
UV (186 mJ/cm^2)	4	6	>4
Free Cl_2 (7 mg-min/L) [a] (Chloramine 1482 mg-min/L)[b]	1	0	1
Total LRV	**5**	**10**	**>8**

Required LRT	**4.5**	**2.5**	**2**
10^{-3} HFCA (0.1% Sewage): Example 3			
Microfiltration	0	4	3
UV (186 mJ/cm^2)	4	6	>4
O_3 (0.85 mg-min/L)[c]	1	0	1
Total LRV	**5**	**10**	**>8**
Required LRT	**4.5**	**2.5**	**2**
10^{-3} HFCA (0.1% Sewage): Example 4			
Microfiltration	0	4	3
UV (231 mJ/cm^2)	5	6	>4
Total LRV	**5**	**10**	**>7**
Required LRT	**4.5**	**2.5**	**2**
10^{-4} HFCA (0.01% Sewage): Example 1			
Microfiltration	0	4	3
UV (186 mJ/cm^2)	4	6	>4
Total LRV	**4**	**10**	**>7**
Required LRT	**3.5**	**1.5**	**1**
10^{-4} HFCA (0.01% Sewage): Example 2			
Microfiltration	0	4	3
O_3 (9.9 mg-min/L)[c]	4	1	4
Total LRV	**4**	**5**	**7**
Required LRT	**3.5**	**1.5**	**1**
10^{-4} HFCA (0.01% Sewage): Example 3			
Microfiltration	0	4	3
Free Cl_2 (16 mg-min/L)[a]	4	0	4
Total LRV	**4**	**4**	**7**
Required LRT	**3.5**	**1.5**	**1**
Treatment Process	**LRV**		
	Virus	**Protozoa**	**Bacteria**
10^{-4} HFCA (0.01% Sewage): Example 4			
Microfiltration	0	4	3
Chloramine (3949 mg-min/L)[b]	4	2	NA
Total LRV	**4**	**6**	**3**
Required LRT	**3.5**	**1.5**	**1**

a*: chlorine CT is for temperature = 10°C,* ***b****: chloramine CT is for pH = 6-9, tempereature = 10°C ,* ***c:*** *ozone CT is for temperature = 10°C.*

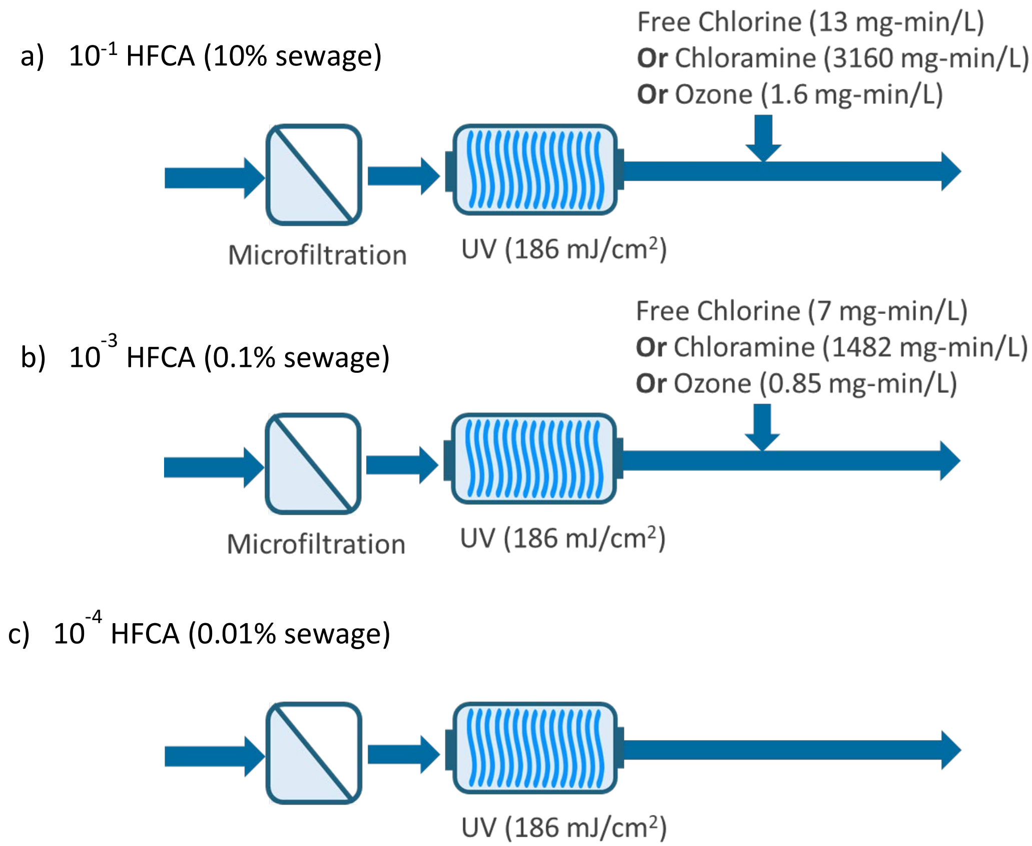

Figure 3-1. Summary of Select Example Treatment Process Trains Required to Achieve LRTs for Unrestricted Irrigation and/or Toilet Flushing

for a) 10^{-1} HFCA (10% sewage), Examples 1 - 3, b) 10^{-3} HFCA (1% sewage), Examples 1 – 3, and c) 10^{-4} HFCA (0.01% sewage), Example 1.

With different options of treatment available for each HFCA scenario (i.e, multiple example treatment process trains), the selection of the treatment process train can be informed by a set of criteria, such as the following:

- Achieve process redundancy to include multiple barriers to meet/exceed pathogen LRTs that are protective of public health. In Australian non-potable reuse, it has been conventional to allow no more that 4-log reduction per unit operation. This convention was formalized in the state of Victoria's validation guidelines for non-potable reuse (VDoH, 2013). By reducing the claimable LRV, installation of more than one type of unit operation is typically required to meet overall LRV targets – hence improving treatment redundancy.
- Ensure that the treatment units will be operable and provide the claimed LRV in the source water matrix. For example, filtration ahead of UV will improve the UVT by removing particulates, allowing the UV dose to penetrate further.
- Minimize monitoring and control requirements.
- Minimize the number of performance monitoring parameters.
- Reduce the complexity of autonomous control (e.g., information required to inform real-time controls for system management including handling of water when system is considered out of specification).

- Minimize chemical addition (e.g., chlorine; Table 3-5).
- Ensure that the combined treatment train reduces pathogens appropriately but also produces a water that is chemically and aesthetically suitable for its intended use, e.g., a highly colored water may cause alarm if used for toilet flushing, an acidic product water may cause internal corrosion, and a disinfectant residual may be required.
- There may be periods where stormwater supply is not available and unit processes should be selected that can be operated intermittently.

The benefits and considerations of each unit treatment process (Table 3-5) and select treatment train examples (Table 3-6) should be accounted for upon selection of the appropriate treatment train. The use of chemical disinfectants creates system complexity, particularly in the case of free chlorine. This is due to the formation of chloramines caused by the presence of uncertain concentration of ammonia in stormwater, which reduces the amount of free Cl_2 available for the pathogen disinfection. Due to uncertainty in stormwater ammonia concentrations, free Cl_2 disinfection in SCU systems would require extensive monitoring and control systems (see Chapter 5). In cases where a chlorine residual is required by regulation, this may be unavoidable. The use of multiple UV reactors in series also has issues due to high reliance on one unit process thus negating the multi-barrier approach for pathogen reduction. Stormwater HFCA 10^{-4} (0.01% sewage) results in more pragmatic treatment process trains where stormwater can be treated to be protective of human health through filtration and UV systems with no additional chemical dosing.

Table 3-5. Benefits and Considerations of Individual Unit Treatment Processes.

Unit Treatment Process	Benefits	Considerations
Bag/Cartridge Filters (EPA, 2020)	+ Very low maintenance requirements + No process residuals are produced + Minimum training requirements + No backwash requirements + Lower capital cost and footprint for small sites	- Single-use filter element cannot be regenerated - Biofilm growth on filter elements might cause premature clogging - For larger SCU projects and/or stormwater with higher particle loads, cartridge filters might not be cost effective - Additional pumping might be needed to reach the required feed pressure - Cartridge filters with the ability to remove protozoa have smaller, effective pore size, thereby necessitating higher differential pressure compared to general looser product (National Sanitation Foundation, 2023)
Microfiltration (MF) and Ultrafiltration (UF) (EPA, 2020)	+ Footprint required for MF/UF is smaller than that for conventional filters + Easily automated process with less onsite intervention, making it favorable for remote locations + Modern MF/UF designs enable operation at low pressures, which provides a whole-life-cost advantage over sand filtration + MF/UF can achieve 1 – 4 virus LRVs, which provides additional virus barriers even though crediting frameworks assign 0 virus LRVs to MF because credits cannot be verified with the current state of monitoring (USEPA, 2005)	- Capital cost for MF/UF is usually higher than that for sand filtration - While less-hands on labor is usually required, specialist knowledge is needed to troubleshoot and manage membranes - MF/UF can be energy intensive with higher energy costs for higher operating pressures - Backwashing and chemical cleaning practices will result in waste residuals requiring neutralization and discharge - To avoid premature fouling, the feed water should be of high quality - Poor operation could result in premature irreversible fouling and shortening the membrane's lifespan
Chlorination	+ Free Chlorine (Cl_2) is reliable and provides an effective barrier against a wide range of bacterial and viral pathogens (USEPA, 1999) + Residual Cl_2 that remains in stormwater effluent could prolong the destruction of pathogens after the initial treatment and provides a measurement of treatment effectiveness (USEPA, 1999)	- Increased/complex monitoring requirements, e.g., pH, temp., turbidity (USEPA, 2020a), ammonia (for Cl_2), and monochloramines (for chloramination) to ensure sufficient residual chlorine or monochloramine. - Monochloramines formed from free chlorine reaction with ammonia in stormwater might interfere with and artificially increase the reading of free Cl_2 sensors using the DPD reagent method (Keegan et al., 2012).

Chloramination	+Ammonia present in stormwater can be used to generate chloramine	- High CTs are required, necessitating larger storage tanks (Keegan et al., 2012). This may be less of a barrier for SCU where large storage tanks are often in place where high CTs may be achieved. - Increased monitoring requirements for correct dosing of Cl2 based on variable influent ammonia.
Unit Treatment Process	**Benefits**	**Considerations**
Ultraviolet Disinfection (UV)	+ UV disinfection does not result in the formation of hazardous byproducts (USEPA, 1986; USEPA, 1986; USEPA, 2003). + UV is not dependent on pH and does not react with ammonia (USEPA, 1986; USEPA, 1986; USEPA, 2003). + UV requires shorter contact time to absorb the dose from low pressure high output lamps and reactors are comparatively smaller than for Cl_2 (USEPA, 1986; USEPA, 1986; USEPA, 1999; USEPA, 2003). + UV is generated onsite, and therefore safety problems related to shipping and handling are less than those for Cl_2 (USEPA, 1999). +Pre-validated UV reactors exist for onsite water systems (SFPUC, 2020)	- Pre-validated UV units can be purchased and operated within validated limits to achieve a certain pathogen removal credit. Pre-validated units may not be an exact match for scheme requirements leading to some energy inefficiency. - Custom validation of UV dose requires use of reactor-specific equations that necessitate automation and integration of lamp status, flow rate, UVT, and UVI sensor signals (USEPA, 2006; Wright et al., 2020) and challenge testing. This activity would only be pursued at larger facilities (>10 mgd) if a suitable revalidated unit was not available. - UV unit validation should occur at flows > onsite design flow rate and at UVTs < typically anticipated to occur onsite (Wright et al., 2020).
Ozonation (O_3)	+ O_3 requires shorter contact time than Cl_2 and thus smaller storage volume (USEPA, 1986; USEPA, 1986; USEPA, 1999; USEPA, 2003). + O_3 can be generated onsite from air but these systems are generally energy inefficient. More efficient ozone generation can occur using liquid oxygen, but this entails more challenging safety problems related to shipping and handling than those for Cl_2 (USEPA, 1999).	- Ozonation is more complex than UV and Cl_2; O_3 requires efficient contacting systems and complicated equipment (USEPA, 1999). - Ozone is toxic and corrosive; contactor off-gases must be destroyed to avoid worker exposure (USEPA, 1999). - Ozonation could require relatively high capital cost and power intensiveness (USEPA, 1999). - Ozonation might require monitoring at multiple segments of the contactor to verify CT (Sharvelle et al., 2022). - Regular maintenance is required for ozone residual sensors (Sharvelle et al., 2022). - Ozonation might require monitoring of $O_3/(TOC+NO_2^-)$ ratio to verify virus LRV, which could simplify residual monitoring but could be cost prohibitive due to the requirement for expensive TOC and NOx analyzers (USEPA, 2020a).

Table 3-6. Benefits and Considerations for Select Treatment Process Train Examples for 10^{-1}, 10^{-2}, 10^{-3} and 10^{-4} HFCAs.

HFCA/Treatment Example	Treatment Train Components	Benefits	Considerations
10^{-1} Treatment Examples 1 and 2	• Microfiltration • UV (276 mJ/cm^2) • Free Cl_2 of 7 mg-min/L (Chloramine 3160 mg-min/L)	+ See benefits for microfiltration (Table 3-5) + See benefits for UV (Table 3-5) + See benefits for chlorination (Table 3-5) + Microfiltration can remove colloids, macromolecules, and suspended solids that might interfere with the disinfection process or contribute to the formation of DBPs. + Increased treatment robustness due to the diversification of unit treatment processes, specifically for disinfection. + Increased process redundancy with protozoa and bacteria total LRVs >> required LRT.	- See considerations for microfiltration (Table 3-5) - See considerations for microfiltration (Table 3-5) - See considerations for chlorination (Table 3-5) - See considerations for choramination (Table 3-5) - See considerations for UV disinfection (Table 3-5)
10^{-1} / Treatment Example 3	• Microfiltration • UV (276 mJ/cm^2) • O_3 (1.23 mg-min/L)	+ See benefits for microfiltration (Table 3-5) + Microfiltration can remove colloids, macromolecules, and suspended solids that might interfere with UV disinfection. + Increased treatment robustness due to the diversification of unit treatment processes, specifically for disinfection. + Increased process redundancy with protozoa and bacteria total LRVs > required LRT. + See benefits for UV and O_3 (Table 3-5)	- See considerations for microfiltration (Table 3-5) - See considerations for UV (Table 3-5) - See considerations for O_3 (Table 3-5)

10^{-2} / Treatment Example 1 and 2	• Microfiltration • UV (186 mJ/cm^2) • Free Cl_2 (10 mg-min/L) (Chloramine 2326 mg-min/L)[a]	+ See benefits for microfiltration (Table 3-5) + See benefits for UV (Table 3-5) + See benefits for chlorination (Table 3-5) + Microfiltration can remove colloids, macromolecules, and suspended solids that might interfere with the disinfection process or contribute to the formation of DBPs. + Increased treatment robustness due to the diversification of unit treatment processes, specifically for disinfection. + Increased process redundancy with protozoa and bacteria total LRVs >> required LRT.	- See considerations for microfiltration (Table 3-5) - See considerations for chlorination (Table 3-5) - See considerations for choramination (Table 3-5) - See considerations for UV disinfection (Table 3-5)

HFCA/Treatment Example	Treatment Train Components	Benefits	Considerations
10^{-2} / Treatment Example 3	• Microfiltration • UV (186 mJ/cm^2) • O_3 (1.23 mg-min/L)	+ See benefits for microfiltration (Table 3-5) + Microfiltration can remove colloids, macromolecules, and suspended solids that might interfere with UV disinfection. + Increased treatment reliability due to the diversification of unit treatment processes, specifically for disinfection. + Increased process redundancy with protozoa and bacteria total LRVs > required LRT. + See benefits for UV and O_3 (Table 3-5)	- See considerations for microfiltration (Table 3-5) - See considerations for UV (Table 3-5) - See considerations for O_3 (Table 3-5)
10^{-2} / Treatment Example 4	• Microfiltration • UV (276 mJ/cm^2)	+ See benefits of microfiltration (Table 3-5) + Simplified treatment with less components and complexity in comparison with Cl_2 and O_3. + Microfiltration can remove colloids, macromolecules, and suspended solids that might interfere with the disinfection process. + See benefits of UV (Table 3-5)	- See considerations for microfiltration and UV (Table 3-5) - Reduced treatment reliability due to the reliance on 1 treatment process, U.V, to meet > 4 log_{10} reduction of virus. This could pose a considerable threat to public health if UV goes offline or is compromised, requires maintenance, or cannot meet virus

			LRTs due to unexpected change in influent characteristics.
10^{-3} / Treatment Example 1 and 2	• Microfiltration • UV (186 mJ/cm²) • Free Cl_2 of 7 mg-min/L (Chloramine 1482 mg-min/L)[a]	+ See benefits for microfiltration (Table 3-5) + See benefits for UV (Table 3-5) + See benefits for chlorination (Table 3-5) + Microfiltration can remove colloids, macromolecules, and suspended solids that might interfere with the disinfection process or contribute to the formation of DBPs. + Increased treatment reliability due to the diversification of unit treatment processes, specifically for disinfection. + Increased process redundancy with protozoa and bacteria total LRVs >> required LRT.	- See considerations for microfiltration (Table 3-5) - See considerations for chlorination (Table 3-5) - See considerations for UV disinfection (Table 3-5)

HFCA/Treatment Example	Treatment Train Components	Benefits	Considerations
10^{-3} / Treatment Example 3	• Microfiltration • UV (186 mJ/cm²) • O_3 (0.85 mg-min/L)	+ See benefits for microfiltration (Table 3-5) + Microfiltration can remove colloids, macromolecules, and suspended solids that might interfere with UV disinfection. + Increased treatment reliability due to the diversification of unit treatment processes, specifically for disinfection. + Increased process redundancy with protozoa and bacteria total LRVs > required LRT. + See benefits for UV and O_3 (Table 3-5)	- See considerations for microfiltration (Table 3-5) - See considerations for UV (Table 3-5) - See considerations for O_3 (Table 3-5)
10^{-3} / Treatment Example 4	• Microfiltration • UV (231 mJ/cm²)	+ See benefits of microfiltration (Table 3-5) + Simplified treatment with less components and complexity in comparison with Cl_2 and O_3.	- See considerations for microfiltration and UV (Table 3-5) - Reduced treatment reliability due to the reliance on 1 treatment process, U.V, to meet > 4 log_{10} reduction of virus. This could pose a considerable threat to public health

		+ Microfiltration can remove colloids, macromolecules, and suspended solids that might interfere with the disinfection process. + See benefits of UV (Table 3-5)	if UV goes offline, requires maintenance, or cannot meet virus LRTs due to unexpected change in influent characteristics.
10^{-4} / Treatment Example 1	• Microfiltration • UV (186 mJ/cm^2)	+ See benefits of microfiltration (Table 3-5) + Simplified treatment with less components and complexity in comparison with Cl_2 and O_3. + Microfiltration can remove colloids, macromolecules, and suspended solids that might interfere with the disinfection process. + See benefits of UV (Table 3-5)	- See considerations for microfiltration and UV (Table 3-5) - Relies on only one treatment process to meet viral LRTs
10^{-4} / Treatment Example 2	• Microfiltration • O_3 (9.9 mg-min/L)	+ See benefits for microfiltration and ozonation (Table 3-5). + Simplified treatment with less components and complexity in comparison with Cl_2 and UV. + Microfiltration can remove colloids, macromolecules, and suspended solids that might interfere with the disinfection process.	- See considerations for microfiltration and ozonation (Table 3-5)

CHAPTER 4

Guidance for Sampling and Analysis of Stormwater Microbial Quality

This chapter addresses the methods and quality assurance / quality control (QA / QC) used to sample and measure stormwater microbial quality. Below is a set of criteria considered important for assessing microbial quality of stormwater:

- Human rather than general or animal source pathogens or source tracking markers should be measured
- Specify the recover method, recovery rate and limit of detection (Schoen et al., 2017)
- Estimate and report percent detection, concentration, and number of collected samples
- Analyze fresh rather than stored samples (Schoen et al., 2017)
- Collect composite or event mean concentration (EMC) samples (Schoen et al., 2017)
- Monitor multiple locations over time (Schoen et al., 2017)

These criteria were applied by Alja'fari et al. (2023) for inclusion of data on microbial quality of stormwater in analyses conducted in support of this project and guidance. References specific to sample collection and analysis for microbial quality of stormwater are recommended in the following sections.

4.1 Collection of Stormwater Samples for Analysis of Microbial Quality

Clary et al. (2014) describes grab sampling techniques which are applicable to both wet and dry weather conditions and automated sampling techniques specific to sampling stormwater for microbial quality. The authors of this guidance recommend automated sampling techniques that characterize event mean concentration of microbial constituents. Sampling protocol considerations are described by CWP and Pitt (2004).

4.2 Measurement of Traditional FIB in Stormwater

Fecal indicator bacteria (FIB) have been conventionally used to monitor the microbial quality of stormwater. Therefore, thorough documentation is available on the methods and quality assurance / quality control used to measure FIB. Clary et al. (2014) and Clary et al. (2016) are suggested references for measurement of FIB in stormwater.

4.3 Measurement of Potentially Human-Infectious Pathogens in Stormwater

In a protocol developed for risk assessment of microorganisms in separate stormwater systems, the Water Environment Research Federation (Olivieri et al., 2007) provided details on establishing a science-directed field program for determining risk associated with exposure to pathogens in stormwater. The program addresses several aspects pertaining to pathogen monitoring and measurement in stormwater. Additionally, the minimum information for publication of quantitative real-time polymerase chain reaction (PCR) experiments (MIQE) guidelines (Bustin et al., 2009) are relevant to the analysis of pathogens in stormwater. The guidelines include a checklist for users to improve the accuracy, relevance, repeatability, and correct interpretation of a quantitative PCR (qPCR) experiment (Bustin et al., 2009). MIQE guidelines are recommended by the authors of this guidance for all analyses of potentially human-infectious pathogens in stormwater where real-time qPCR is used as the methods of analysis.

4.3.1 Measurement of Virus

In 2010, the United States Environmental Protection Agency (USEPA) published method 1615: Measurement of Enterovirus and Norovirus Occurrence in Water by Culture and RT-qPCR (USEPA, 2010). The methods were revised in September 2014 (USEPA, 2014). The first part of the methods describes the procedure to measure total infectious viruses by culture methods, and the second part describes the procedure to measure enterovirus and norovirus using real-time qPCR. In a recent research effort quantifying pathogens in untreated wastewater in California, Pecson et al. (2021) used the culture-based method outlined by Rigotto (2011) to quantify adenoviruses. Pecson et al. (2021) also used the primers and probes detailed by Ko (2005) to quantify adenoviruses using molecular-based methods. Pecson et al. (2021) suggested modifications to both culture- and molecular-based methods to evaluate, and they suggested matrix spikes.

4.3.2 Measurement of Protozoa

In 2014, the USEPA published Method 1693: Cryptosporidium and Giardia in Disinfected Water which is a culture based method that is recommended for measurement of protozoa in stormwater samples.

4.3.3 Measurement of Bacteria

The USEPA Selected Analytical Methods for Environmental Remediation and Recovery recommends methods for analysis of pathogens (Hall et al., 2022). *Campylobacter jujuni* and *Salmonella* are common human-infectious pathogenic bacteria measured in water samples. For *Campylobacter jujuni,* Hall et al. (2022) recommend ISO 17995 (2019) as a culture method and Cunningham et al. (2010) for real-time qPCR measurements. Real time qPCR is used for confirmation of culture assays. USEPA Method 1682 (2006) or 1200 (2012b) are recommended for culture analysis of *Salmonella* and Jyoti et al. (2011) is recommended for qPCR measurement of *Salmonella*.

4.4 Measurement of Human Microbial Source Tracking Markers (MST)

In 2019, the USEPA published method 1696: Characterization of Human Fecal Pollution in Water by HF183/BacR287 TaqMan Quantitative Polymerase Chain Reaction (qPCR) Assay (USEPA, 2019a). Although this method addresses the characterization of human fecal contamination in recreational waters, it is also applicable to analyze wet or dry weather samples collected from stormwater outfalls.

4.5 Stormwater Control Measure Performance Monitoring for Removal of Microbial Constituents

Geosyntec Consultants and Wright Water Engineers (2009) provide standards and protocols for the collection, storage, analysis, and reporting of stormwater control measure monitoring data and provides guidance for the monitoring of low impact development practices at the site level.

CHAPTER 5

Monitoring for Stormwater Capture and Use Projects to Assure Pathogen Reduction

This chapter provides guidance on monitoring for SCU projects to assure pathogen reduction. Routine monitoring (Section 5.1) is suggested for all SCU projects regardless of treatment level (i.e., selected LRTs). Additional monitoring is suggested for projects to be characterized as Low Treatment Category (Figure 5-1, Section 5.2). The conservative treatment category (Figure 5-1, Option 1) is recommended as the suggested default and the low treatment category is considered a voluntary category (Figure 5-1, Option 2) to reduce treatment required with the tradeoff of additional monitoring of human MST markers.

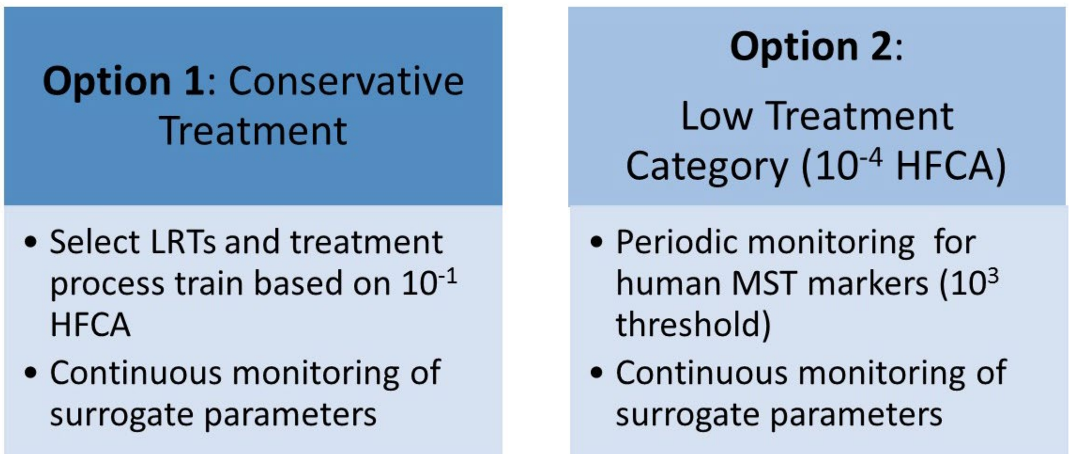

Figure 5-1. Option 1 (Conservative) and Option 2 (Low) Treatment Categories for SCU.

Based on currently available data on stormwater quality, selection of LRTs to meet stormwater HFCA 10^{-1} (10% sewage) is considered conservative treatment of stormwater, as described in Chapter 2 (Section 2.5.2). When SCU treatment process trains that meet LRTs consistent with HFCA 10^{-1} (10% sewage) are selected, the only monitoring that is needed is for surrogate parameters to verify performance of unit treatment processes. Surrogate parameters are monitored parameters correlated with performance of a unit process, and are typically parameters that can be readily monitored continuously, e.g., turbidity, UV transmittance (UVT), electrical conductivity.

Because predictors (e.g., land use, region, scale of collection area) have not been identified to justify selection of LRTs for lower stormwater HFCA (Alja'fari et al., 2023), the authors of this guidance suggest monitoring beyond routine surrogate parameters to categorize stormwater into a low treatment category (Figure 5-1). The low treatment category is defined as HFCA 10^{-4} (0.01% sewage) because treatment requirements are substantially reduced at 10^{-4} HFCA (0.01% sewage), because microfiltration and UV treatment can be used to meet LRTs without the need for addition of chemical disinfectants (see Chapter 3, Table 3-4 and Figure 3-1). In addition, 10^{-4} HFCA is near to the median HFCA observed in nationally collected stormwater of $10^{-4.5}$ (Table 2-4). Selection of treatment from stormwater HFCA 10^{-1} to 10^{-3} (10% - 0.1% sewage) does not result in substantive changes to treatment requirements with the only difference being disinfection dose requirements. Thus, 10^{-4} HFCA (0.01% sewage) is selected as the cutoff for the low treatment category. Monitoring to confirm SCU projects fall within and stay within this category (i.e., new sources of human fecal contamination do not appear) is described in Section 5.2.

5.1 Routine Monitoring of SCU Treatment Processes to Assure Pathogen Reduction

Monitoring and process validation approaches have already been described within the context of decentralized non-potable water systems (Sharvelle et al., 2017). Routine monitoring of surrogate parameters is recommended that are readily measured using commercially available water quality monitoring technology. This section aims to provide additional information and considerations on how processes for stormwater capture and use trains could be continuously monitored to verify performance.

The high infectivity of pathogens at very low levels, combined with the long analysis turnaround times (weeks to months) means that end of pipe testing is not a practical means to assure pathogen reduction. The approach of defining critical control points (CCPs) to manage pathogen reduction has been increasingly applied in water reuse (Walker et al., 2014, 2015). The CCP approach is generally accepted as an appropriate way to verify that the acute health risk associated with low exposure to pathogens is managed. To effectively implement a CCP approach to manage pathogens it is important to identify a particular barrier, typically a treatment process, and an associated single or set of monitoring parameter(s). The monitored parameters should be able to confirm that the process is achieving a nominal LRV. Ideally, the monitored parameters will report at a frequency sufficient to allow for corrective action prior to significant failure of a treatment barrier. Sharvelle et al. (2017) applied the CCP approach to develop recommendations for pathogen control points (PCPs) for decentralized non-potable water systems.

In addition to the CCP and PCP approach, treatment technology credits have been assigned to processes. Treatment technology credits are typically granted based on empirical LRV evidence associated with specific design and operational constraints. For some specific processes, products can be independently tested and pre-validated by independent certifiers, e.g., membrane or cartridge filters that have undergone NSF 419 testing. Although a pre-validation does not guarantee performance on installation, follow-up field testing or periodic auditing to confirm that the product is being operated within pre-validated limits may be sufficient to control risks for non-potable SCU.

This section summarizes potential treatment technologies and provides references to validation and monitoring frameworks and approaches. SCU specific considerations are noted for each technology or validation approach (Table 5-1). Some of these frameworks may not be accepted in specific states and prior to implementation it is advised to consult local regulators.

The monitoring requirements are quite extensive for relevant unit treatment processes. An alternate approach for SCU systems to reduce monitoring required could be prescriptive pre-validation. For example, membranes and cartridge filters could be certified by the National Sanitation Foundation (NSF) through a prescribed process with specified operational and maintenance conditions.

Table 5-1. Monitoring Requirements and Considerations for Unit Process for SCU Projects.

Treatment Process	Required Monitoring	Considerations	References
Cartridge Filters	• Requirements per NSF419 validation which may specify maximum: ○ Flow, ○ Differential pressure, ○ Filtrate turbidity and/or ○ Total filtered volume or service life	• A small number of cartridge filters have undergone NSF validation for protozoa removal, achieving LRV of approximately 2. • Cartridge filters for protozoa removal would need to have a smaller effective pore/mesh size which would likely result in a higher differential pressure than looser product. • Cartridge filters typically exclude in the 1 – 25 µm range and would not be expected to remove viruses. • Operation of a NSF pre-validated cartridge filter, per validated requirements, and assuming the validated LRV may be appropriate for SCU. • Onsite testing using polystyrene microspheres (as used during NSF419 testing) could further assure protozoa removal. • Monitoring of filtrate turbidity (or differential feed to filtrate turbidity) would provide online assurance of filter integrity.	National Sanitation Foundation, 2020.
Chloramination	• Concentration x time (CT) necessitates monitoring/knowledge of ○ Exposure time: ▪ Contactor volume ▪ Contactor baffling factor ▪ Flow ○ Total or Monochloramine residual ○ Temperature ○ pH ○ Turbidity	• Chloramination CTs are high and would necessitate large storage which may be appropriate for SCU. • Residual monitoring of total chlorine (or monochloramine) could be conducted at the storage outlet. If a high chlorine demand was anticipated, residual could be monitored at multiple points to integrate a CT, similar to ozone. • The assumption of chloramine CTs means that variable ammonia in the source water is less of a concern. • Corrective action for low residual could be to recirculate to storage and boost dosing rate. • The referenced CT tables are considered valid at relatively high turbidities. As a result, monitoring of turbidity may not be required (2 – 20 NTU) if the highest turbidity bin was assumed. •	Smart Water Fund Chloramination Research Report (Keegan et al., 2012) USEPA Disinfection Profiling and Benchmarking Technical Guidance Manual (USEPA, 2020a)
Chlorination (free)	• Concentration x time (CT) necessitates monitoring/knowledge of ○ Exposure time: ▪ Contactor volume ▪ Contactor baffling factor ▪ Flow ○ Free chlorine ○ Temperature ○ pH	• Free chlorine sensors using the DPD reagent method may be interfered with by monochloramine resulting in an overestimate of actual residual. Calibrated amperometric meters do not appear to suffer from the same interferences but may not perform well in environments where pH is >7 or varies and pressure or flow at the monitoring point is not constant. Setting a maximum limit on inlet ammonia could be used to ensure that free chlorination can be reliably performed but would require free ammonia monitoring.	WaterVal Chlorination Validation Guideline (WaterSecure, 2017a) Smart Water Fund Chloramination

Treatment Process	Required Monitoring	Considerations	References
	○ Turbidity ○ Ammonia (recommended)		Research Report (Keegan et al., 2012) USEPA Disinfection Profiling and Benchmarking Technical Guidance Manual (USEPA, 2020a)
Membrane Bioreactors	• Filtrate turbidity should be maintained below 0.2 NTU 95th percentile and never exceed 0.5 NTU. • Operating flux (flow per area of membrane), transmembrane pressure and suspended solids should be within manufacturer specifications.	• Conventional operation of a MBR may not be possible for stormwater due to low nutrient levels. Supplementary nutrient addition may be necessary to achieve optimum operation. • The default LRVs and turbidity monitoring requirement correspond to the "Tier 1" WRF 4997 report recommendations. This report recommends the default LRVs are valid for submerged membrane bioreactor systems with a nominal pore size less than 0.4 µm.	WRF 4997 MBR Validation Guidelines (Salveson et al., 2021)
Membrane Filtration (MF/UF)	• LRV for protozoa can be calculated from pressure decay test (PDT) results according to the USEPA membrane filtration guidance manual. • Filtrate turbidity should be maintained below 0.15 NTU. • Membranes should be NSF 419 approved and be operated within the limits of the product specific NSF 419 validation testing.	• Although virus LRV is possible with MF/UF systems, it is typically not able to be verified with monitoring and is not claimed. • The PDT is an intermittent test typically occurring once per day to confirm that the membrane barrier is intact. In between PDTs, filtrate turbidity is monitored to confirm membrane integrity. • Individual product vendors should provide the membrane and system specific calculations to convert PDT results into equivalent protozoa LRVs. • An exceedance of turbidity should be used to trigger an immediate PDT to ensure that the membrane cannot produce off specification water for a period longer than one day.	Membrane Filtration Guidance Manual (USEPA, 2005)
Ozone	• CT Approach ○ Ozone residual monitoring single or multiple points ○ Flow ○ Temperature • Non-CT approaches ○ Applied Ozone	• Ozone decays rapidly, often using a final outlet concentration is conservative. • *Cryptosporidium* is more resistant to Ozone than *Giardia*. At the same CT, a lower *Cryptosporidium* LRV will be achieved. • CTs for virus inactivation by ozone are low. However, decay characteristics of ozone are very fast. Often, multiple segments of an ozone contactor are monitored to verify the CT.	WRF 5129 new project evaluating Ozone to TOC + nitrite for virus inactivation

Treatment Process	Required Monitoring	Considerations	References
	○ Inlet TOC ○ Inlet Nitrite	• Ozone residual sensors require regular maintenance. • Ozone to TOC+Nitrite is being investigated to verify virus LRV. Monitoring would require online TOC and nitrite which may be cost prohibitive for SCU schemes. TOC analyzers in particular require specialist maintenance to achieve reliable readings.	(Sharvelle et al. 2022). USEPA Disinfection Profiling and Benchmarking Technical Guidance Manual (USEPA, 2020a)

5.1.1 Sensor Maintenance

Installation of sensors to monitor CCPs will necessitate maintenance and calibration of the sensors. It should be anticipated that verification of the sensors included in Table 5-1 would be performed weekly. Verification would involve either a calibration standard check following sensor manufacturer protocols and/or comparison of the sensor readout with a calibrated grab sample instrument. A relative difference of more than 10% is typically adopted as a trigger for sensor maintenance or recalibration.

Although implementation of a CCP approach will result in more rapid response to treatment failures and potential for automation of diversion, there will be an additional requirement for maintenance of the more complex instrumentation.

5.1.2 Chlorination and Chloramination Considerations

Stormwater quality is variable and depending on the catchment may contain ammonia (0 – 11.9 mg/L with median of 0.3 mg/L; Pitt et al., 2018). When attempting free chlorination it will be necessary to reach breakpoint with breakpoint chlorination typically requiring a ratio of 5 - 10 mg/L of chlorine as Cl_2 to every 1 mg/L of free ammonia. For a concentration of 5 mg/L ammonia in stormwater, 25 - 50 mg/L of chlorine may need to be applied to exceed breakpoint and achieve a free chlorine residual. At these doses it is likely that odor due to chlorine may be an issue and chlorine use may become excessive.

Chloramine concentration multiplied by (x) time (CT)s to achieve virus removal are orders of magnitude higher than for free chlorine (see Table 3-2). However, SCU projects may have the benefit of larger storages which could be suitable as reservoirs. With an increased residual (targeting 6 mg/L), pH of 7 – 8, and conservatively assuming a baffling factor of 0.1, it would be possible to achieve a virus removal credit due to chloramination in the order of 1 log per day of storage (assuming CTs at 10°C provided in Keegan et al., 2012). Design improvements could be made to a contactor to improve the baffling factor or increases to the applied dose to achieve higher LRVs. Although much lower than free chlorine residuals, use of chloramine CTs would mean that the claimed virus LRVs are resistant to an unknown ammonia concentration. Some contingencies should be incorporated to account for variability in chlorine demand of the incoming stormwater so that a residual could be reliably achieved.

For a SCU scheme intending to use free chlorine CT tables to verify a virus LRV due to free chlorine (e.g., WaterSecure, 2017b or USEPA, 1999), monitoring of inlet ammonia may be best practice. In addition, if a source water was expected to contain a high ammonia residual, then aerobic biological treatment to nitrify the ammonia would likely benefit downstream processes. If inlet ammonia (or after initial nitrification) could be confirmed to be at low concentrations, then the performance of free chlorination would be more certain. If ammonia spiked, the scheme could either adopt a chloramination credit or divert until ammonia reaches an appropriate level.

5.2 Monitoring and Response for Low Treatment Category SCU Projects

For low treatment category SCU projects, monitoring is suggested to confirm less than 10^{-4} HFCA (0.01% sewage) for stormwater. Human MST trackers, such as HF183, are suggested to estimate HFCA. Other potential biological constituents that could be used for estimation of HF183 are FIB and potentially human-infectious pathogens. FIB is not well correlated to potentially human-infectious bacteria (Alja'fari et al., 2023), and issues with detection frequency and detection limits of potentially human-infectious pathogens create limitations for their application to estimate HFCA. Consequently, human MSTs have been determined to be the most appropriate biological constituent to estimate human source fecal contamination in stormwater (Alja'fari et al., 2023). Human MSTs such as HF183 can be readily measured in many commercial laboratories. Recommended references for stormwater sample collection and monitoring for HF183 are described in Chapter 4.

5.2.1 Threshold Concentration of HF183 for Categorization of SCU Projects in Low Treatment Category

The recommended threshold of HF183 in stormwater to meet the low treatment category is 10^3 GC/100mL. The basis for this estimate is the median concentration of $10^{7.4}$ GC/100mL in wastewater collected nationally (Alja'fari et al., 2023). A concentration of $10^{3.4}$ GC/100mL HF183 (10^4 / $10^{7.4}$) would be consistent with HFCA 10^{-4}. The threshold concentration is rounded from $10^{3.4}$ GC/100mL to 10^3 GC/100mL for simplification purposes. A threshold of 10^3 GC/100mL is consistent with the threshold identified by Boehm and Soller (2020) for full body contact in recreational waters and also used by Hampton Roads Sanitation District (HRSD, personal communication) for detection of sewage contamination in stormwater to detect compromised wastewater collection systems in need of repair.

5.2.2 Use of Chemical Human MST Markers as Surrogates to Detect Fecal Contamination in Stormwater

Alja'fari et al. (2023) found that sensitive detection of human fecal contamination below HFCA 10^{-4} (0.01% sewage) is unlikely to be possible with current commercially available analysis. However, detection of human chemical source tracking markers could be used as screening to detect high levels of human fecal contamination (> 10^{-3} HFCA). For the detection of human fecal contamination in stormwater in the U.S., a combination of conservative (acesulfame, sucralose, carbamazepine) and labile (acetaminophen, metformin) chemical source tracking markers are recommended. See Chapter 6 of Alja'fari et al. (2023) for more details on these possible human chemical source tracking markers.

5.2.3 Monitoring of HF183 for Low Treatment Category and Action for Out of Compliance

For a SCU Project to meet low treatment category requirements, stormwater should be collected for the planned project area and analyzed for HF183. If HFCA is below the 10^3 GC/100mL threshold for at least three storm events, then a low treatment category SCU treatment process train could be installed. Periodic monitoring is recommended to ensure that new sources of fecal contamination (e.g., from compromised wastewater collection systems) are not present. Quarterly monitoring of HF183 is recommended after project startup. A plan should be in place if HF183 is above the threshold of 10^3 GC/100mL. A possible example monitoring and action plan is presented here (Figure 5-2). Note that this is an example only and is not intended to serve as a recommended plan. Another example of an action plan for when water quality criteria are not met is in California Title 22 (Section 60320.112) for Indirect Potable Reuse (CA State Water Resources Control Board, 2018). This served as a basis to develop the example action plan presented in Figure 5-2.

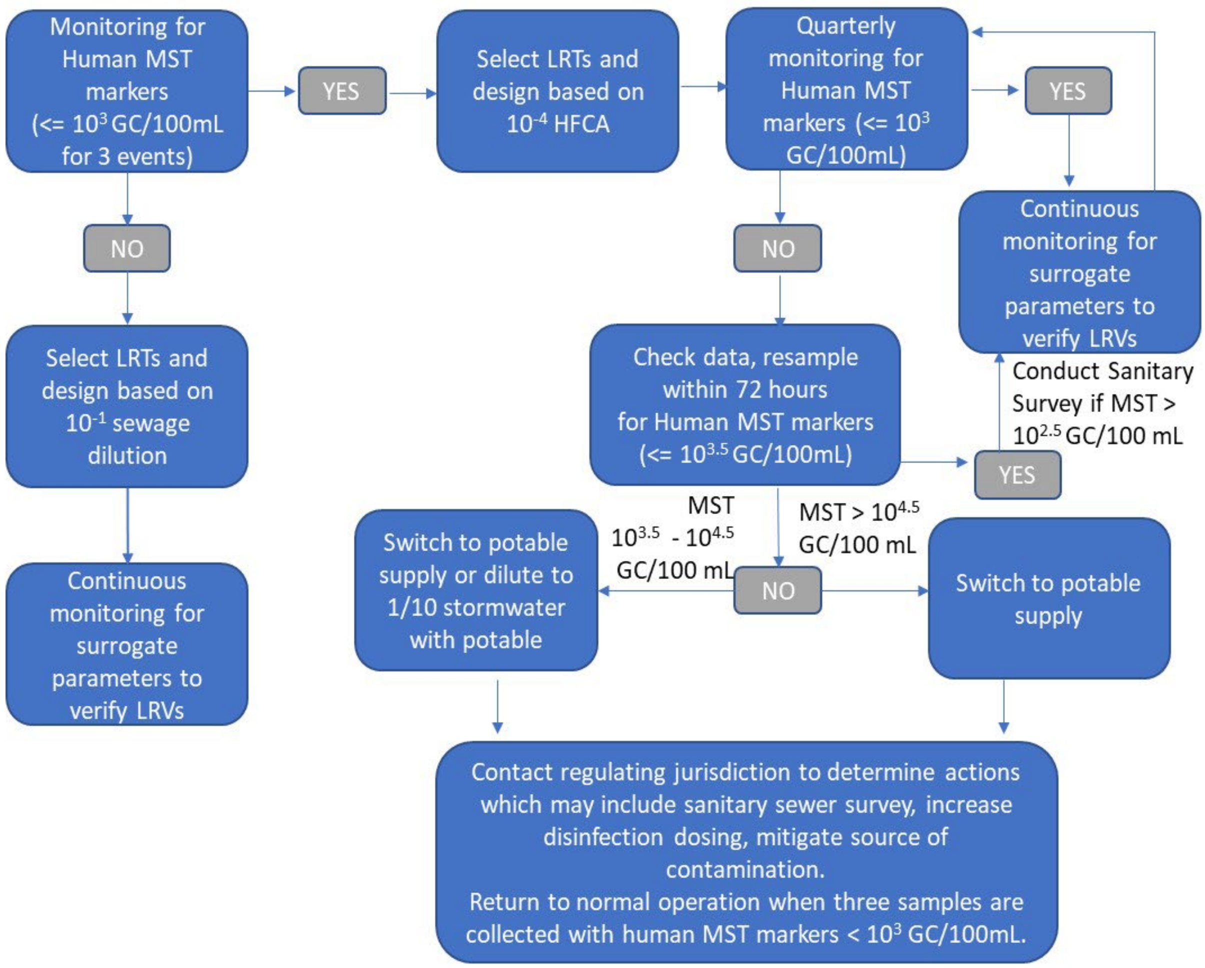

Figure 5-2. Example of Possible HF183 Monitoring and Action Plan for Non-compliance for Low Treatment Category SCU Projects.

5.2.4 Challenges for Low Treatment Categorization for New Development SCU Projects

The approach described for monitoring for the SCU low treatment category (5.2.3) has challenges for application of new SCU projects in new development areas. It may be difficult to obtain a stormwater sample from the catchment area that is planned before development occurs, complicating decisions on design of a SCU treatment process train. It is important to note that the difference between a conservative treatment SCU project (10^{-1} HFCA, 10% sewage) and a low treatment category SCU project (10^{-4} SCU, 0.01% sewage) is the need for chemical disinfectant (Figure 3-1). One approach could be to design for addition of chemical disinfectant, but only include that step for implementation on an as-needed basis. It is recognized that the uncertainty in treatment level required may serve as a barrier to implementation of SCU projects in new development areas and recommended that this is addressed as an area for development of refined and improved approaches in the future.

CHAPTER 6

Guidance for Treatment of Microbial Constituents in Stormwater for Industrial Use

Although the most popular uses of SCU systems are irrigation and groundwater recharge (Alja'fari et al., 2023), some SCU systems in the United States have started utilizing stormwater for industrial end uses such as cooling tower makeup, energy production, use in concrete plants, and ash quenching (Minnesota Department of Health, 2016; MWMO, 2021; Philadelphia Water Department, 2021). Example systems are summarized in Section 9.1 of the Summary and Synthesis of Literature on Stormwater Microbial Quality for Stormwater Capture and Use (Alja'fari et al., 2023). Unlike the common end uses of stormwater, there is typically not direct human contact with water used for industrial purposes and health concerns stemming from industrial end uses arise from opportunistic rather than enteric pathogens. Consequently, the management of stormwater for industrial end uses merit a separate discussion. The most popular industrial end use of stormwater is cooling tower makeup. Therefore, much of the focus in this chapter will be on stormwater management considerations for use in cooling towers. Important to note is that chemical quality of stormwater, especially total dissolved solids, may impact its suitability for use such applications and is known to be highly variable both spatially and temporally (NSQD, 2018). Chemical quality considerations are outside the scope of this report.

For systems using stormwater for cooling tower makeup, direct contact with and routine/significant ingestion of stormwater are not expected because public exposure is limited (Sharvelle et al., 2017). However, indirect contact and inhalation of aerosols require careful management of SCU systems storage and distribution networks to eliminate/limit exposure to *Legionella* and non-tuberculous mycobacterial pathogens (Ashbolt, 2015). As a result, the risk driver for SCU systems utilizing stormwater in cooling towers is opportunistic pathogens, e.g., *Legionella*, rather than enteric pathogens. Guidance exists on management of systems to prevent opportunistic pathogens and is provided below in Section 6.3. Few guidelines address risk management for the specific use of stormwater in cooling towers. Nevertheless, the management challenges of SCU systems are similar to those of reclaimed water systems; therefore, best management practices for reclaimed water could be modified to address stormwater characteristics (Sharvelle et al., 2017) and are summarized in Section 6.1.

6.1 Examples of Guidelines for Use of Non-Potable Water for Industrial End Uses

Most regulations for SCU projects do not specifically address industrial end uses. The District of Columbia includes cooling tower as an end use and guidance for management of opportunistic pathogens post-treatment (District of Columbia, 2020; Section M.5). New York City Department of Health and Mental Hygiene regulations also address use of rainwater and recycled water in cooling towers with a requirement to install a drift eliminator and testing and treating water according to an approved alternative water source plan (New York City, 2023). Sharvelle et al. (2017) present two examples illustrating the application of a risk-based framework for the Decentralized Non-Potable Water Systems (DNWS) used to provide cooling tower makeup water. The first example outlines the process for the evaluation, design, and management of a multi-user system which collects condensate from heating, ventilation, and air conditioning (HVAC) system for use in a cooling tower. The outlined process could be adapted to SCU systems using stormwater in cooling towers. The second example presents a hypothetical case in which wastewater collected from sinks, laundry, showers, and toilets in addition to supplemental stormwater will be subject to treatment and use for irrigation, laundry, sidewalk maintenance, toilet flushing, and cooling tower makeup. For more details on both examples, refer to Chapter 9 in Sharvelle et al. (2017).

In 2012, the USEPA published guidelines for the use of reclaimed water (i.e., treated municipal wastewater effluent) in different categories including industrial end uses (USEPA, 2012). The guidelines covered industrial reuse for once-through cooling and recirculating cooling towers. The suggested guidelines include recommended treatment, effluent concentrations, monitoring frequency of water quality, and setback distances (refer to Table 4-4 in EPA 2012 Guidelines for Water Reuse). Guidelines or regulations for the use of reclaimed water in industrial applications are provided in the following states: Washington, North Carolina, Virginia, Florida, Texas, Nevada, California, and Hawaii (USEPA, 2012). On the other hand, New Jersey and Arizona apply a case-by-case approach to review industrial end uses and determine regulations (USEPA, 2012).

The treatment requirements and quality of reclaimed water differ according to the end use and exposure potential (USEPA, 2012). For instance, California's requirements for reclaimed water use in cooling towers vary based on whether a mist is formed or not (USEPA, 2012). Reclaimed water produced in North Carolina by industrial facilities does not have to comply with reuse criteria if the end use does not involve public access (USEPA, 2012). Refer to Table 4-14 in the EPA 2012 Guidelines for Water Reuse to obtain information on system design requirements (i.e., unit processes, UV dose, and/or Cl_2 disinfection requirements), and effluent water quality requirements including indicator organisms and pathogens for industrial end uses by state.

6.2 Categories of Industrial Non-Potable Water Uses for Determination of Management and/or Treatment Requirements

Guidance for LRTs for industrial exposure is limited. In addition, industrial water exposures are highly variable depending on the specific industrial water use. It is not possible to capture every potential industrial water use that may exist to provide recommendations for each of those uses. Here, it is suggested that type of exposure to non-potable water source is considered to determine the appropriate management or treatment approach. Industrial exposures to water are described by three categories:

- No mist/spray or potential for aerosolization (water not heated above room temperature)
- No mist/spray , but potential for aerosolization exists (e.g., cooling tower)
- Water mist or spray exists in vicinity of human exposure

Management and/or treatment strategies are suggested based on these three possible exposures (Figure 5-1). Management strategies for control of opportunistic pathogens are included in Section 6.3. The basis for selection of LRTs when water is sprayed is from Schoen et al. (2020). This research assessed pathogen treatment requirements for spray exposures based on varying exposure assumptions. The models showed that LRTs required for indoor use that includes accidental exposures (e.g., cross connection; indoor use LRTs in Table 2-2) is protective for daily occupational exposure to spray at a distance greater than 2 m (8 hours per day of exposure). Thus, a distance cut off of 2 m is applied for the treatment suggestions provided in Figure 6-1. Note that personal protective equipment (PPE) can be required for individuals with possible exposures to non-potable water to provide an additional layer of protection.

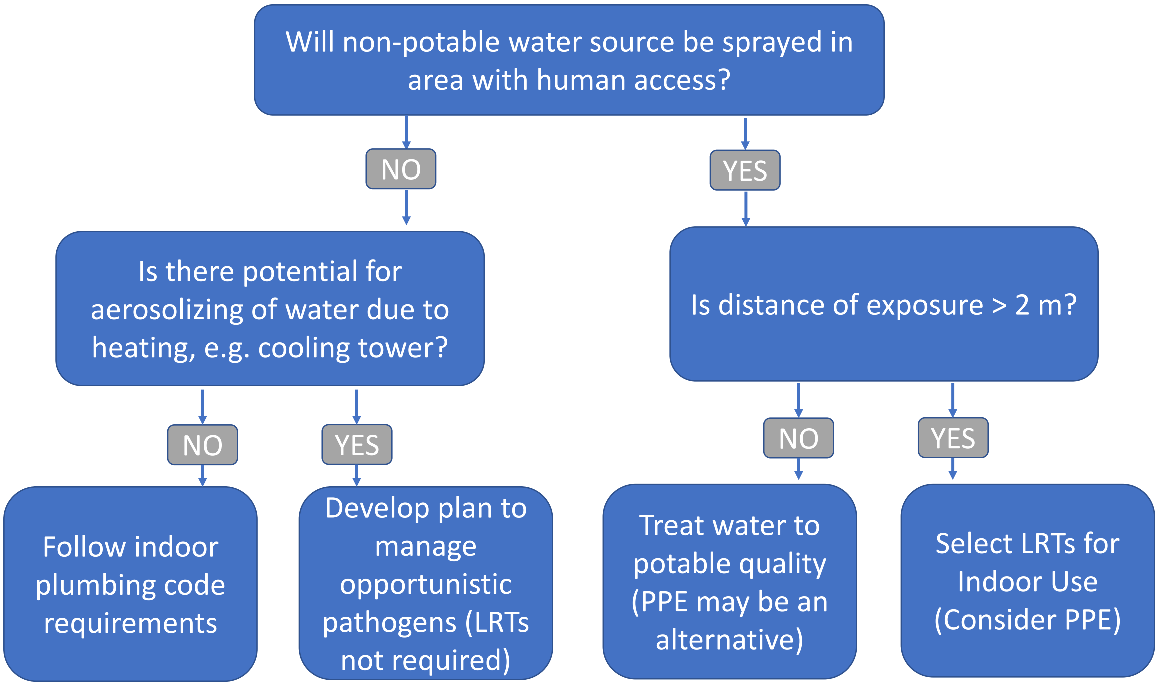

Figure 6-1. Management and Treatment Strategies for Categories of Non-Potable Water Uses for Industrial Applications

6.3 Management of Water Systems for Control of Opportunistic Pathogens

Growth of opportunistic pathogens in storage and distribution systems within SCU systems employing stormwater for industrial end uses should be controlled to protect public health (Sharvelle et al., 2017). The Risk-Based Framework for the Development of Public Health Guidance for Decentralized Non-Potable Water Systems provides general approaches to reduce/eliminate microbial growth in storage and distribution systems such as the production of non-potable water with a low nutrient and carbon content, the production of highly disinfected water, the use of biologically stable, non-reactive construction material, the provision of disinfectant residual, cleanup of storage tanks, temperature control, and distribution system flushing (Sharvelle et al., 2017). A detailed description of each approach is provided in Section 7.2 in Sharvelle et al., 2017. An important consideration specific to stormwater is the possible difficulty in achieving consistent free chlorine residual due to variable ammonia concentration (see Section 5.1.2).

The management of *Legionella* in storage and distribution networks is a critical consideration for SCUs systems using stormwater in cooling towers (Sharvelle et al., 2017). *Legionella* is an opportunistic pathogen that could be found in source water, (e.g., stormwater, and/or the environment); it is able to multiply in engineered water systems and potentially cause infection through inhalation (Ashbolt, 2015). Important references to consult for managing *Legionella* include the ANSI/ASHRAE Standard 188-2015 *Legionellosis*: Risk Management for Building Water Systems which establishes guidelines for best management practices for non-potable and potable water systems and the book entitled *Legionnaires'* Disease: The Control of *Legionella* Bacteria in Water Systems is another reference which constitutes the United Kingdom's Approved Code of Practice (Health and Safety Executive, 2013). Both references address risk mitigation for non-potable and potable water systems; the references also require analyses of uses and fixtures (Sharvelle, et al., 2017).

Chemical and physical control methods can be applied to prevent the growth and persistence of *Legionella* in plumbing systems (Kim et al., 2002; Wang et al., 2013). Water age has a positive correlation with the growth of *Legionella* (Wang et al., 2012; Rhoads et al., 2016). Therefore, reducing water age could serve as a control strategy (Prussin et al., 2017). Disinfectant type could influence the persistence of *Legionella*, with monochloramine exhibiting the potential to hinder Legionellosis (Moore et al., 2006; Wang et al., 2012). Other engineering controls that can be used to prevent *Legionella* in plumbing systems include ozone and UV light (Muraca et al., 1987; Langmark et al., 2007).

Given that aerosols are a transmission route of *Legionella*, disinfection of air should be examined to make it a less hospitable environment (Prussin et al., 2017). Aerosol-focused remediation procedures should be studied and validated considering that research investigating *Legionella* disinfection strategies in air is limited because studies have so far focused on the prevention of *Legionella* growth in plumbing systems (Prussin et al., 2017). The efficacy of cleaning and treatment protocols recommended by cooling towers manufacturers has been questioned; this necessitates studying these *Legionella* control protocols further (England et al., 1982).

Incorporation of ultraviolet (UV) germicidal irradiation into indoor air systems is a potential engineering control which has been effective for other respiratory pathogens (Brickner et al., 2003; Kowalski, 2010). The use of photocatalytic or UV treatment to disinfect airborne *Legionella* has shown promise (Josset et al., 2010; Chang et al., 2012); nonetheless, fungi could protect *Legionella* from these treatment types (Alum and Isaacs, 2016). Regular cleaning of cooling systems is also important to inhibit biofilm growth (Morey, 1988; Luongo and Miller, 2016).

Engineers and scientists have recently started to shift from trying to destruct all microorganisms in buildings to attempting to harness beneficial microbes and apply a probiotic approach to make the built environment healthier (Gilbert, 2017; Adams et al., 2016). Some *Bacillus* bacteria have exhibited the potential to prevent *L. pneumophila*'s growth (Temmerman et al., 2007). For instance, using *B. subtilis* in cooling towers reduced *L. pneumophila* concentration from 53,000 to less than 1,000 CFU/L in a period of three weeks. However, before practitioners move to a probiotic approach to reduce outbreaks of *Legionella*, more research is required to determine the safety and efficacy of this strategy (Prussin et al., 2017).

Risks from using reclaimed water in cooling towers could be decreased by using towers constructed with efficient drift eliminators and lower stack height (Lucas et al., 2012). Lower stack heights lower the distance traveled by aerosols (Hamilton et al., 2018). Risk factors for outbreaks of *Legionella* include water stagnation, biofilm growth, cooling tower deficiencies, poor microbial water quality, poor maintenance, inadequate design or positioning of the system that causes large exposures (Department of Health and Human Services, 2015; ASHRAE, 2015; Sharvelle et al., 2017; CDC, 2017).

Measures that can be used to mitigate risks from the use of reclaimed water in cooling towers include (Department of Health and Human Services, 2015; ASHRAE, 2015; Sharvelle et al., 2017; Hamilton et al., 2018; CDC, 2017):

- Treatment before initial startup after long shut down periods or commissioning
- Routine monitoring (including *Legionella*) and inspection (See example in New York City, 2023)
- Requirement to register cooling tower equipment with regulating body
- Restriction of access to cooling towers
- Utilization of drift eliminators
- "Bleed-off" to limit accumulation of solids
- Protection from sunlight

- Using critical control points and hazard analysis methodology and/or documentation of all strategies for controlling, monitoring, planning, and responding to problems that arise
- Independent audits
- Installation of automatic biocide dosing devices
- Training cooling tower employees in safety and health practices
- Use of windbreaks

Many state and county health departments have regulations related to cooling tower operations including when non-potable water is used. These local regulations should be consulted prior to use of non-potable water sources in cooling towers. Examples also exist for operator certification.

Another important aspect of managing SCU systems using stormwater for industrial end uses is the allocation of roles and responsibilities for storage and distribution systems (Sharvelle et al., 2017). A responsible management entity (RME) refers to a person, company, or governmental body that is legally responsible for the performance of a DNWS (Sharvelle et al., 2017), of which a SCU system is an example. The Risk-Based Framework for the Development of Public Health Guidance for Decentralized Non-Potable Water Systems Section 7.4 provides an example of shared responsibility when non-potable water is used for cooling tower makeup (Sharvelle et al., 2017). In this example, ensuring that non-potable water quality complies with specifications and that best management practices are applied for the storage and distribution network, up to the cooling tower, may be the responsibility of the RME whereas the cooling tower operation and maintenance and related water quality controls are the responsibility of the owner. Sharvelle et al. (2017) expound on this example by considering the allocation of responsibilities and roles in the case of condominium ownership form of buildings; for more information refer to section 7.4 in Sharvelle et al. (2017).

CHAPTER 7

Guidance for Treatment of Microbial Constituents in Stormwater for Use to Irrigate Edible Crops

Stormwater generated from urban areas could be used for the irrigation of nearby agricultural areas or urban gardens where food crops are grown for human consumption (edible food crops). Urban gardens are defined as areas of land that are formally organized, managed, and maintained by a person or a group to plant and harvest food crops and/or ornamental crops (City of Wheat Ridge, 2021). This chapter focuses on the use of stormwater in urban gardens or nearby agricultural areas for the irrigation of edible food crops. Types of urban gardens include (City of Wheat Ridge, 2021):

- **Community gardens**: land plots which are leased for a minimum cost, and crops are either donated or consumed
- **Market gardens**: harvested crops are sold to gain profit
- **Community Supported Agriculture**: harvested crops are donated or sold for consumption by shareholders

Treatment requirements for stormwater to be used either in urban gardens or larger agricultural fields is consistent, with the primary concern being the risk associated with human consumption of contaminants present in irrigation water.

7.1 Background on SCU for Edible Food Crops

A clear consensus on the safety or advisability of using stormwater to irrigate food gardens has not been reached yet. However, the Metropolitan Council in Minnesota has developed a Stormwater Reuse Guide identifying food gardens irrigation among the potential uses of stormwater (Metropolitan Council, 2011). Nonetheless, the Council did not establish water quality standards and treatment guidelines for the stormwater to be used for the irrigation of food gardens (Metropolitan Council, 2011). Health concerns caused by stormwater constituents can be classified as:

- Concerns related to human exposures of stormwater constituents and environmental impact including:
  - Microbial constituents (bacterial, viral, and protozoan pathogens)
  - Physicochemical constituents (TSS, volatile suspended solids, free Cl_2, turbidity, chemical oxygen demand, biochemical oxygen demand, total Kjeldahl N, nitrate-N, ammonia-N, total P, soluble reactive P, and total dissolved P)
  - Organics (pesticides, oil & grease, and hydrocarbons)
- Concerns related to constituent's uptake into crops through irrigation with stormwater (Al, As, Be, B, Cd, Cr, Co, Cu, F^-, Fe, Pb, Li, Mn, Hg, Mo, Ni, Se, Sr, Sn, W, Ti, V, and Zn)

This report focuses on microbial risks associated with use of stormwater for irrigation of food crops, which is where known acute risks exist. Chemical risks are also important to understand for SCU where food crop irrigation is the end use of the water and research is needed to address this topic. The Southern California Coastal Water Research Project (SCCWRP) developed monitoring strategies in 2018 for constituents of emerging concern in recycled wastewater use for food crop irrigation. However, stormwater chemical contaminants are too different from those in wastewater to make conclusions based on findings of SCCWRP (2018).

In the absence of standards regulating the use of stormwater to irrigate food crops, state water reuse criteria can be used to provide guidance on the microbial quality and treatment required to use stormwater for the irrigation of food crops. A detailed summary of state water reuse criteria for irrigation of edible crops is included in Alja'fari et al. (2023; Chapter 10).

7.2 Selection of LRTs for SCU for Edible Food Crops

LRTs for bacterial, viral, and protozoan pathogens in stormwater have not yet been established for the safe use of stormwater to irrigate edible crops. To fill this data gap, dilution of untreated wastewater (sewage) is used to estimate contamination of stormwater with human infectious pathogens and thus allow for estimating LRVs for use of stormwater for unrestricted irrigation of food crops (Sharvelle et al., 2017; Olivieri et al., 2021).

To provide some context on the interpretation of the stormwater LRV estimates a relative comparison was made against LRV estimates for accepted level of treatment of wastewater based on California Title 22 Recycled Waters for Unrestricted Irrigation of Food Crops (State of California, 2000). Table 7-1 contains a summary of a relative comparison between two different approaches: one used to generate estimated LRVs needed to meet an annual risk goal (10^{-4} ppy) of infection for an artificial stormwater based on dilution of untreated wastewater (Pecson et al., 2021) and the second used to estimate the annualized risk based on field measured plant performance of pathogen data and estimated LRVs (Cooper et al., 2012; Rose et al., 2004; Olivieri et al. 2014). It is important to note that the assumptions used in the two approaches have not been harmonized and thus this summary represents only a general comparison. Recognizing the limitations of the comparison related to harmonization of assumptions, the comparison does indicate that the results of the two approaches are qualitatively similar .

The estimated LRVs recommended by Pecson et al. (2022) for treatment of stormwater for unrestricted irrigation based on an assumption of 10% sewage in stormwater (HFCA = 10^{-1}; see Table 2-2 and 7-2) are near 1 – 2 log lower than achieved by wastewater treatment meeting Title 22 regulations (Table 7-2), while LRVs for stormwater treatment for indoor use are 1 log or less lower than wastewater treatment meeting Title 22 regulations (Table 7-2). When stormwater is assumed to contain 10% wastewater (HFCA = 10^{-1}), treatment to meet LRTs for indoor use should be consistent with or more conservative than requirements for Title 22 treatment for food crop irrigation.

Table 7-1. Relative Comparison of Estimated LRVs Between Stormwater and California Title 22 Recycled Waters for Unrestricted Irrigation of Food Crops

		Log Reduction Values (LRVs) for selected Pathogens		
Source of Water for Treatment	**Treatment Processes**	***Giardia*** (95th% estimated)	**Enteric Virus** (95th% estimated)	**Risk Goal**
Stormwater (10% sewage, HFCA = 10^{-1})[1]	Membrane Filter, UV and Chlorine Disinfection[2]	Estimated performance 4.3 (95th% estimate) to achieve risk goal[3]	Estimated 6.2 performance (95th% estimate) to achieve risk goal[3]	Annualized 10^{-4} (infection)[4]
Untreated Wastewater	Oxidized, Filtered and Disinfected[5]	Measured plant performance: 5.6 (95th% est.)[6] 6.9 (95th% est.)[7] 6.4 (95th% est.)[8]	Measured plant performance: 6.0 (95th% est.)[6] 7.6 (95th% est.)[7]	Estimated Annualized (infection) varies 10^{-4} to 10^{-8}(QMRA est.)[9]
Stormwater (0.1% sewage, HFCA = 10^{-3})[1]	Membrane Filter, UV and Chlorine Disinfection[2]	Estimated performance 2.3 (95th% estimate) to achieve risk goal[3]	Estimated performance 4.2 (95th% estimate) to achieve risk goal[3]	Annualized 10^{-4} (Infection)[4]

1) Based on California NWRI-ONWS report (Olivieri et.al, 2021) and DPR-2 WRF pathogen report (Pecson et.al, 2021)
2) Treatment processes from NWRI-ONWS report for unrestricted irrigation.
3) Estimated LRT 95th% based on CA NWRI-ONWS report and for annualized risk goal of 10^{-4} infections/year (Olivieri et.al, 2021).
4) Risk Goal for estimating LRT 95th%. EV risk estimates based on rotavirus dose-response see Olivieri et.al (2021).
5) CA Title 22 Criteria (State of California, 2000):
   a) Disinfected tertiary recycled water: means a filtered and disinfected wastewater that meets a CT (product of total chlorine residual and modal contact time measured at the same point) value of not less than 450 mg-min. per L at all times with a modal contact time of 90 min. (based on peak dry weather design flow) or provides a 5 log removal/reduction of MS2 F-specific phage or polio virus or similar virus).
   b) Filtered wastewater: an oxidized, coagulated, clarified wastewater which has been passed through natural undisturbed soils of filter media, such as sand or diatomaceous earth, so that the turbidity, as determined by an approved laboratory method, does not exceed 5 turbidity units more than 5 percent of the time during any 24-hour period, an average of 2 NTU during a 24-hour period, and does not exceed a 10 NTU at any time; in addition, the filter may not exceed 5 gals per min per square foot (traveling bridge automatic backwash filters cannot exceed 2 gals per min).
6) Based on re-analysis (Cooper et.al, 2012 and Olivieri et.al, 2014) of Rose et.al. data (2004); no confirmation of CT.
7) Based on City of Vacaville data (Seto et.al, 2018); no confirmation of CT and virus based on MS-2.
8) Based on Monterey data (Bartolo and Kenny 2019); no confirmation of CT.
9) Based on Cooper et.al (2012) and Olivieri et.al (2014).

Table 7-2. Comparison of Stormwater LRVs and LRVs Achieved for wastewater treatment meeting Title 22 Unrestricted Food Crop Irrigation Requirements

(based on achieving an annual risk goal of 10^{-4} ppy of infection)

Source of LRVs	Virus	Protozoa
Stormwater estimated LRV (10% sewage, HFCA = 10^{-1}) for unrestricted irrigation	6.5	4.5
Stormwater estimated LRV (10% sewage, HFCA = 10^{-1}) for indoor use	7.0	6
Range of LRVs in wastewater meeting Title 22 Unrestricted Food Crop Irrigation (Table 7-1)	6.0 - 7.6	5.6 - 6.9

Data Source: (Pecson et al., 2022)

CHAPTER 8

Guidance for Dry Weather Flow Capture and Use Projects

Dry weather flows refer to chronic or perennial flows and or may be present in groundwater or even building foundation water, even when there have been no recent precipitation events. Sources of dry weather flow can include runoff that enters the separate stormwater network from several activities such as over-irrigation, illegal discharges, lawn watering, groundwater seepage, and car washing (Engelhorn and Krish, 2018). Dry weather flows can serve multiple beneficial uses including: the provision of an alternative water source to sell; injection of dry weather flows for subsequent groundwater withdrawal; the collection and pumping of dry weather flows to spreading grounds and subsequent treatment; and potable use following advanced purification (CASQA, 2016). The motivation to capture dry weather flows is that those flows are present consistently throughout the year with little daily variation, so projects do not require large storage that may be required for wet weather capture projects. It should be noted that wet weather flows are also captured in many dry weather flow projects. In addition, dry weather flow are typically captured in most wet weather flow projects due to the design of most diversion systems. And, like wet weather flows, dry weather flows may have considerable variations in microbial loading due to variables within the watershed.

8.1 Treatment Requirements for Dry Weather Capture and Use Projects

Descriptive statistics show that the median concentration of human MST markers in dry weather flows is approximately three orders of magnitude less than that in wet weather flows, on a national scale (Table 8-1, Alja'fari et al., 2023). Using human MST markers as a surrogate for the HFCA in stormwater, dry weather flows have a lower human fecal contamination (10^{-7} median HFCA, Table 8-1) compared to wet weather flows ($10^{-4.5}$ median HFCA, Table 2-4). The 95th percentile HFCA in dry weather flow of $10^{-2.6}$ indicates that 10^{-2} HFCA (1% sewage contamination) would be conservative for selection of LRTs from Table 2-2 to inform treatment process train design. However, due to the large uncertainty in dry weather flows and the low relative difference for treatment requirements for HFCA 10-2 compared to HFCA 10-1, it may be recommended that treatment requirements (Chapter 3) and characterization of Low Treatment Category projects (Chapter 5) for dry weather flows be the same as those for wet weather flows.

Table 8-1. Descriptive Statistics for HFCAs in Dry weather Flows based on Human MST Markers on a National Scale

(n = 1000 iterations).

Percentile	HFCA Estimates Based on Human MST Markers
5th	10^{-12}
25th	10^{-9}
Median	10^{-7}
75th	$10^{-5.4}$
95th	$10^{-2.6}$

8.2 Dry Weather Flow Capture and Use Design Considerations

Few examples were found in the literature on dry weather flows capture and use systems (Alja'fari et al., 2023). Similarly, the information available on the design considerations for dry weather flows capture and use systems was limited. However, important factors to consider in the design process are the potentially variable flow rate and water chemistry (CASQA, 2016). Following wet weather events, variable dry weather flow rates and water chemistry are encountered (CASQA, 2016). Additionally, if the capture and treatment facility is solely designed for dry weather flows, then no withdrawal should take place during wet weather events (CASQA, 2016). Treatment system process variation is another consideration for the design of dry weather flows capture and use systems (CASQA, 2016).

Despite the lack of guidance for design of dry weather flow capture and use, the practice has been in place in the U.S. since the 1980s. Primary drivers for early dry weather flow facilities were often water quality related. Increasingly, water supply drivers are also playing a role in projects. Projects can range from diversions to the sanitary sewer system to green infrastructure projects to onsite capture and use projects (e.g., Penmar Water Quality Project - CNRA, 2021) to flow-through treatment projects such as: Santa Monica's SMURRF (Santa Monica Public Works, 2021), the Ballona Creek TMDL Project (City of Los Angeles, 2021a), the Dana Point's Salt Creek Project (City of Dana Point, 2007) and Long Beach's LB-MUST Project (CASQA, 2021). Some dry weather projects, by design, also capture small storm events. Most wet weather projects, by design, capture dry weather flows. Most of the long-standing dry weather flow projects are found in Southern California therefore, most of the lessons learned are gleaned from this region.

Lessons learned include:

- For some projects, the original assessment of dry weather flowrates was found to be significantly overestimating flows; especially if flow monitoring was conducted during non-drought times. The early 2000's assessments of dry weather flow found generation rates exceeding 200 gpd per developed acre with variability related to land use. The overall incidental urban runoff rate determined from the City of Los Angeles Water Integrated Resource Plan was found to be 190 gallons per day (gpd) per impervious acre (LASAN & LADWP, 2004). Drought and water conservation measures are found to significantly impact dry weather generation rates. The City of Los Angeles operates a significant number of dry weather diversions (referred to as low flow diversions) from its storm drain system to its sanitary sewers. Low flow monitoring data from 2012 to 2016 (aligned with a significant period of drought) determined the median value for incidental runoff is approximately 84 gpd) per impervious acre (LASAN and LADWP 2018). Projects planned and designed in southern California prior to this drought were found to have overestimated dry weather flow generation rates. It is interesting to note that these projects generally did not observe notable increases in flow post-drought. This could be related to long term behavior changes post-drought.
- Dry weather flows have been considered relatively stable in terms of daily flow variations and loading, so there is not much continuous monitoring data. Often large-scale, urban area's MS4 permits only require annual sampling of dry weather flow (City of Los Angeles Bureau of Sanitation, 2015). While this approach may work well for obtaining rough estimates for planning purposes, others have acknowledged the variabilities that exist within urban watersheds where spills, washdown, leaks and other events make cause spikes in flow or microbial parameters (Engelhorn and Krish, 2018).
- Many of the projects that require dry weather flow for continued operations (such as constructed wetlands, direct use projects and some bioswales) are designed to make use of other sources of water supply as make-up water in the event of shortfalls in dry weather flows.

- With the exposure to the watershed, most dry weather flow projects include some form of preliminary treatment such as a screen or similar. While the approach for this may differ significantly, most preliminary treatment is not found to reduce microbials.
- Given the flow variation and overlap that exists with dry weather flow projects and wet weather projects, storage of the flow is a part of most projects. The storage may range from that found within a pump station wet well or screening structure, to large regional facilities that store larger volumes for other purposes. Examples of this range include:
    - City of Los Angeles' dry weather (low) flow diversions initially focused on diversions from the storm drainage system to sewer facilities, but increasingly looks to multi-benefit and nature-based solutions. These additional features often require storage as part of the project (City of Los Angeles, 2021b).
    - Los Angeles County's dry weather (low) flow diversions have systems that treat and release, so it is assumed some minimum storage volume is required to avoid treating peak events (Los Angeles County Public Works, 2021).
    - Los Angeles County's Safe, Clean Water Program Feasibility Study Guidelines (Los Angeles County Flood Control District, 2019) contain guidance and incentives for dry weather projects including a path to funding projects which capture, treat, and beneficially utilize dry weather flow from watershed areas greater than 200 acres. These beneficial uses often require storage as part of the project
- The approach and reasons for storage may differ significantly, however impacts of storage on microbial quality should be considered (See Section 4.8 Alja'fari et al., 2023).
- Given the variation in microbial loading in dry weather flows (Alja'fari et al., 2023), lack of established standards and variation in end uses, many approaches including sodium hypochlorite, UV, and ozone have been utilized for disinfection purposes. Formal guidance on process selection and sizing are not readily found with the exceptions noted from Los Angeles County Department of Public Health (2016). Early systems such as: Dana Point's Ozone system, Moonlight Beach UV System, Santa Monica SMURRF were sized based on assessing flow measurement and laboratory monitoring data to arrive at process selection and sizing. Laboratory testing for these early facilities was limited to selected sampling times.
- Diversions are found to be an important part of dry weather flow facilities as sediment, trash and other debris can impact influent water quality, and the performance and required maintenance of the facility.

Other findings from phone interviews conducted in 2018 with the California cities of: Dana Point, San Diego, Los Angeles, and Imperial Beach (Southern California) emphasizing small dry weather diversion projects:

- While vortex separation or continuous deflection separation may be common approaches to remove floatables, trash and debris at many larger diversion facilities, some smaller facilities were found to rely on the static screens, wet wells, and small pumps for this purpose.
- Smaller dry weather diversion facilities were also more commonly found to have less instrumentation and control features. Many relied on manual valves or gates to isolate the flow from the sanitary sewer. This was also more common when the dry weather flow was small relative to the flow in the sanitary sewer.
- Most dry weather diversion facilities discharging to a sanitary sewer have agreements and permit terms set up with the sewer agency. Monitoring requirements for these facilities are also mostly driven by the sewer agency.

CHAPTER 9

Research Needs

This chapter identifies gaps in current knowledge where research is needed to improve feasibility for pathogen reduction in SCU projects, ensuring projects remain pragmatic and protective of public health.

9.1 Data Collection on Pathogens and Human MST Markers in Stormwater and Wastewater from Same Collection Areas

The data on stormwater microbial quality in stormwater and wastewater presented in Alja'fari et al. (2023) enabled analysis of observed HFCA nationally in stormwater. While the existing data sets were extremely valuable to provide an assessment of the range of human fecal contamination observed in stormwater, the data sets had limitations. The most important limitation was lack of data where human infectious pathogens and/or human MST markers were measured from the same collection area and at the same time. Specifically, samples need to be collected where contamination of stormwater from wastewater is possible. Limited data was available from Virginia where stormwater and wastewater samples were collected from the same catchment area, but not at the same time (Alja'fari et al., 2023). Collection and analysis of microbial quality of stormwater and wastewater samples from the same catchment area has two purposes, 1) Refining estimates of stormwater HFCA nationally, and 2) Providing best practices for stormwater sample collection and analysis to estimate HFCA and treatment requirements. Correlations between human MST markers and human infectious pathogens in stormwater and wastewater collected from the same collection area at the same time should be established. Guidance is needed on most appropriate microbial constituents to analyze to estimate human fecal contamination of stormwater as well as methods of sample collection and analysis, including QA/QC guidance.

9.2 Explore Use of Certified Unit Treatment Process for SCU Systems to Reduce Continuous Monitoring Requirements

The continuous monitoring recommended for SCU unit treatment processes (Section 5.1) may be overly burdensome. A possible alternative could be prescriptive pre-validation. For example, membranes and cartridge filters could be certified by National Sanitation Foundation through a prescribed process with specified operational and maintenance conditions. National Sanitation Foundation certification processes typically require systems to be verified to maintain performance over a specified duration and operational conditions. This approach could reduce continuous monitoring requirements. However, guidance is needed on a testing protocol that would be appropriate for systems to meet certification requirements specific to application in SCU projects.

9.3 Estimation of Pathogen Reduction in Nature-Based Treatment Systems and Recommendations on Validation Approaches

Nature-based treatment systems (nature-based solutions) are often applied for treatment of stormwater prior to discharge to surface water or in SCU projects. Nature-based treatment systems make use of plants and soil media to achieve contaminant removal. Examples include constructed wetlands, rain gardens, and bioswales. While these systems can be effective to achieve removal of pathogens, the systems do not receive LRCs due to lack of validation and crediting frameworks. Research is needed to assess performance of nature-based treatment systems and to provide guidance for validation protocols for pathogen reduction in the systems.

9.4 Approaches to Determine Treatment Requirements for New Development SCU Projects

The high levels of treatment suggested in this guidance may render small scale SCU project infeasible unless projects are categorized into the low treatment category. As noted in Section 5.2.4, the approach recommended here to categorize a project as low treatment category (5.2.3) has challenges for application of SCU projects in new development areas. It may be difficult to obtain representative stormwater samples from the catchment area that is planned before development occurs, complicating decisions on selection of a SCU treatment process train. In many cases, treatment of stormwater to meet 10^{-1} HFCA may result in decision makers considering other water sources (e.g., treated wastewater, roof runoff or graywater). A more extensive data set is needed that assesses human MST markers and human infectious pathogens in stormwater collected in areas unlikely to be impacted by deteriorating wastewater collection systems, i.e. stormwater collected on a surface that is directly diverted to storage before interception with below ground stormwater collection systems. In addition to the need for more data, careful consideration is needed to establish best practices for new development areas when information is not available a priori to categorize the project into the low treatment category.

9.5 Review Approach for QMRA to Develop LRTs and Select Treatment Process Trains

Recent recommendations for pathogen LRTs are high in the US in comparison to guidelines by the World Health Organization and other countries that employ this approach. There is concern that a tendency toward conservative assumptions in risk models, estimation of pathogen concentrations, and quantitative microbial risk assessment have compounded to result in overly conservative treatment targets. Further exasperating the issue is that conservative assumptions are made with respect to LRCs assigned to each unit process. Treatment process trains that comply with recommended LRTs and meet validation protocols for LRCs may be too expensive and difficult to operate to be practical. A review of the approach to recommend LRTs and provide LRCs to unit treatment process is needed to assess whether the approaches have become overly conservative and to provide recommendations on which, if any, assumptions may be overly conservative. An expert panel is recommended to carefully consider the approaches to implement LRTs.

9.6 Consider Inclusion of Bacteria in Crediting Frameworks

While pathogen crediting frameworks in the U.S. include virus and protozoa, bacteria LRVs are not included in existing U.S. regulatory frameworks. Sharvelle et al. (2017) included bacteria LRTs as part of the guidance. Olivieri et al. (2021) conducted analysis to estimate bacteria LRTs for varying source water-end use combinations but recommended that regulations do not include bacteria LRTs due to the lack of crediting frameworks including bacteria. In addition, Olivieri et al. (2021) noted that meeting bacteria and virus LRTs would be protective of public health when residual chlorine is required. As new source water and end use combinations are introduced in combination with new unit treatment processes, it may be important to consider the need for bacteria crediting frameworks. Consideration of if and how bacteria should be included in future crediting frameworks requires further attention.

APPENDIX A

Summary of LRVs for Unit Treatment Processes

A.1 LRVs for Filtration Technologies

For slow sand filtration, a range of studies, reports, factsheets, and guidelines were reviewed to select LRV credits (Table A-1). For protozoan and viral LRVs achieved by slow sand filtration, values reported by the USEPA (2019) were selected because they were among the most recent and conservative values reported for slow sand filtration (Table 3-3). Bacterial LRVs were absent from nearly all the reviewed literature on slow sand filtration. The WHO (2017) Guidelines for Drinking Water Quality assigned 2 to 6 log reduction credits for the removal of bacterial pathogens in slow sand filters. For the purposes of this effort, a conservative value of 2 LRVs was selected for the removal of bacterial pathogens in slow sand filters (Table 3-2). Rapid sand filtration is not included in this guidance because it is not a common technology for stormwater treatment.

Pathogen LRVs achieved by ultrafilters (UF) are reported in multiple sources (Table A-1). Similar to sand filtration, the removal credits of viruses and protozoa assigned by the USEPA (2019) and California SWTR (2018), respectively, to ultrafilters were selected as they reflect recent and conservative estimates (Table 3-2). Fewer values of bacterial LRVs achieved by ultrafilters are reported in the literature, i.e., Sharvelle et al. (2017), WHO (2017), and Soller et al. (2019). Soller et al. (2019) compared allowable bacterial LRV credits for different unit treatment processes currently used in U.S. states to LRVs in the peer-reviewed literature. In their assessment of microbial risk, Soller et al. (2019) analyzed treatment process trains in direct potable reuse projects using allowable LRV credits in lieu of literature review values. As such, the selected bacterial LRV for ultrafilters was 3 which was also used for the selection of appropriate treatment process trains here (Table 4).

Pathogen LRVs achieved by microfilters (MF) have been extensively examined (Table A-1). Virus and protozoa log reduction credits assigned by the USEPA (2019b) and California SWTR (2018), respectively, to microfilters were used for the selection of appropriate treatment process trains here (Table 3-3) because they are among the most conservative and recent estimates reported for microfilters. Following the methodology used by Soller et al. (2019) to assess microbial risk from direct potable reuse projects, a bacterial LRV of 3 for microfilters was selected (Table 3-3). Removal credits for sand filtration, ultrafiltration, and microfiltration assigned by the USEPA (2019b) are based on filtration systems conforming to the operational and design requirements in the Surface Water Treatment Rule (SWTR) policy No. 2. The filtration systems should also consistently meet the specified individual and combined filter effluent turbidity requirements (Table 3-2). The SWTR approach is considered appropriate for stormwater treatment because LRVs were developed for surface water, where most stormwater is anticipated to be captured.

Note that within the context of MF vs UF there may be differences in virus removal, with higher virus removal by the tighter nominal pore-sized UF. However, there is no direct integrity test (DIT) that can verify virus sized defects in either MF or UF (USEPA, 2005). To that end, following the requirements of the USEPA MFGM MF or UF are typically not credited with virus removal. Any potential virus credit is often granted to the use of coagulation before MF and UF per the monitoring and control requirements in the USEPA Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) (USEPA, 2010). Protozoa removal by either MF or UF can be verified daily using pressure decay testing as a DIT and it is typically possible to demonstrate more than 4-log protozoa removal.

The following list includes pathogen crediting frameworks for filtration treatment technologies summarized in Table A-1:

- USEPA Surface Water Treatment Rule Fact Sheet (USEPA, 2019b).
- California Surface Water Treatment Rule, Alternative Filtration Technology – Membrane Filtration (California SWTR, 2018).
- USEPA Membrane Filtration Guidance Manual (USEPA, 2005).

Table A-1. Pathogen LRVs Achieved by Filtration Technologies as Reported in Studies, Reports, Guidelines, and Factsheets

Filtration Technology	Bacteria	Protozoa		Viruses	Source Water	Crediting Framework or Pathogen Removal Studies	Reference
		Giardia	*Cryptosporidium*				
Slow Sand Filtration	2 (0.6 - 5)	4 (3.9 - 7.1)		2 (2 - 3)	NA[a]	Official Report based on U.S crediting framework and another official report	Sharvelle et al. (2017) based on EPHC et al. (2008), USEPA (2005), Harrington et al. (2001)
	NA[a]	2	> 2	2	surface water	U.S Crediting Framework	USEPA (2019b)
	NA[a]	3	3	2	surface or groundwater	International Crediting Framework	Manitoba Sustainable Development (2017)
	2 - 6	0.3 - > 5		0.25 - 4	surface or groundwater	Official Report	WHO (2017)
	NA[a]	1.16 - > 2.6	0.28	1 - 5	intended for use as drinking water	Official Report based on Research Studies	WHO (2004)
	NA[a]	2.03 - 3.98	0.11 - 1.04	0.27 - 1.2	wastewater sampled from 6 plants	Official Report	Rose et al. (2004) as reported by Oakley and Mihelcic (2019)
	NA[a]	3	3	2	intended for use as drinking water	International Crediting Framework	Health Canada (2012)
	NA[a]	4		Cannot be demonstrated daily	Surface water	U.S Crediting Framework	California SWTR (2018)
Ultrafiltration	> 6	> 6		> 6 (4 - > 6)	NA[a]	Official Report based on U.S crediting framework and another official report	Sharvelle et al. (2017) based on USEPA (2005), EPHC et al. (2008), and Harrington et al. (2001)
	5.6 - 9	4.7 - 7.4	4.4 - 6	4.5 - 4.9	secondary effluent for norovirus and adenovirus	Peer-reviewed literature based on U.S and international crediting frameworks, peer-reviewed literature, and official reports	Soller et al. (2017) based on Kachelesky and Masterson, (1995), Jacangelo et al. (1997), USEPA (2001), EPHC et al. (2008), and Qiu et al. (2015)
	3	4	4	0	NA[a]	Peer-reviewed literature based on official report	Soller et al. (2019) as reported by Olivieri et al. (2016)
	NA[a]	NA[a]	NA[a]	> 5.4 - 7.9	NA[a]	Official report, conference proceedings	Jacangelo et al. (1997), Dwyer et al. (1995), Trussel et al. (1998), and Kruithof et al. (1999) as reported by the EPA membrane filtration guidance manual (USEPA 2005)
	NA[a]	1 - 4	2 - 4	0 - 4	NA[a]	U.S Crediting Framework	State-awarded removal credits as reported by the EPA Membrane

							Filtration Guidance Manual (USEPA 2005)
Ultrafiltration	NA[a]	> 3	> 2	0	surface water	U.S Crediting Framework	USEPA (2019b): Surface Water Treatment Rule Fact Sheet
	NA[a]	> 2.4	> 1.84	NA[a]	secondary WW treated effluent	Peer-reviewed literature cited in official report	Fu et al. (2010) as reported by Oakley and Mihelcic (2019): Pathogen Reduction and Survival in Complete Treatment Works/Pathogen LRVs in WW Sand Filters
	3 - 6	3 - 6		3 - 6	water to be treated by household treatment technologies	Official report based on studies reported in the scientific literature	WHO (2017) Guidelines for Drinking-Water Quality, Fourth Edition; these are LRVs achieved by household treatment technologies
	NA[a]	> 3	> 3	0	surface or groundwater	International crediting framework	Manitoba Sustainable Development (2017)
	NA[a]	> 4.7 - > 7	> 4.4 - > 7	> or = 6	NA[a]	Peer-reviewed literature cited in official report	Jacangelo et al. (1991) as reported in WHO (2004): Water Treatment and Pathogen Control
	NA[a]	> 4	NA	> 6.5	4 different source waters	Peer-reviewed literature cited in official report	Jacangelo et al. (1991) as reported in WHO (2004): Water Treatment and Pathogen Control

Table A-1. Pathogen LRVs Achieved by Filtration Technologies as Reported in Studies, Reports, Guidelines, and Factsheets (Continued)

Treatment Process	Bacteria	Protozoa		Viruses	Source Water	Crediting Framework or Pathogen Removal Studies	Reference
		Giardia	*Cryptosporidium*				
Microfiltration	NA[a]	4		Cannot be demonstrated daily	Surface water	U.S Crediting Framework	California SWTR (2018)
	6 (3.5 - > 6)	> 6 (4 - >6)		1 (0 - > 2)	NA[a]	Official Report based on U.S crediting framework and another official report	Sharvelle et al. (2017) based on USEPA (2005), EPHC et al. (2008), and Harrington et al. (2001)
	3 - 9	4 - 7		1.5 - 4.9	NA[a]	Peer-reviewed literature based on official report and peer-reviewed literature	Soller et al. (2017) based on Reardon et al. (2005), Francy et al. (2012)
	3	4		0	NA[a]	Peer-reviewed literature based on official report	Soller et al. (2019) as reported by Olivieri et al. (2016)
	NA[a]	NA[a]	NA[a]	0 - 4	NA[a]	Official report, conference proceedings reported in U.S crediting framework	Jacangelo et al. (1997), Wilinghan et al. (1993), Schneider et al. (1999), and Trussel et al. (1998) as reported by the EPA membrane filtration guidance manual (2005)
	NA[a]	1 - 4	2 - 4	0 - 0.5	NA[a]	U.S Crediting Framework	State-awarded removal credits as reported by the EPA Membrane Filtration Guidance Manual (2005)
	NA[a]	> 3	> 2	0	surface water	U.S Crediting Framework	USEPA (2019b): Surface Water Treatment Rule Fact Sheet
	2 - 4	2 - 6		0 - 4	water to be treated by household treatment technologies	Official report based on studies reported in the scientific literature	WHO (2017) Guidelines for Drinking-Water Quality, Fourth Edition; these are LRVs achieved by household treatment technologies
	NA[a]	> 3	> 3	0	surface or groundwater	International crediting framework	Manitoba Sustainable Development (2017)

	NA[a]	> 4.7 - > 7	> 4.4 - > 6.9	< 1	NA[a]	Peer-reviewed literature cited in official report	Jacangelo et al. (1991) as reported in WHO (2004): Water Treatment and Pathogen Control
	NA[a]	3.3 - 4.4	2.3 - 3.5	NA[a]	NA[a]	Peer-reviewed literature cited in official report	Karimi et al. (1999) as reported in WHO (2004): Water Treatment and Pathogen Control
	NA[a]	NA[a]	5.3	2.7 - 3.7	NA[a]	Conference proceedings cited in official report	Parker et al. (1999) as reported in WHO (2004): Water Treatment and Pathogen Control
	NA[a]	NA[a]	> 3	NA[a]	NA[a]	Peer-reviewed literature cited in official report	Yoo et al. (1995) as reported in WHO (2004): Water Treatment and Pathogen Control

a: not available

A.2 LRVs for Disinfection Technologies

The use of stormwater for unrestricted irrigation or indoor use necessitates some form of disinfection using ultraviolet (UV) radiation, chlorination, and/or ozonation. For UV doses required to achieve different LRV credits, different guidelines, reports, and studies were reviewed (Table A-2).

A.2.1 LRVs from UV Disinfection

The USEPA developed a comprehensive guidance manual for UV disinfection for the final Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) (USEPA, 2006) in addition to Innovative Approaches for Validation of Ultraviolet Disinfection Reactors for Drinking Water Systems (USEPA, 2020b). These guidance manuals were selected for protozoan and viral LRV credits that can be achieved using different UV doses (Table 3-2) because they provide the most detailed guidelines among the reviewed documents.

The USEPA (2006) guidance manual provides technical information on the selection, design, and operation of UV installations and compliance with UV disinfection requirements in the LT2ESWTR (USEPA, 2006). Furthermore, the manual provides states with the necessary tools to evaluate UV installations during different phases including the design, startup, and operational phases. It also provides manufacturers with performance and testing standards for UV reactors.

Due to the lack of bacteria crediting frameworks in the U.S., bacterial LRV credits were absent from most of the reviewed literature on UV disinfection, e.g., USEPA (2006), Olivieri et al. (2016), and Olivieri et al. (2021). However, an Australian framework (WaterVal™) providing national consistency in treatment technologies validation for the water industry (WaterSecure, 2017a) reported on a study analyzing the inactivation kinetics of pathogens using UV (Hijnen et al., 2006). In their study, Hijnen et al. (2006) calculated bacterial LRVs for *Campylobacter jejuni*, *E. coli O157*, and *Salmonella typhi*. Literature review data was used to calculate the inactivation rate constant k and find the UV dose required to achieve a certain LRV.

Ultraviolet disinfection doses found by Hijnen et al. (2006) were selected herein (Table 3-3) to assign 1 to 4 LRV credits to UV disinfection in stormwater treatment process trains. It is assumed that the dose achieving 5 and 6 virus LRV credits are capable of achieving more than 4 (> 4) bacteria LRV credit.

Another important UV disinfection guidance to which SCU project managers can refer is the Ultraviolet Disinfection Guidelines for Drinking Water Reuse (NWRI, 2012). In this guidance, minimum UV doses and transmittance downstream of media filtration, membrane filtration, and reverse osmosis are specified. For instance, following media filtration, a minimum 100 mJ/cm^2 UV dose is required at the maximum daily flow rate, and the influent to the disinfection process should have a UV transmittance of 55% or more at 254 nm wavelength (NWRI, 2012). If membrane filtration, e.g., microfiltration or ultrafiltration, is used upstream of UV disinfection, then the following criteria should apply (NWRI, 2012):

- The minimum UV dose at the maximum daily flow rate should be 80 mJ/cm^2.
- The maximum filtered effluent turbidity should be 0.2 NTU 95% of the time, and it should not exceed 0.5 NTU.
- The UV transmittance of the influent to the disinfection process should be at least 65% or more at 254 nm wavelength.

The UV Disinfection Guidelines also provide details on design conditions, ongoing monitoring parameters, and microbiological testing (NWRI, 2012).

A.2.2 LRVs from Chlorination and Chloramination

Chlorination can be achieved using free chlorine or different chlorinated compounds such as chloramines. Of note is that achieving free chorine disinfection in stormwater is complicated by the presence of ammonia and subsequent formation of chloramines. Either breakpoint chlorination should be achieved, and ideally free chlorine residual monitored or monochloramine formation monitored to appropriately credit disinfection due to chloramine residual. Due to variable concentrations of ammonia in stormwater (0 – 11.9 mg/Lwith median of 0.3 mg/L; NSQD, 2018), chorine dosing may vary and requires continuous monitoring to ensure appropriate dosing to achieve pathogen LRTs (see Monitoring section).

Pathogen LRVs achieved using different free chlorine doses (Table 3-2) were selected based on a review of multiple reports and studies (Table A-2). Pathogen LRV credits achieved using free chlorine in this guidance document were selected based on the values provided by WaterSecure (2017b). The WaterSecure (2017b) protocol approach is consistent with the USEPA (1999) manual: Disinfection Profiling and Benchmarking Guidance, which is concentration x time (CT) is used to correlate disinfectant dose requirements with LRV. However, WaterSecure (2017b) outlines specific CT values that are more conservative (i.e., require higher CTs) when compared to USEPA (1999) values based on more recent studies conducted using coxsackievirus B5. In addition, WaterSecure (2017b) CT values associated with a range of potential water matrix turbidities (0.2 – 20 NTU) that can account for varying turbidity encountered in stormwater. The Virus inactivation was the main focus of WaterSecure (2017b) protocol. This is because enteric viruses have a stronger resistance to free chlorine compared to enteric bacteria (WaterSecure, 2017b). As such, the same free chlorine CT can be used for bacterial and viral LRVs (WaterSecure, 2017b). Chorine is not effective for *Cryptosporidium* inactivation; therefore, no attempt was made to claim *Cryptosporidium* LRV credits by chlorination under WaterSecure (2017b) protocol. *Giardia* is resistant to chlorination, but CTs are provided by USEPA (1999) that should be suitable to claim a *Giardia* LRV.

Pathogen LRVs achieved by free chlorine are a function of water temperature, pH, and turbidity (WaterSecure, 2017b). Bacterial and viral LRVs achieved under different CT values (Table 3-2) are for pH ≤ 8 (NSQD, 2018), turbidity ≤ 2 NTU, and temperature = 10°C (NSQD, 2005; WaterSecure, 2017b).

Chloramines can be used to disinfect stormwater. The USEPA recommended chloramine CT values for *Giardia* and viruses in their Disinfection Profiling and Benchmarking Guidance Manual (USEPA, 1999). Water Services Association of Australia (WSAA, 2015) published a manual for application of health-based targets for drinking water safety in which they prescribe chloramine CT required to achieve 2 bacterial and viral LRV credits (Table A-2). The USEPA CTs for chloramination (USEPA 1999) suggest lower CTs than specified in Keegan et al. (2012) for virus reduction. This may be due to the fact that Keegan used preformed chloramine, and the USEPA (1999) recommend adding chlorine first and then ammonia. In stormwater that already contains ammonia it may not be appropriate to assume the CTs reported in the USEPA CT tables (USEPA 1999). The viral LRVs suggested by Keegan et al. (2012) have been selected to provide conservative estimates of treatment, for example treatment process trains presented herein (Table 3-2).

A.2.2 LRVs from Ozonation

Several studies and reports were reviewed to obtain pathogen LRV credits achieved by ozonation (Table A-2). WaterSecure (2017c) validation protocol provides comprehensive guidance for validating the disinfection of bacteria, protozoa, and viruses using ozone. Thus, pathogen LRV credits achieved using ozone selected herein (Table 3-2) are based on WaterSecure (2017c). The protocol established by

WaterSecure (2017c) is largely based on the USEPA (2006) guidance and on research by Melbourne Water for the validation of ozone treatment processes.

WaterSecure (2017c) validation protocol recommends the same values of CT for the removal of bacteria and viruses using ozone (Table A-2). CT values for pathogens (Table A-2) are for a temperature of 10°C (NSQD, 2018; WaterSecure, 2017b). It should be noted that bacterial and viral LRVs were developed for wastewater. Protozoan CT values required to achieved 1 to 3 LRV credits as recommended by WaterSecure (2017c) protocol are based on the USEPA (2006) guidance.

The following list includes pathogen crediting frameworks for disinfection treatment technologies in Table A-2:

- Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Surface Water Treatment Rule (USEPA, 2006).
- Ultraviolet Disinfection, WaterVal Validation Guidance Document (WaterSecure, 2017a).
- USEPA Disinfection Profiling and Benchmarking Guidance Manual (USEPA, 1999).
- Chlorine Disinfection, WaterVal Validation Protocol (WaterSecure, 2017b).
- USEPA Disinfection Profiling and Benchmarking Technical Guidance Manual (USEPA, 2020a).
- USEPA Innovative Approaches for Validation of Ultraviolet Disinfection Reactors for Drinking Water Systems (USEPA, 2020b).
- Ozone Disinfection, WaterVal Validation Protocol (WaterSecure, 2017c).
- USEPA Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources (USEPA, 1991).

Table A-2. UV Doses Required to Achieve Pathogen LRVs Using UV, Free Cl_2, Chloramines, and Ozone Disinfection Based on Literature Review

Virus Log_{10} Removal (LRV)	1	2	3	4	5	6	Crediting Framework or Pathogen Removal Studies	References
UV Disinfection Dose (mJ/cm^2)	50 - 60	90 - 110	140 - 150	180 - 200	NA[a]	NA[a]	Official report based on U.S crediting framework	Sharvelle et al. (2017) based on USEPA (2006)
	58	100	143	186	231	276	U.S Crediting Framework	USEPA (2006), USEPA (2020b) using adenovirus
	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	800	Peer-Reviewed Literature	Soller et al. (2017) based on USEPA (2006) and Gerba et al. (2002)
	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	> 300	Official Report	Olivieri et al. (2016)
	10 - 56	20 - 111	29 - 167	39 - 167	NA[a]	NA	Peer-reviewed literature	Hijnen et al. (2006)[d, e]
	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	276[f]	Official Report	Olivieri et al. (2021)
	4 – 63	7 – 120	14 – 167	22 – 222	29 - 234	211 - 235	Peer-Reviewed Literature	Malayeri et al. (2016)*
	NA	40	NA	100	NA	186	Validated UV systems	SFPUC (2020)
Protozoa Log_{10} Removal (LRV)	**1**	**2**	**3**	**4**	**5**	**6**	**Crediting Framework or Pathogen Removal Studies**	**References**
UV Disinfection Dose (mJ/cm^2)	2 - 3	5 - 6	11 - 12	20 - 25	NA[a]	NA[a]	Official Report	Sharvelle et al. (2017) based on USEPA (2006)
	2.5	5.8	12	22	45	85	U.S Crediting Framework	USEPA (2006), USEPA (2020b) based on Crypto.
	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	800	Peer-reviewed literature	Soller et al. (2017) based on USEPA (2006) and Gerba et al. (2002)
	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	> 300	Official report	Olivieri et al. (2016)[b]
	NA[a]	NA[a]	12 - 26.8	22 - 27.7	NA[a]	NA[a]	Australian Crediting Framework	WaterSecure (2017a)[g]
	2 - 3	5 - 6	11 - 12	NS[h]	NA[a]	NA[a]	Peer-reviewed literature	Hijnen et al. (2006)[i]
	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	276[j]	Official Report	Olivieri et al. (2021)
	<0.5 - <10	<0.5 - <10	<0.5 – 28+tailin g	<1 - ~60	<10	NA	Peer-reviewed literature	Malayeri et al. (2016)*
	NA	NA	40	NA	NA	100 - 186	Validated UV systems	SFPUC (2020)

Bacteria Log_{10} Removal (LRV)	1	2	3	4	5	6	Crediting Framework or Pathogen Removal Studies	References
UV Disinfection Dose (mJ/cm^2)	NA[a]	NA[a]	NA[a]	10[k]	NA[a]	800[l]	Peer-reviewed literature	Soller et al. (2017) based on USEPA (2003), USEPA (2006), and Gerba et al. (2002)
	3 - 6	7 - 12	10 - 17	14 - 51	NA[a]	NA[a]	Peer-reviewed literature	Hijnen et al. (2006)[m]
	0.4 – 4	0.7 – 5.7	1 – 7.8	1.1 – 8.3	1.3 – 14	1.4 – 29	Peer-reviewed literature	Malayeri et al. (2016)*
	NA	40	NA	100	NA	186	Validated UV systems	SFPUC (2020)

Table A-2. Disinfectant Doses Required to Achieve Pathogen LRV Credits Using UV, Free Cl_2, Chloramines, and Ozone Disinfection Based on Literature Review (Continued)

Virus Log_{10} Removal (LRV)	1	2	3	4	Crediting Framework or Pathogen Removal Studies	References
Free Cl_2 CT (mg.min)/L	NA[a]	1.5 - 1.8	2.2 - 2.6	3 - 3.5	Official report based on values reported in textbook	Sharvelle et al. (2017) based on Tchobanoglous et al. (2014)
	NA[a]	3	4	6	U.S Crediting Framework	USEPA (1999)[n]
	NA[a]	NA[a]	NA[a]	12[o]	Peer-reviewed literature	Soller et al. (2019)
	7	10	13	16	Australian Crediting Framework	WaterSecure (2017b)[p]
	NA[a]	NA[a]	NA[a]	6	U.S Crediting Framework	USEPA (2020a)[q]
Chloramine CT (mg-min/L)	1482	2326	3160	3949	Official Report/Pathogen Removal Study*	Keegan et al. (2012)
	NA[a]	643	1067	1491	U.S Crediting Framework	USEPA (1999)[n]
***Giardia* Log_{10} Removal (LRV)**	**1**	**2**	**3**	**4**	**Crediting Framework or Pathogen Removal Studies**	**References**
Free Cl_2 CT (mg.min)/L	2000 - 2600	NA	NA	NA	Official report based on values reported in textbook	Sharvelle et al. (2017) based on Tchobanoglous et al. (2014)
	50 – 67	99 – 134	149 – 201	NA[a]	U.S Crediting Framework	EPA (1999)[r] based on Malcolm Pirnie Inc., and HDR Engineering (1991)
	12[s]	NA[a]	NA[a]	NA[a]	Peer-reviewed literature based on U.S crediting framework	Soller et al. (2017) based on USEPA (1991)
	Protozoa LRVs cannot be claimed under WaterSecure (2017) protocol				Australian Crediting Framework	WaterSecure (2017b)
	NA[a]	NA[a]	149 – 201	NA[a]	U.S Crediting Framework	USEPA (2020a)[r]
Chloramine CT (mg-min/L)	615	1230	1850	NA[a]	U.S Crediting Framework	USEPA (1999)
***Cryptosporidium* Log_{10} Removal (LRV)**	**1**	**2**	**3**	**4**	**Crediting Framework or Pathogen Removal Studies**	**References**
Free Cl_2 CT (mg.min)/L	2000 - 2600	NA[a]	NA[a]	NA[a]	Official report based on values reported in textbook	Sharvelle et al. (2017) based on Tchobanoglous et al. (2014)
	800 - 900	NA[a]	NA[a]	NA[a]	Peer-reviewed literature	Soller et al. (2017) based on Hirata and Hashimoto (1998) and Nasser (2016)
	Protozoa LRVs cannot be claimed under WaterSecure (2017) protocol				Australian Crediting Framework	WaterSecure (2017b)

Table A-2 (continued). Disinfectant Doses Required to Achieve Pathogen LRV Credits Using UV, Free Cl_2, Chloramines, and Ozone Disinfection Based on Literature Review (Continued)

Bacteria Log_{10} Removal (LRV)	1	2	3	4	Crediting Framework or Pathogen Removal Studies	References
Free Cl_2 CT (mg.min)/L	0.4 - 0.6	0.8 - 1.2	1.2 - 1.8	1.6 - 2.4	Official report based on values recommended in textbook	Sharvelle et al. (2017) based on Tchobanoglous et al. (2014)
	7	10	13	16	Australian Crediting Framework	WaterSecure (2017b)[u]
Virus Log_{10} Removal (LRV)	**1**	**2**	**3**	**4**	**Crediting Framework or Pathogen Removal Studies**	**References**
Ozone CT (mg.min)/L	NA	0.25 - 0.3	0.35 - 0.45	0.5 - 0.6	Official report based on values recommended in textbook	Sharvelle et al. (2017) based on Tchobanoglous et al. (2014)
	NA	0.5	0.8	1	American Crediting Framework	USEPA (1999)[v]
	NA	NA	NA	1	American Crediting Framework	USEPA (2020a)[w]
	0.85	1.23	1.63	2.01	Australian Crediting Framework	WaterSecure (2017c)[x]
	Adenovirus LRVs were reported based on USEPA (1991) guidelines				Peer-reviewed literature based on U.S crediting framework	Soller et al. (2017)
***Giardia* Log_{10} Removal (LRV)**	**1**	**2**	**3**	**4**	**Crediting Framework or Pathogen Removal Studies**	**References**
Ozone CT (mg.min)/L	4 - 4.5	8 - 8.5	12 - 13	NA	Official report based on values recommended in textbook	Sharvelle et al. (2017) based on Tchobanoglous et al. (2014)
	0.48	0.95	1.43	NA	U.S Crediting Framework	USEPA (1999)[v]
	NA	NA	1.43	NA	U.S Crediting Framework	USEPA (2020a)[w]
	9.9	20	30	NA	Australian Crediting Framework	WaterSecure (2017c)[y]
	NA	0.55[z]	1[a1]	NA	Peer-reviewed literature and U.S crediting framework	Soller et al. (2017) based on Wickramanayake et al. (1985) and USEPA (1991)
***Cryptosporidium* Log_{10} Removal (LRV)**	**1**	**2**	**3**	**4**	**Crediting Framework or Pathogen Removal Studies**	**References**
Ozone CT (mg.min)/L	4 - 4.5	8 - 8.5	12 - 13	NA	Official report based on values recommended in textbook	Sharvelle et al. (2017) based on Tchobanoglous et al. (20140
	9.9	20	30	NA	Australian Crediting Framework	WaterSecure (2017c)[y]

	the potential max. allowable LRVs are set according to USEPA CT tables				Official report recommending values from U.S crediting framework	Olivieri et al. (2016)
	5[b1]	NA	NA	NA	Peer-reviewed literature	Soller et al. (2017)
Bacteria Log_{10} Removal (LRV)	**1**	**2**	**3**	**4**	**Crediting Framework or Pathogen Removal Studies**	**References**
Ozone CT (mg.min)/L	0.005 - 0.01	0.01 - 0.02	0.02 - 0.03	0.03 - 0.04	Official report based on values recommended in textbook	Sharvelle et al. (2017) based on Tchobanoglous et al. (2014)
	0.85	1.23	1.63	2.01	Australian Crediting Framework	WaterSecure (2017c)[x]
	the potential max. allowable LRVs are set according to USEPA CT tables				Official report recommending values from U.S crediting framework	Olivieri et al. (2016)
	NA	NA	NA	1[c1]	Peer-reviewed literature	Soller et al. (2017)

a**: not available, **b**: this is the current maximum allowable LRV, **c**: Viruses were not credited with an LRV because considering validation uncertainty results in a < 39 mJ/cm^2 validated dose needed to achieve 0.5 log_{10} reduction, **d**: The LRVs are reported for adenovirus type 40, adenovirus type 2, 15, 40, and 41, adenovirus (no type 40), and rotavirus SA-11, **e**: this is based on literature review data used to calculate the inactivation rate constant k and find the UV dose required to achieve a certain LRV, **f**: Olivieri et al. (2021) assumed 10% wastewater contribution to stormwater; the model virus assumed is adenovirus. The dose can be achieved with 1 UV reactor or several reactors in series, **g**: these are validated UV doses for both Giardia and Cryptosporidium based on Bacillus subtilis RED = 40 mJ/cm^2 for UVT = 50% - 98%, **h**: no value due to tailing, **i**: these values are calculated for Cryptosporidium and Giardia based on data from the USEPA, **j**: Olivieri et al. (2021) assumed 10% wastewater contribution to stormwater; the dose can be achieved with 1 UV reactor or several reactors in series, **k**: UV dose of less than 10 mJ/cm^2 (8.4 mJ/cm^2) can result in 4 log_{10} removal of E. coli (USEPA, 2003) as reported by Soller et al. (2017); Soller et al. (2017) assumed that Salmonella spp. and Campylobacter spp. LRV = E. coli LRV, **l**: based on Soller et al. (2017), Soller et al. (2019), and Olivieri et al. (2016), **m**: the LRVs are reported for Campylobacter jejuni, E. coli O157, and Salmonella typhi; this is based on literature review data used to calculate k and find the UV dose required to achieve a certain LRV, **: These are CT doses using 15 mg/L of monochloramine for at pH=8, temp.=10°C, turbidity of 2 NTU for the removal of adenovirus 2 from wastewater, **n**: the chlorine/chloramine dose is for pH = 6 - 9, and temp.=10°C; as temp. decreases, the required dose increases; the chloramine CT is provided for human adenovirus, **o**: the free chlorine dose for which the removal was estimated is less than or equal to 12 (mg.min)/L. This dose can achieve 4 to 5 log reduction of adenovirus and 1 to 4 log reduction of norovirus, **p**: CT values are for pH ≤ 8 (NSQD, 2018), turbidity ≤ 2 NTU, and temperature = 10°C (NSQD, 2005; WaterSecure, 2017b). WaterSecure (2017b) mentioned that the same free Cl_2 CT can be used for bacterial and viral LRVs, **q**: this is for pH=6-9 and Temp.=10°C; as pH increases the required CT increases, and as Temp. decreases, the required CT increases, **r**: The chlorine CT is for pH=8 and Temp.=10°C. As temp decreases, the required dose increases, and as pH increases, the required dose increases; the chloramine CT is for pH = 6-9, temp. = 10°C, **s**: the maximum reduction of Giardia at this dose is 0.5 log (Soller et al., 2017; USEPA, 1991), **t**: the free chlorine dose for which the removal was estimated is less than or equal to 12 (mg.min)/L, **u**: CT values are for pH ≤ 8 (NSQD, 2018), turbidity ≤ 2 NTU, and temperature = 10°C (NSQD, 2005; WaterSecure, 2017b); the same free Cl_2 CT can be used for bacterial and viral LRVs, **v**: The USEPA (1999) cited Malcolm Pirnie Inc., and HDR Engineering (1991) as the source for CT; the values were modified by linear interpolation between increments of 5°C. This is at temp. of 10°C. As temperature decreases the required CT increases, **w**: the temp. = 10°C; as the temp. decreases, the required CT increases, **x**: these values are for wastewater at a temp. of 10°C; the WaterSecure (2017c) report recommends the same values of CT for the removal of bacteria and viruses, **y**: WaterSecure (2017c) cites USEPA (2006) as the source/reference; the operating temp. is 10°C; these values are for protozoa without a distinction between Giardia and Cryptosporidium, **z**: A dose of 0.55 (mg.min)/L at 5 °C can achieve at least 2 log_{10} Giardia removal (Wickramanayake et al., 1985) as reported in Soller et al. (2017), **a1**: using 1 (mg.min)/L results in removal of Giardia spp. of more than 3 log_{10} at 20 °C. This is based on USEPA (1991) guidelines, **b1**: Korich et al. (1990) as reported in Soller et al. (2017), **c1**: A CT dose of less than 1 (mg.min)/L achieves 4 log_{10} removal of Campylobacter spp. and Salmonella spp.*

*assuming that the removal of E. coli is equal to that of bacterial pathogens (Sigmon et al., 2015), *Malayeri et al. (2016) reported UV doses to achieve different virus LRVs obtained from these studies: Nwachuku et al. (2005), Gerba et al. (2002), Ballester and Malley (2004), Shin et al. (2005), Linden et al. (2007), Eischeid et al. (2009), Linden et al. (2009), Baxter et al. (2007), Sirikanchana et al. (2008), Shin et al. (2009), Bounty et al. (2012), Rodriguez et al. (2013), Beck et al. (2014), Ryu et al. (2008), Boczek et al. (2016), Guo et al. (2010), Rattanakul et al. (2014), Rattanakul et al. (2015), Oguma et al. (2001), Thurston-Enriquez et al. (2003), Blatchley et al. (2008), Ko et al. (2005), Battigelli et al. (1993), Liltved et al. (2006), Lee et al. (2008), and Park et al. (2011); Malayeri et al. (2016) reported UV doses to achieve different protozoa LRVs obtained from these studies: Johnson et al. (2005), Bolton et al. (1998), Bukhari et al. (1999), Clancy et al. (2000), Craik et al. (2001), Shin et al. (2001), Belosevic et al. (2001), Zimmer et al. (2003), Bukhari et al. (2004), Clancy et al. (2004), Amoah et al. (2005), Ryu et al. (2008), Oguma et al. (2001), Beck et al. (2015), Qian et al. (2004), Campbell and Wallis (2002), Linden et al. (2002), Mofidi et al. (2002), Craik et al. (2000), and Mofidi et al. (2002); Malayeri et al. (2016) reported UV doses to achieve different bacteria LRVs obtained from these studies: Wilson et al. (1992), Butler et al. (1987), Tosa and Hirata (1999), Yaun et al. (2003), Sommer et al. (2000), Chang et al. (1985), Chen et al. (2009), and Hu et al. (2012)*

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