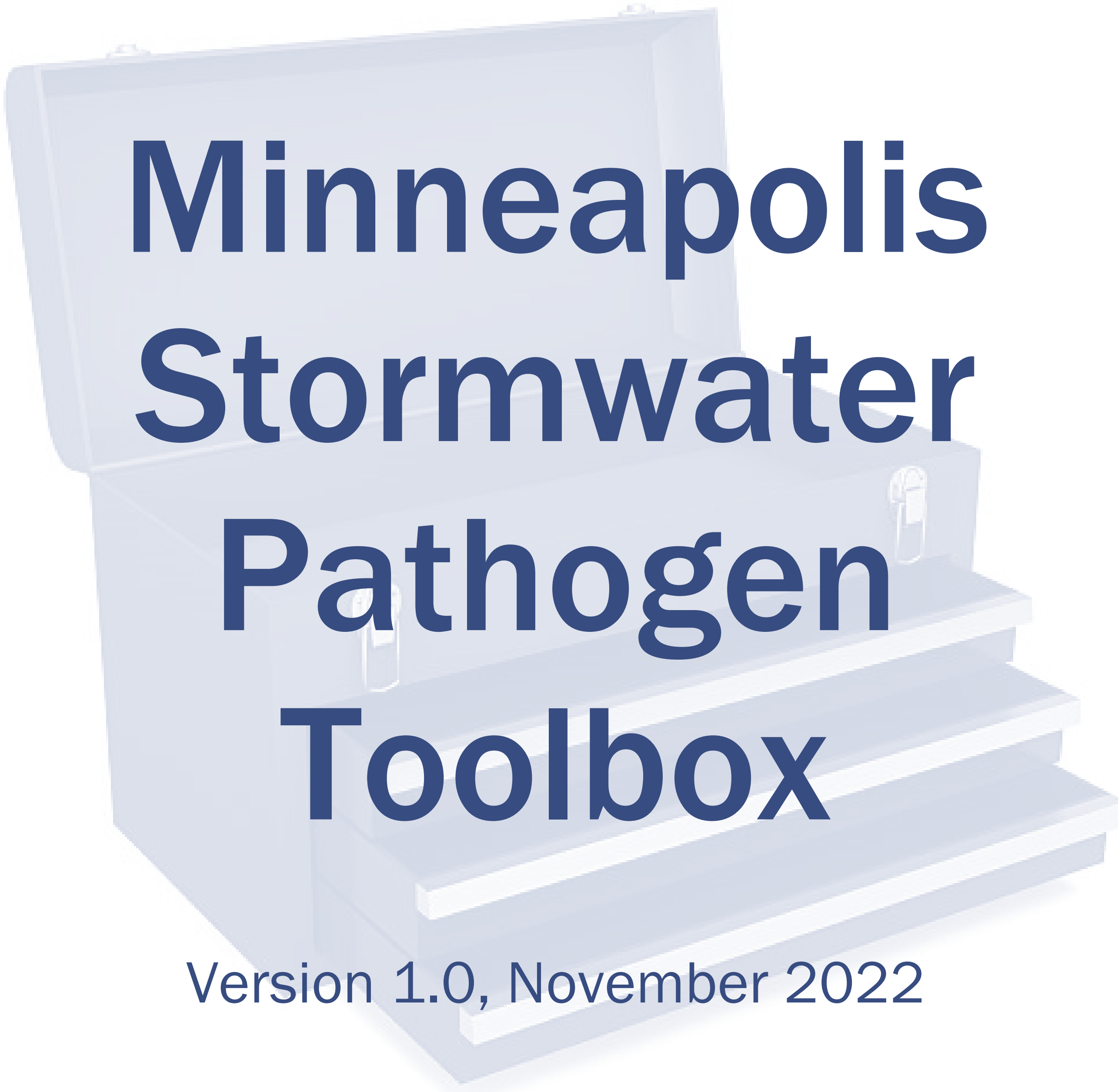


Minneapolis Stormwater Pathogen Toolbox

Version 1.0, November 2022

Minneapolis Pathogen Toolbox – Introduction

Welcome to the City of Minneapolis Pathogen Toolbox for Evaluating and Reducing Pathogens in Urban Water Resources! These tools are intended to provide procedures and resources to identify, investigate, analyze, and, ultimately, mitigate the source of pathogens in an urban environment.

This toolbox was developed by CDM Smith with support from the City of Minneapolis and the Minneapolis Pathogen Task Force.

Background Information

Pathogens Found in Urban Water Resources – Compiled list of pathogens that may be present in urban water resources including likely sources and related illnesses.

Pathogen Toolbox Glossary – List of important terms and definitions used throughout this toolbox.

Studies, Research, and Guidance Documents for Pathogens in Urban Water Resources – Matrix containing links to literature and other resources used in the development of this toolbox that can be referenced for additional information on these topics.

Urban Pathogen Sources – Infographic displaying the potential sources of pathogens in urban environments including primary sources, transport mechanisms, and reservoirs.

Pathogen Investigation Tools

START HERE Pathogen Identification, Investigation, and Mitigation Decision Tree – Decision tree to assist in identifying next steps and relevant tools for investigating and mitigating pathogens in urban water resources

Pathogen Testing Techniques – Table of techniques for detecting and quantifying pathogen levels from the standard practice of using indicator pathogens to emerging DNA-based methods.

Pathogen Sampling and Monitoring Techniques – Step-by-step checklist for pathogen sampling and monitoring actions.

Pathogen Source Identification Techniques – Flow chart to guide decision making for the best methods for pathogen source identification as well as a table containing additional details.

Models With Applications for Pathogens – Table of available modeling software that can be used for modeling and predicting pathogen concentrations and transport.

Pathogen Mitigation Techniques – Matrix of pathogen mitigation techniques to guide decisions on which techniques are effective based on the pathogen source.

MS4 Compliance Tools

Pathogen Annual Reporting Requirements – Guide to using this toolbox to assist in annual TMDL and MS4 reporting requirements with links to permit applications and additional guidance.

Pathogens Found in Urban Water Resources

Introduction

This Pathogen Glossary lists pathogenic organisms that may be of concern in water environments, including stormwater systems, streams, lakes, and wetlands. The food- and water-borne pathogens contained in this glossary are listed as pathogens of concern by the Minnesota Pollution Control Agency (https://stormwater.pca.state.mn.us/index.php?title=Overview_and_management_strategies_for_bacteria_in_stormwater), World Health Organization/Center for Disease Control (list of pathogens found to be responsible for 97% of non-foodborne illnesses, from Pathogens in Urban Stormwater Systems https://www.asce-pgh.org/Resources/EWRI/Pathogens%20Paper%20August%202014.pdf), National Institute of Allergies and Infectious Diseases (food and waterborne pathogens found at https://www.niaid.nih.gov/research/emerging-infectious-diseases-pathogens), and the Journal of Water and Health (based on epidemiological studies relevant to the development of TMDLs (https://iwaponline.com/jwh/article/5/1/149/1991/Waterborne-pathogens-in-urban-watersheds). This list is intentionally expansive and contains all the pathogens of concern listed by these sources and may contain pathogens that are not of concern in Minnesota surface waters.

Organism	Disease	Common Source of Pathogen	Links	Notes
Bacteria				
Campylobacter jejuni	Gastroenteritis (Camplyobacteriosis), may lead to Guillain-Barre syndrome	Animal feces	Campylobacter (Campylobacteriosis) | Campylobacter | CDC https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7774540/	More commonly foodborne, but occasional waterborne outbreaks have occurred.
Cyanobacteria (Blue green algae) / Cyanotoxins	Gastrointestinal, neural, hepatic, or dermal toxicity	Water rich in nutrients, typically from fertilizer runoff or sewage	https://www.cdc.gov/habs/materials/factsheet-cyanobacterial-habs.html https://www.pca.state.mn.us/water/blue-green-algae-and-harmful-algal-blooms#:~:text=What%20are%20blue%2Dgreen%20algae,warm%2C%20nutrient%2Drich%20water https://www.nalms.org/event/benthic-harmful-cyanobacteria-bloom-hcb-2-training/	HAB (Harmful Cyanobacteria Blooms) typically occur in the water column of surface waters. Recent research has shown that HABs may also occur in the benthic (bottom) layer of surface waters.
Escherichia coli, pathenogenic (E. coli)	Gastroenteritis, hemorrhagic colitis	Human and animal, especially cattle, waste.	https://www.cdc.gov/healthywater/drinking/private/wells/disease/e_coli.html	
Fecal coliform	Generally, not harmful	Sewage	Coliform Bacteria Fact Sheet - EH: Minnesota Department of Health (state.mn.us)	Fecal coliform is listed as pathogen of concern because of its use as an indicator bacteria in older impairment and TMDL studies.
Legionella pneumophila	Legionnaire's disease, Pontiac fever, pneumonia	Naturally occurring in freshwater, especially in warm temperatures	Legionnaires Disease Cause and Spread | CDC	Many outbreaks have been associated with the built environment features, such as cooling towers, whirlpools, decorative fountains, or even showers.

Organism	Disease	Common Source of Pathogen	Links	Notes
Leptospira interrogans	Leptospirosis	Urine from dogs, livestock, rodents, and other wild animals	Leptospirosis | CDC	
Pseudomonas aeruginosa	Eye and ear infections, pneumonia, blood infections, "swimmer's itch"	Naturally occurring in soil and water	Pseudomonas aeruginosa Infection | HAI | CDC	
Salmonella enterica (including A. Typhi) (formerly Salmonella choleraesuis)	Salmonellosis	Domestic and wild animal feces	Salmonella and Drinking Water from Private Wells | Wells | Private Water Systems | Drinking Water | Healthy Water | CDC	
Shigella	Shigellosis, dysentery	Feces of an infected individual	Shigella and Drinking Water from Private Wells | Wells | Private Water Systems | Drinking Water | Healthy Water | CDC	
Staphylococcus aureus	Staph infections	Frequently found in the nose and skin of humans	The Potential for Waterborne Spread of MRSA – WCP Online	
Vibrio cholera	Cholera	Feces of an infected individual	https://www.cdc.gov/cholera/general/index.html	Rarely found in the U.S.
Vibrio vulnificus	Kidney, skin, wound infections	Naturally occurring in coastal waters	https://www.cdc.gov/vibrio/wounds.html	Only found in saltwater or brackish water
Protozoa				
Balamuthia mandrillaris	Granulomatous amebic encephalitis (GAE)	Naturally occurring in soil	Sources of Infection & Risk Factors | Balamuthia | Parasites | CDC	
Cryptosporidium (including Cryptosporidium parvum)	Cryptosporidosis	Human sewage and animal waste - particularly cattle	Parasites - Cryptosporidium (also known as "Crypto") | Cryptosporidium | Parasites | CDC	Leading cause of waterborne disease in humans. Most common source is from drinking water. Occasional outbreaks are related to recreational water exposure.
Cyclospora cayatanensis	Cyclosporiasis	Human sewage	CDC - Cyclosporiasis https://www.health.state.mn.us/diseases/cyclosporasis/stats.html	More commonly foodborne. Increasing number of outbreaks occurring in Minnesota.
Entamoeba histolytica	Amoebic dysentery	Feces of an infected individual	Parasites - Amebiasis | Amebiasis | Parasites | CDC	More common in tropical environments
Giardia lamblia	Giardiasis	Human sewage and animal waste, including pet waste	Giardia | Parasites | CDC	

Organism	Disease	Common Source of Pathogen	Links	Notes
Naegleria fowleri	Primary amebic meningoencephalitis (PAM)	Bird and aquatic mammal feces, especially in warm freshwater	General Information | Naegleria fowleri | CDC	
Toxoplasma gondii	Toxoplasmosis	Cat feces	CDC - Toxoplasmosis	
Virus				
Adenovirus	Respiratory disease, gastroenteritis, conjuctivitis (eye infection)	Feces of an infected individuals	Adenovirus | CDC	
Astroviruses	Gastroenteritis	Feces of an infected individuals	Astrovirus - an overview | ScienceDirect Topics	
Caliciviruses	Gastroenteritis	Feces of an infected individuals	Human Caliciviruses - an overview | ScienceDirect Topics	
Enterovirus	Mild illness, respiratory cold-like symptoms	Feces of an infected individuals	https://www.cdc.gov/non-polio-enterovirus/index.html	
Hepatitis A	Infectious hepatitis	Feces of an infected individuals	What is Hepatitis A - FAQ | CDC	
Mosquito borne viruses: Zika virus, West Nile virus, Chikungunya virus, dengue, and malaria	Zika virus, West Nile virus, Chikungunya virus, dengue, and malaria	Infected mosquitoes	Mosquito-Borne Diseases | NIOSH | CDC https://stormwater.pca.state.mn.us/index.php/Mosquito_control_and_stormwater_management	Not waterborne; however, waterbodies, including stormwater management structures, are critical habitats for mosquito population. West Nile Disease is transmitted by Mosquitoes in Minnesota. Other mosquito transmitted diseases are tropical and associated with people who have traveled to regions where these diseases are prevalent.
Norovirus	Norovirus (gastroenteritis)	Feces of an infected individuals	Norovirus | CDC	
Rotavirus	Gastroenteritis	Feces of an infected individuals	Rotavirus | CDC	
Sapovirus	Gastroenteritis	Feces of an infected individuals	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3358050/	Foodborne virus with outbreaks in long-term care facilities in Minnesota
Fungi [1]				
Microsporidia	Microsporidiosis	Feces of an infected individual, also considered ubiquitous in the environment	CDC - DPDx - Microsporidiosis	

Notes:

[1] The extent of toxicity and health problems caused by fungi is unknown. Fungi in surface waters is a topic of emerging research.

Tool Glossary

The definitions in this glossary are those terms and acronyms found in this Pathogen Toolbox.

Term	Description	Link
Alternate Indicators	Alternate indicators are indicators of pathogens other than E coli or Fecal coliform	https://www.ncbi.nlm.nih.gov/pmc/articles/MPC2996186/
Bacteria	A free-living single celled organism that does not contain a distinct nucleus. Typically classified according to shape. Bacteria may be pathogenic that cause human disease.	bacteria - Diversity of structure of bacteria | Britannica
Bifidobacteria	Alternate indicator for bacteria. Not widely accepted.	https://www.sciencedirect.com/topics/biochemistry-genetics-and-molecular-biology/bifidobacterium
Clostridium perfringens	Bacteria that produce spores. Associated with food-borne illnesses. Used in Hawai'i as a secondary indicator.	https://www.cdc.gov/foodsafety/diseases/clostridium-perfringens.html
		https://www.pacioos.hawaii.edu/voyager/info/clostridium.html
		https://www.iso.org/obp/ui/#iso:std:iso:14189:ed-1:v1:en
Coliphage	Virus that is used to monitor for fecal contamination in drinking water	https://www.sciencedirect.com/topics/immunology-and-microbiology/coliphage
Capital Improvement Plan (CIP)	Strategic planning of projects and associated budgets for a local government that typically includes public works and other infrastructure-related improvements.	Completed Capital Improvement Projects - City of Minneapolis (minneapolismn.gov)
Catchment area	Also known as "watershed" or "drainage basin"; Area of land on which runoff flows to the same outlet point. May include contributing waterbodies and groundwater flow.	Watersheds and Drainage Basins | U.S. Geological Survey (usgs.gov)
Chronic	On-going or recurring regularly.	NA
Combined Sewer Overflow (CSO)	Point where a combined waste stream consisting of stormwater runoff, sanitary waste, and industrial discharges can be discharged untreated directly into a waterbody in the event that capacity of a treatment system is exceeded.	Combined Sewer Overflows (CSOs) | US EPA
Cyanobacteria (Cyanotoxin)	More commonly known as blue-green algae. Microscopic organisms that use sunlight to make food and can "bloom" or multiply quickly in warm and nutrient-rich environments. These blooms may produce cyanotoxins which are harmful to people and animals.	NCEH Cyanobacteria Blooms Fact Sheet (cdc.gov)
Dry weather flow /sources	Flow through a sanitary sewer not during a rain event. This flow should represent only sanitary flow and infiltration sources.	Guide for Estimating Infiltration and Inflow, June 2014 (epa.gov)
Fecal Indicator Bacteria (FIB)	Group of organisms that indicate the presence of fecal contamination which is the most common source of pathogens in stormwater or water bodies.	https://mi.water.usgs.gov/h2oqual/BactHOWeb.html
Fecal coliform	Indicator bacteria used to test for presence of sewage or fecal contamination.	https://www.pca.state.mn.us/water/bacteria

Term	Description	Link
Escherichia coli (E. coli)	Indicator bacteria used to test for likely presence of bacteria in drinking water, source waters (including groundwater and surface water), and freshwater recreational waters.	https://www.pca.state.mn.us/water/bacteria
Enterococci	Indicator bacteria used to test for presence of bacteria in recreational waters, primarily used in marine environments where E coli tests are less reliable.	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3510518/
Fungi	Spore producing organisms. Fungi may be parasitic.	https://en.wikipedia.org/wiki/Fungus
Gastroenteritis	More commonly known as "stomach flu", illness with symptoms of diarrhea and vomiting caused by a variety of bacterial and viral infections.	Gastroenteritis (Stomach Flu): Symptoms, Causes, Treatments (webmd.com)
Harmful Algal Bloom (HAB)	Algal bloom that produces toxic or harmful effects to people or aquatic animals.	Harmful Algal Blooms (HABs) Fact Sheet - Minnesota Dept. of Health (state.mn.us)
Benthic HAB	Algae that grows on the sediment or bottom of a water body (benthic zone) rather than suspended. Some species may also produce toxins.	My Water Quality: California Harmful Algal Blooms (HABs)
Illicit Discharge Detection and Elimination (IDDE)	Identification and mitigation of non-stormwater discharges (yard or pet waste, pesticides, motor oil, paint, etc.) to a stormwater system	https://www3.epa.gov/npdes/pubs/idde_manualwithappendices.pdf
Impaired Water	A body of water that fails to meet water quality standards.	https://www.pca.state.mn.us/defining-impared-waters
Indicator Bacteria	The Minnesota numeric standard for determining whether a waterbody is impaired for bacteria is determined by the presence and concentration of E coli.	https://www.pca.state.mn.us/water/bacteria
Microbial Source Tracking (MST)	Use of molecular methods and DNA markers to determine if sources of fecal contamination are human or animal. Animal sources can be narrowed by species.	MICROBIAL SOURCE TRACKING GUIDE DOCUMENT | Science Inventory | US EPA
Municipal Separate Storm Sewer System (MS4)	Publicly owned or operated stormwater conveyance system. An MS4 general permit is required if it is located in an urbanized area used by a population >1,000, and/or owned by a municipality with a population > 10,000, and/or has a population >5,000 and discharges to specially classified water body.	Municipal stormwater (MS4) | Minnesota Pollution Control Agency (state.mn.us)
National Pollutant Discharge Elimination System (NPDES)	Permitting system for point source pollutants into waters of the United States. Permits include discharge limits and monitoring and reporting requirements.	National Pollutant Discharge Elimination System (NPDES) | US EPA
Parasite	An organism that survives in or on a host organism and steals nutrients at the expense of the host.	parasitic disease | Definition, Types, & Causes | Britannica
Pathogen	An organism that causes a disease. Pathogen types include bacteria, fungi, protozoa, and viruses.	https://www.biologyonline.com/dictionary/pathogen
Pathogen Source - Primary Source	Initial source of pathogen. Typical sources of pathogens found in the urban water environment originate from wildlife and humans.	City of Minneapolis Department of Public Works, Minnehaha Creek Bacterial Source Identification Study, prepared by Burns & McDonnell Engineering Company, 2019
Pathogen Source - Reservoir (Secondary) Source	Locations within the environment that contain conditions that allow for the growth of pathogens outside of the source or host. Typically, areas where stormwater runoff may pool or create conditions for pathogens to multiply.	

Term	Description	Link
Pathogen Source - Transport Mechanism	Water flow that moves pathogen from source or reservoir to downstream surface waterbody. May include stormwater runoff, non-stormwater discharges to storm sewers, over-irrigation, and wash water directed to storm sewers, see Tool 3 for a more complete overview of urban transport mechanisms.	City of Minneapolis Department of Public Works, Minnehaha Creek Bacterial Source Identification Study, prepared by Burns & McDonnell Engineering Company, 2019
Protozoa	A class of parasite that includes single celled organism that survive in moist environments including fresh water, salt water, and soil.	https://en.wikipedia.org/wiki/Protozoa
PCR (Polymerase Chain Reaction)	Technique used to generate millions of copies of a particular section of DNA allowing the presence/absence and/or quantity of pathogens in a sample. Real-time or quantitative PCR (qPCR) uses fluorescing dyes and a fluorometer to measure the concentration of the DNA to allow for a quantitative level of pathogens.	https://www.ncbi.nlm.nih.gov/probe/docs/techpcr/
QMRA (Quantitative Microbial Risk Assessment)	Methodology to evaluate the level of risk associated with exposure to pathogen including hazard identification, dose response, and exposure assessment.	http://qmrawiki.org/
Recreational Water Illness	"Recreational water illnesses (RWIs) are caused by germs and chemicals found in the water we swim or play in, including swimming pools, water parks, hot tubs, splash pads, lakes, rivers, or oceans. They are spread by swallowing, breathing in mists or aerosols of, or having contact with contaminated water."	Causes and Symptoms of Waterborne Illness - Minnesota Dept. of Health (state.mn.us)
Sanitary Sewer Overflow (SSO)	Event when a sanitary sewer system releases untreated sewage.	Sanitary Sewer Overflows (SSOs) | US EPA
Stormwater Best Management Practice (BMP)	Stormwater practices designed to reduce runoff flows, volumes and pollutant loading. These include structural (e.g., retention ponds, rain gardens) or non-structural (e.g., street sweeping, reuse) methods.	https://stormwater.pca.state.mn.us/index.php?title=Process_for_selecting_Best_Management_Practices
Total Maximum Daily Load (TMDL)	The maximum amount (loading) of a specified pollutant allowed to enter a waterbody to remain under water quality limits. TMDLs must be established for all impaired waters.	Overview of Total Maximum Daily Loads (TMDLs) | US EPA
Virus	A type of pathogen that is an infectious organism that survives within a host organism and must use the host's cells to replicate.	virus | Definition, Structure, & Facts | Britannica

Studies, Research, and Guidance Documents for Pathogens in Urban Water Resources

There is a wealth of information about water borne pathogens, including research papers, guidance documents, and case studies. Many of these reports were reviewed for the purpose of developing this toolbox. This list focuses on those reports that provided important information for this toolbox, plus some additional studies that may be relevant to those who are working to manage pathogens in urban waterbodies and/or stormwater. The matrix serves to summarize the information that is contained in each referenced study. The section following the matrix contains a complete citation and links for each study listed in the matrix.

Title	Literature Type			Specific Topic							Link
	Research	Case Study	Guidance	Sources	Risk Assessment	Testing Techniques	Source Investigation	Management and Mitigation	Modeling	MN Guidance	
A microfluidic droplet digital PCR for simultaneous detection of pathogenic *Escherichia coli* O157 and *Listeria monocytogenes*	X					X					https://doi.org/10.1016/j.bios.2015.07.016
A primer on emerging field-deployable synthetic biology tools for global water quality monitoring	X					X					https://doi.org/10.1038/s41545-020-0064-8
A review of the impact of environmental factors on the fate and transport of coronaviruses in aqueous environments	X				X			X			https://doi.org/10.1038/s41545-020-00096-w
A review on microbial contaminants in stormwater runoff and outfalls: Potential health risks and mitigation strategies	X			X	X			X			https://doi.org/10.1016/j.scitotenv.2019.07.055
An integrated method for removal of harmful cyanobacterial blooms in eutrophic lakes	X							X			https://doi.org/10.1016/j.envpol.2011.09.003
Bacteria removal from stormwater runoff using tree filters: a comparison of a conventional and an innovative system	X							X			https://doi.org/10.3390/w8030076
Bacteria Sources and Fate Report		X		X	X						https://www.mmsd.com/application/files/9614/8475/4276/BSTF_PhaseI_Volume3_report.pdf
Bacteriophages in water pollution control: Advantages and limitations	X					X		X			https://doi.org/10.1007/s11783-020-1378-y
Canine Scent Detection and Microbial Source Tracking of Human Waste Contamination in Storm Drains	X						X				https://doi.org/10.2175/106143013X13807328848496
Contamination of Water Resources by Pathogenic Bacteria	X			X	X						https://doi.org/10.1186/s13568-014-0051-x
COVID-19: Coronaviruses in water environments	X							X			https://www.cebm.net/study/covid-19-coronaviruses-in-water-environments/
Cyanotoxin Occurrence in the United States: A 20 Year Retrospective	X			X				X			https://corpslakes.erdc.dren.mil/employees/learning/webinars/21Jun23-HAB-DrinkingWater.pdf
Detection of pathogens in water: from phylochips to qPCR to pyrosequencing	X					X					https://doi.org/10.1016/j.copbio.2011.11.016
Detection of Wastewater Contamination	X	X		X			X				https://www.wef.org/globalassets/assets-wef/3---resources/topics/a-n/intelligent-water-systems/technical-resources/usgs_uwm_wef_detection_of_wastewater_contamination_2019---4printing.pdf
Development of a Protocol for Risk Assessment of Microorganisms in Separate Stormwater Systems	X				X						https://doi.org/10.2166/9781780403809
Discharge-based QMRA for estimation of public health risks from exposure to stormwater-borne pathogens in recreational waters in the United States	X				X						https://doi.org/10.1016/j.watres.2013.06.001

Title	Literature Type			Specific Topic							Link
	Research	Case Study	Guidance	Sources	Risk Assessment	Testing Techniques	Source Investigation	Management and Mitigation	Modeling	MN Guidance	
Effectiveness of Best Management Practices for Bacteria Removal, Developed for the Upper Mississippi River Bacteria TMDL			X					X		X	https://www.pca.state.mn.us/sites/default/files/wq-iw8-08q.pdf
Effort Launched to Quantify Microfracture Leaks in Sewers		X		X			X				https://www.sccwrp.org/news/effort-launched-to-quantify-microfracture-leaks-in-sewers/
Electrochemical oxidation for stormwater disinfection: How does real stormwater chemistry impact on pathogen removal and disinfection by-products level?	X							X			https://doi.org/10.1016/j.chemosphere.2018.09.038
Emerging investigator series: bacteriophages as nano engineering tools for quality monitoring and pathogen detection in water and wastewater	X					X					HTTPS://PUBS.RSC.ORG/EN/CONTENT/ARTICLELANDING/2021/EN/D0EN00962H
Engineered Infiltration Systems for Urban Stormwater Reclamation	X							X			https://doi.org/10.1089/ees.2012.0312
Estimated human health risks from recreational exposures to stormwater runoff containing animal faecal material	X				X						https://doi.org/10.1016/j.envsoft.2015.05.018
Evaluation of three full-scale stormwater treatment systems with respect to water yield, pathogen removal efficacy and human health risk from faecal pathogens	X	X			X			X			https://doi.org/10.1016/j.scitotenv.2015.11.056
Field studies of microbial removal from stormwater by bioretention cells with fly-ash amendment	X	X						X			https://doi.org/10.3390/w9070526
Groundwater Impacts from Stormwater Infiltration Practices	X							X			HTTPS://DOI.ORG/10.1002/9781119300762.WSTS0103
Lambert Creek Treatment Wetland Pilot Project		X						X			https://www.vlawmo.org/files/5415/9741/0345/VLAWMO_Treatment_Wetland_Pilot_Project_-_Final_Report_-_07-28-20_-_FINAL_with_Attachments.pdf
Large-scale comparison of *E. coli* levels determined by culture and a qPCR method (EPA Draft Method C) in Michigan towards the implementation of rapid, multi-site beach testing	X	X				X					https://doi.org/10.1016/j.mimet.2021.106186
Microbes and Urban Watersheds: Concentrations, Sources, & Pathways			X	X							https://owl.cwp.org/mdocs-posts/elc_pwp17/
Microbial pathogens and contaminants of emerging concern in groundwater at an urban subsurface stormwater infiltration site	X							X			https://doi.org/10.1016/j.scitotenv.2021.145738
Microbial Source Tracking Guide Document			X				X				https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=2000D20V.txt
Microbial source tracking in impaired watersheds using Phylochip and machine-learning classification	X						X				https://doi.org/10.1016/j.watres.2016.08.035
Microbial Source Tracking Using Quantitative and Digital PCR to Identify Sources of Fecal Contamination in Stormwater, River Water, and Beach Water in a Great Lakes Area of Concern	X						X				https://doi.org/10.1128/AEM.01634-18

Title	Literature Type			Specific Topic							Link
	Research	Case Study	Guidance	Sources	Risk Assessment	Testing Techniques	Source Investigation	Management and Mitigation	Modeling	MN Guidance	
Middle Santa Ana River Bacteria Synoptic Study and TMDL Triennial Report		X									https://sawpa.org/wp-content/uploads/2020/05/Final-Synoptic-Study-Report_021020_BabcockLabQAQC-Report-Appended_051920.pdf
Minnehaha Creek Bacterial Source Identification Study, Final Report		X		X			X				
Mitigating Harmful Cyanobacterial Blooms in a Human- and Climatically-Impacted World	X							X			https://doi.org/10.3390/life4040988
MNDNR Watershed Health Assessment Framework (WHAF) Glossary			X							X	https://www.dnr.state.mn.us/whaf/about/glossary.html
MNDNR Watershed Health Assessment Framework (WHAF) References			X							X	https://www.dnr.state.mn.us/whaf/about/references.html
Models for Predicting Beach Water Quality			X						X		https://www.epa.gov/beach-tech/models-predicting-beach-water-quality
MPCA Stormwater Wiki: 2020 MS4 General Permit TMDL Application			X							X	https://stormwater.pca.state.mn.us/index.php?title=Annual_TMDL_forms_submitted_by_MS4_permittees
MPCA Stormwater Wiki: Checklist for bacteria source inventory			X							X	https://stormwater.pca.state.mn.us/index.php?title=File:Checklist_for_bacteria_source_inventory.xlsx
MPCA Stormwater Wiki: Guidance for completing the TMDL reporting form			X							X	https://stormwater.pca.state.mn.us/index.php?title=Guidance_for_completing_the_TMDL_reporting_form
MPCA Stormwater Wiki: Guidance for meeting bacteria TMDL MS4 permit requirements			X							X	https://stormwater.pca.state.mn.us/index.php?title=Guidance_for_meeting_bacteria_TMDL_MS4_permit_requirements
MPCA Stormwater Wiki: Overview and Management strategies for bacteria in stormwater			X							X	https://stormwater.pca.state.mn.us/index.php?title=Overview_and_management_strategies_for_bacteria_in_stormwater
MPCA Stormwater Wiki: Pathogen types and examples			X							X	https://stormwater.pca.state.mn.us/index.php?title=Pathogen_types_and_examples
MPCA Stormwater Wiki: Recommendations and guidance for utilizing monitoring to meet TMDL permit requirements			X							X	https://stormwater.pca.state.mn.us/index.php?title=Recommendations_and_guidance_for_utilizing_monitoring_to_meet_TMDL_permit_requirements
MPCA Stormwater Wiki: Summary of TMDL requirements in stormwater permits			X							X	https://stormwater.pca.state.mn.us/index.php?title=Summary_of_TMDL_requirements_in_stormwater_permits
MPCA Stormwater Wiki: Support document for Checklist for bacteria source inventory			X							X	https://stormwater.pca.state.mn.us/index.php?title=Support_document_for_Checklist_for_bacteria_source_inventory
MPCA TMDL policy and guidance			X							X	https://www.pca.state.mn.us/water/tmdl-policy-and-guidance
Multiple pathways to bacterial load reduction by stormwater best management practices: Trade-offs in performance, volume, and treated area	X							X			https://doi.org/10.1021/acs.est.8b00408

Title	Literature Type			Specific Topic							Link
	Research	Case Study	Guidance	Sources	Risk Assessment	Testing Techniques	Source Investigation	Management and Mitigation	Modeling	MN Guidance	
NIAID (National Institute of Allergy and Infectious Diseases) Emerging Infectious Diseases/Pathogens			X		X						https://www.niaid.nih.gov/research/emerging-infectious-diseases-pathogens
Pathogen Management in Surface Waters: Practical Considerations for Reducing Public Health Risk			X					X			https://doi.org/10.5772/55367
Pathogens in Urban Stormwater Systems			X	X		X	X	X	X		https://www.asce-pgh.org/Resources/EWRI/Pathogens%20Paper%20August%202014.pdf
Pathogens in Urban Stormwater Systems: Where Are We Now?	X			X	X	X	X	X			https://doi.org/10.1061/JSWBAY.0000969
Plants that can kill; improving E. coli removal in stormwater treatment systems using Australian plants with antibacterial activity	X							X			https://doi.org/10.1016/j.ecoleng.2017.07.009
Potential roles of soil fauna in improving the efficiency of rain gardens used as natural stormwater treatment systems.	X							X			https://doi.org/10.1111/1365-2664.12525
Predicting *E. coli* concentrations using limited qPCR deployments at Chicago beaches	X	X				X					https://doi.org/10.1016/j.wroa.2018.100016
Predictive Tools for Beach Notification Volumes 1 & 2			X						X		https://www.epa.gov/sites/default/files/2015-11/documents/predictive-tools-volume1.pdf https://www.epa.gov/sites/default/files/2018-12/documents/predictive-modeling-beaches-volume2.pdf
QMRA Wiki (supported by Michigan State University)			X		X						http://qmrawiki.org/
Quantitative Microbial Risk Assessment Basics			X		X					X	https://www.health.state.mn.us/communities/environment/risk/guidance/dwec/basics.html
Refined ambient water quality thresholds for human-associated fecal indicator HF183 for recreational waters with and without co-occurring gull fecal contamination	X				X						https://doi.org/10.1016/j.mran.2020.100139
Removal of Microbial Indicators from Stormwater Using Sand Filtration, Wet Detention, And Alum Treatment Best Management Practices.	X							X			https://p2infohouse.org/ref/41/40254.pdf
Removal of nutrients, heavy metals, and pathogens by stormwater biofilters.	X							X			https://www.researchgate.net/publication/228476983_Removal_of_nutrients_heavy_metals_and_pathogens_by_stormwater_biofilters
Residential urban stormwater runoff: A comprehensive profile of microbiome and antibiotic resistance	X			X							https://doi.org/10.1016/j.scitotenv.2020.138033
Role of microbial cell properties on bacterial pathogen and coliphage removal in biochar-modified stormwater biofilters.	X							X			https://pubs.rsc.org/en/content/articlelanding/2014/ew/c8ew00297e/unauth
Source Verification of Inappropriate Discharges to Storm Drain Systems	X						X		X		https://www.epa.gov/sites/default/files/2015-11/documents/sw_idde_sourcever.pdf

Title	Literature Type			Specific Topic							Link
	Research	Case Study	Guidance	Sources	Risk Assessment	Testing Techniques	Source Investigation	Management and Mitigation	Modeling	MN Guidance	
Storm Water Management Fact Sheet Visual Inspection			X				X				https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=200044CU.txt
Survival of Coronaviruses in Water and Wastewater	X			X							https://doi.org/10.1007/s12560-008-9001-6
Sustainable Stormwater Management: Infiltration vs. Surface Treatment Strategies	X							X			https://www.waterrf.org/research/projects/sustainable-stormwater-management-infiltration-vs-surface-treatment-strategies
The California Microbial Source Identification Manual: A Tiered Approach to Identifying Fecal Pollution Sources to Beaches			X				X				https://www.waterboards.ca.gov/water_issues/programs/beaches/cbi_projects/docs/sipp_manual.pdf
The Impact of coronavirus SARS-CoV-2 (COVID-19) in water: potential risks	X			X							https://doi.org/10.1007/s11356-021-16024-5
The Impact of Stormwater Infiltration Practices on Groundwater Quality	X							X			https://conservancy.umn.edu/handle/11299/169456
The Role of Stormwater Research in BMP Design - Pathogens and Regulatory Demands	X							X			https://ascelibrary.org/doi/abs/10.1061/40792(173)220
Tools for Tracking Human Fecal Pollution in Urban Storm Drains, Creeks, and Beaches			X				X				https://www.santabarbaraca.gov/civicax/filebank/blobdload.aspx?BlobID=16722
Twenty-first century methods for microbiological analysis of recreational and source waters	X					X					https://www.sciencedirect.com/journal/journal-of-microbiological-methods/special-issue/10CPX4K3DTN
Urban BMP Performance Monitoring			X					X			https://static1.squarespace.com/static/5f8dbde10268ab224c895ad7/t/604926dae8a36b0ee128f8ac/1615406817379/2009MonitoringManualSingleFile.pdf
Use of Tracers to Identify Sources of Contamination in Dry Weather Flow	X						X				https://www.riverkeeper.org/wp-content/uploads/2015/03/CWP_Use-of-Tracers-to-Identify-Sources-of-Contamination-in-Dry-Weather-Flow.pdf
Variation of microorganism concentrations in urban stormwater runoff with land use and seasons	X			X							https://pubmed.ncbi.nlm.nih.gov/16604843/
Waterborne Pathogens in urban watersheds			X	X	X	X	X	X			https://doi.org/10.2166/wh.2006.001
Waterborne Pathogens: Detection Methods and Challenges	X				X	X					https://doi.org/10.3390/pathogens4020307
WEF Stormwater, Watershed and Received Water Quality Modeling			X						X		https://www.wef.org/resources/publications/books/stormwater-modeling/

General

Arnone, R.D., & Perdek Walling, J. (2007). **Waterborne pathogens in urban watersheds.** Journal of Water and Health, 5(1), 149-162. Retrieved from https://iwaponline.com/jwh/article/5/1/149/1991/Waterborne-pathogens-in-urban-watersheds

- Primary pathogens are bacteria, viruses, and protozoa. Helminths (parasitic worms) and fungi are not found to be responsible for significant levels of contamination in the U.S.
- Second TMDL may need to be developed if impairment continues to exist after compliance with indicator bacteria goals is achieved.
- There were 95 disease outbreaks in U.S. recreational waters. Four outbreaks were associated with 10 or greater number of outbreaks: Unknown (22), *E. coli* (12), Naegleria Fowleri (16), Shigella (20).
- Characteristics of pathogens of concern: Shed to environment in high numbers, ability to multiply outside of host in favorable conditions, and can survive and remain infectious in the environment for long periods and/or are highly resistant to treatment.

Clary, J., Pitt, R., & Streets, B. (2014). **Pathogens in Urban Stormwater Systems.** American Society of Civil Engineering Environmental and Water Resources Institute. Retrieved from https://www.asce-pgh.org/Resources/EWRI/Pathogens%20Paper%20August%202014.pdf

- Comprehensive report on pathogens in urban stormwater systems including sections on sources, fate and transport, monitoring and source tracking, statistical analysis, control methods, and case studies.

Clary, J., Ervin, J., Streets, B., & Olson, C. (2022). **Pathogens in Urban Stormwater Systems: Where Are We Now?** Journal of Sustainable Water in the Built Environment, 8(2), 1-6. Retrieved from https://doi.org/10.1061/JSWBAY.0000969

- Follow-up report to the *Pathogens in Urban Stormwater Systems* publication reviewing progress and ongoing research related to the list of research and policy needs included in the conclusion of the original document.

Schueler, T. (2000). **Microbes and Urban Watersheds: Concentrations, Sources, & Pathways.** Watershed Protection Techniques, 3(1): 554-565. Accessed April 29, 2022. Retrieved from https://owl.cwp.org/mdocs-posts/elc_pwp17/

- Article including brief guide to microbes and pathogens found in urban waters including indicators summarized in a helpful table. This is followed by discussion of typical pathogen densities found in waste streams and common sources of pathogens in watersheds.

Sources of Pathogens

Burns & McDonnell Engineering Company. (2019). **Minnehaha Creek Bacterial Source Identification Study, Final Report.** Minneapolis, Minnesota.

- Analysis of both dry and wet weather.
- Assessed sources and transport mechanisms of *E. coli* and estimated relative impact on *E. coli* levels in Minnehaha Creek within Minneapolis.
- Birds and bird feces are highest source of *E. coli* within study area.
- Dog (6% of samples) and human (2% of samples) markers were found but considered insignificant source of *E. coli*.
- *E. coli* was transported by over-irrigation within watershed and stormwater runoff.
- No exceedances of *E. coli* found during dry weather.

- *E. coli* concentrations were positively correlated with total suspended solids during storm events.

- Recommended BMPs include enhanced street sweeping, improved construction site erosion and sediment control management, inlet protection to control runoff and irrigation discharge from grassy areas, investigate and control over-spray of irrigation at City facilities, repair stream bank erosion, enhance IDDE program to identify and mitigate dry weather sources, increase frequency of grit chamber cleaning, eliminate practice of discharge grit chamber leachate to surface waters, periodic cleaning of outfall structures, implement public education.

Clark, S. E., Baker, K.H., Treese, D.P., Mikula, J.B., Sui, C., & Burkhardt, C.S. (2010). **Sustainable Stormwater Management: Infiltration vs. Surface Treatment Strategies.** Retrieved from https://www.waterrf.org/research/projects/sustainable-stormwater-management-infiltration-vs-surface-treatment-strategies

- Appendix G.4.5 summaries information on sources of microorganisms in stormwater runoff. Concluded that fecal coliform concentrations are directly related to density of urbanization (housing, population, development). Impervious surfaces and domestic animals) and the risk of human illnesses is increased where swimming occurs near storm outfalls. Illnesses include infections in recreational waters caused by ingestion, inhalation, and via skin wounds with gastroenteritis being the most common RWI.

Lee, S., Suits, M., Wituszynski, D., Winston, R., Martin, J., & Lee, J. (2020). **Residential urban stormwater runoff: A comprehensive profile of microbiome and antibiotic resistance.** Science of the Total Environment, 723, 138033. Retrieved from https://doi.org/10.1016/j.scitotenv.2020.138033

- Study that analyzed the relationship between rainfall depth and intensity and *E. coli* densities (fecal indicator) in stormwater from four MS4 outflows in Columbus, Ohio in 2017. The results showed a significant positive relationship between outflow *E. coli* density and rainfall intensity.

McLellan, S. L., E. Jensen Hollis. (2006). **Bacteria Sources and Fate Report. Bacteria Source, Transport and Fate Study – Phase 1, Volume 3.** 122 p. Accessed April 19, 2022. Retrieved from https://www.mmsd.con/application/files/9614/8475/4276/BSTF_PhaseI_Volume3_report.pdf

- Results of a three-year study of Lake Michigan beaches and nearshore waters to determine the impact of CSOs and SSOs on *E. coli* concentrations. Results of the study indicated an increase in *E. coli* levels associated with CSOs and SSOs. 13% of the stormwater outfalls had *E. coli* levels greater than 100,000 CFU/100mL. Source tracking indicated that both human and non-human sources contribute to the contamination. Fecal coliforms were determined to be better indicators than *E. coli* in Lake Michigan but not useful for measuring pathogens such as *Cryptosporidium* or *Giardia*. *Bacteroides* were also useful for detecting human and agricultural pathogens sources, however quantifying the level of contamination was not possible with this indicator.

Pandey, P. K., Kass, P. H., Soupir, M. L., Biswas, S., & Singh, V.P. (2014). **Contamination of Water Resources by Pathogenic Bacteria.** AMB Express, 4, 51. Retrieved from https://doi.org/10.1186/s13568-014-0051-x

Selvakuma, R., & Borst, M. (2006). **Variation of microorganism concentrations in urban stormwater runoff with land use and seasons**. Journal of Water and Health, 4(1), 109-124. Retrieved from https://pubmed.ncbi.nlm.nih.gov/16604843

- From samples collected from three land use areas, it was discovered that concentrations were similar to that reported in NPDES stormwater database, but less variable. Major source of feces were domestic animals and wildlife. Concentrations are affected by season and relations between indicators and pathogens were poorly correlated and not statistically significant. The correlation between traditional indicators (total coliforms and fecal coliform) and substitutes (enterococci and *E. coli*) is weak.

Risk

Boehm, A. B., & Soller, J.A. (2020). **Refined ambient water quality thresholds for human-associated fecal indicator HF183 for recreational waters with and without co-occurring gull fecal contamination**. Microbial Risk Analysis, 16, 100139. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S2352352220300451?via%3Dihub

- Updates rate of pathogen decay which considers temperature specific organism decay and considers the presence of human sewage contamination.

McBride, G. B., Stott, R., Miller, W., Bambic, D., & Wuertz, S. (2013). **Discharge-based QMRA for estimation of public health risks from exposure to stormwater-borne pathogens in recreational waters in the United States.** Water Research, 47(14), 5282–5297. Retrieved from https://doi.org/10.1016/j.watres.2013.06.001

- Application of QMRA on pathogens detected in stormwater discharges including Cryptosporidium, Giardia, Salmonella, Norovirus, Rotovirus, Enterovirus, and Adenovirus.

Minnesota Department of Health. (2022). **Quantitative Microbial Risk Assessment Basics**. Retrieved from https://www.health.state.mn.us/communities/environment/risk/guidance/dwec/basics.html

- Simple guidance document from MDH on the QMRA process and procedure. QMRA is at the forefront of innovative strategies to address general fecal bacteria impairments based on illness risk.

Mitchell, Jade, Weir, Mark H., & Rose, Joan. (2022). **QMRA Wiki**. Accessed April 19, 2022. Retrieved from http://qmrawiki.org/

- Website supported and edited by Michigan State University Center for Advancing Microbial Risk Assessment containing an overview of the Quantitative Microbial Risk Assessment (QMRA) framework. Links to case studies, additional tools, and additional resources are provided as well as a list of pathogens and other supporting information. The "wiki" format of the site allows for continual improvements and updates.

NIAID (National Institute of Allergy and Infectious Diseases) Emerging Infectious Diseases/Pathogens. (2018, July 26). Accessed April 19, 2022. Retrieved from the National Institute of Allergy and Infectious Diseases Website: https://www.niaid.nih.gov/research/emerging-infectious-diseases-pathogens

- List of emerging infectious diseases. Pathogens are categorized according to risk. Category B contains the following food and waterborne pathogens: Bacteria (Diarrheagenic E. coli, Pathogenic Vibrios, Shigella species, Salmonella, Listeria monocytogenes, Campylobacter jejuni, Yersinia enterocolitica); Viruses (Caliciviruses, Hepatitis A); Protozoa (Cryptosporidium parvum, Cyclospora cayatanensis, Giardia lamblia, Entamoeba histolytica, Toxoplasma gondii, Naegleria fowleri, Balamuthia mandrillaris); Fungi (Microsporidia).

Olivieri, A. (2007). **Development of a protocol for risk assessment of microorganisms in separate stormwater systems**. Retrieved from https://iwaponline.com/ebooks/book/365/Development-of-a-Protocol-for-Risk-Assessment-of

- Literature review, web-based questionnaire, science-directed data collection plan, waterborne pathogens that pose greatest risk to human health, and environmental fate of pathogens in stormwater. Contains information on the effectiveness of microorganism control technologies and their associated cost.

Soller, J., Bartrand, T., Ravenscroft, J., Molina, M., Whelan, G., Schoen, M., & Ashbolt, N. (2015). **Estimated human health risks from recreational exposures to stormwater runoff containing animal faecal material.** Environmental modelling & software, 72, 21-32. Retrieved from https://doi.org/10.1016/j.envsoft.2015.05.018

- Evaluation of human illness potential from recreational exposure to pathogens in freshwater containing rainfall-induced runoff from agricultural animal fecal material. Risks would be at least an order of magnitude lower than the benchmark level of public health protection associated with current US recreational water quality criteria, which are based on contamination from human sewage sources.

Testing Techniques and MST

Aw, T. G., & Rose, J. B. (2012). **Detection of pathogens in water: from phylochips to qPCR to pyrosequencing.** Current opinion in biotechnology, 23(3), 422-430. Retrieved from https://doi.org/10.1016.j.copbio.2011.11.016

- Overview of current and emerging testing techniques for pathogens in water including microarrays, qPCR, and pyrosequencing. The article includes comparisons to traditional culture-based methods and the advantages and disadvantages of each method.

Bayat, F., Didar, T.F., & Hosseinidoust, Z. (2021). **Emerging investigator series: bacteriophages as nano engineering tools for quality monitoring and pathogen detection in water and wastewater**. Environmental Science: Nano, 8(2), 367-389.

- Emerging use of bacteriophages-based sensors to detect pathogen of interest and to differentiate between viable and non-viable bacteria.

Bian, X., Jing, F., Li, G., Fan, X., Jia, C., Zhou, H., ... & Zhao, J. (2015). **A microfluidic droplet digital PCR for simultaneous detection of pathogenic Escherichia coli O157 and Listeria monocytogenes**. Biosensors and Bioelectronics, 74, 770-777. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0956566315302633

- Tested droplet digital PCR (ddPCR) technique for the purpose of bacteria detection. Technique was found to be highly sensitive.

Dubinsky, Eric A., Butkus, Steven R., & Andersen, Gary L. (2016). **Microbial source tracking in impaired watersheds using PhyloChip and machine-learning classification**. Water Research, Volume 105, Pages 56-64, ISSN 0043-1354, Retrieved from https://doi.org/10.1016/j.watres.2016.08.035

- Study using Berkeley Lab's microarray testing technology, PhyloChip, for microbial source tracking in the Russian River watershed in California. Results from a single test were used to identify human, dog, ruminant, pig, and horse fecal contamination. Comparisons to traditional fecal indicator testing found the PhyloChip was more sensitive and was successful at identifying contamination.
- This work has evolved into a new commercially available technology called Veracet (https://www.veracet.com/)

Haugland, Richard, Oshima, Kevin, Sivaganesan, Mano, Dufour, Alfred, Varma, Manju, Siefring, Shawn, Nappier, Sharon, Schnitker, Brian, & Briggs, Shannon. **Large-scale comparison of E. coli levels determined by culture and a qPCR method (EPA Draft Method C) in Michigan towards the implementation of rapid, multi-site beach testing.** Journal of Microbiological Methods, Volume 184, 2021, 106186, ISSN 0167-7012. Retrieved from https://doi.org/10.1016/j.mimet.2021.106186

- Case study comparing the results of traditional culture-based method to qPCR testing for *E. coli* at multiple Michigan beaches. A linear regression analysis was used to correlate results. The application of study results to beach management decisions are discussed.

Ji, M., Liu, Z., Sun, K., et al. (2021). **Bacteriophages in water pollution control: Advantages and limitations.** Front. Environ. Sci. Eng. 15, 84. Retrieved from https://doi.org/10.1007/s11786-020-1378-y

- Review of bacteriophage tools for the purpose of monitoring and tracking pathogens.

Lucius, N., Rose, K., Osborn, C., Sweeney, M. E., Chesak, R., Beslow, S., Schenk, T. (2019). **Predicting E. coli concentrations using limited qPCR deployments at Chicago beaches.** Water Research X, Volume 2, 2019, 100016, ISSN 2589-9147. Retrieved from https://doi.org/10.1016/j.wroa.2018.100016. Retrieved from https://pubs.rsc.org/en/content/articlelanding/2021/en/d0en00962h/unauth

- Chicago beach case study using limited qPCR testing to supplement culture-based methods. A predictive model was used in combination with the qPCR testing results to enable beach managers to make faster informed decisions on beach closures while minimizing the additional cost of testing.

Ramírez-Castillo, F. Y., Loera-Muro, A., Jacques, M., Garneau, P., Avelar-González, F. J., Harel, J., & Guerrero-Barrera, A. L. (2015). **Waterborne pathogens: detection methods and challenges**. Pathogens (Basel, Switzerland), 4(2), 307–334. Retrieved from https://doi.org/10.3390/pathogens4020307

- Includes a summary of waterborne pathogens and their related diseases. Testing methods included in this overview are PCR, microarrays, pyrosequencing, fluorescence in situ hybridization, immunology-based methods, and biosensors. Quantitative microbial risk assessment (QMRA) and its relationship to testing results is also discussed.

Thavarajah, W., Verosloff, M.S., Jung, J.K. et al. **A primer on emerging field-deployable synthetic biology tools for global water quality monitoring.** npj Clean Water 3, 18 (2020). Retrieved from https://doi.org/10.1038/s41545-020-0064-8

- A synopsis of the current development progress of "biosensors" which could be deployed to test for pathogens or chemicals and receive results while in the field. An overview of the technology's theory and design is included as well as the current obstacles to large-scale use. The article has a developing world water quality angle in mind, however similar applications to stormwater could be inferred.

Source Investigation Methods – General Guidance

Geosyntec Consultants, Wright Water Engineers. (2009, October). **Urban Stormwater BMP Performance Monitoring.** Prepared for USEPA, WERF, FHWA, ASCE. Retrieved from https://static1.squarespace.com/static/5f8dbde10268ab224c895ad7/t/604926dae8a36b0ee128f8ac/1615406817379/2009MonitoringManualSingleFile.pdf

- Reference document developed specifically for BMP monitoring that contains information that is applicable to general stormwater monitoring. Includes information on methods, equipment, training, and data management.

Griffith, John F., Layton, Blythe A., Boehm, Alexandria B., Holden, Patricia A., Jay, Jennifer A., Hagedorn, Charles, McGee, Charles D., Weisberg, Stephen B. (2013, December). **The California Microbial Source Identification Manual: A Tiered Approach to Identifying Fecal Pollution Sources to Beaches.** Southern California Coastal Water Research Project, Technical Report 804. Retrieved from https://www.waterboards.ca.gov/water_issues/programs/beaches/cbi_projects/docs/sipp_manual.pdf

- Tiered approach to tracking microbial sources. This approach includes a step-by-step process from simple to complex for microbial source identification including visual inspection, historical FIB monitoring, IDDE tracking, sanitary sewer inspection, testing for human genetic markers, non-human genetic markers, and additional genetic community analysis methods. Some of the approaches may need to be modified or reviewed for a freshwater context.

U.S. Environmental Protection Agency. (2005). **Microbial Source Tracking Guide Document.** National Service Center for Environmental Publications. Retrieved from https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=2000D20V.txt

- Reference produced by the US EPA to guide practitioners and other interested people in the use of microbial source tracking (MST) methods for the identification of nonpoint sources of fecal pollution. Document walks through the process of choosing methods and approaches, data collection and analysis, assumptions and limitations, and several case studies.

USGS, University of Wisconsin Madison, Water Environment Federation. (2019). **Detection of Wastewater Contamination.** Knowledge Development Forum. WSEC-2019-KDF_TR-001. Retrieved from

https://www.wef.org/globalassets/assets-wef/3---resources/topics/a-n/intelligent-water-systems/technical-resources/usgs_uwm_wef_detection_of_wastewater_contamination_2019---4printing.pdf

- Summary of current wastewater contamination detection, including human bacterial markers, chemistry techniques, canine scent tracking, and optical properties of wastewater.
- Three case studies summarized: Incorporating Molecular Testing, Collection System MST, and IDDE Investigation Examples.
- Developing technologies reviewed include Mobile aPCR, Sequencing, and others.

Source Investigation Methods – Specific Techniques

City of Santa Barbara, Creeks Division. (2012, September). **Tools for Tracking Human Fecal Pollution in Urban Storm Drains, Creeks, and Beaches.** Retrieved from https://www.santabarbaraca.gov/civicax/filebank/blobdload.aspx?BlobID=16722

- City of Santa Barbara, California's guide to tools and methods for investigating the source of human fecal pollution. Methods included are IDDE detection, sanitary system investigation, microbial source tracking, GIS tools, and canine scent tracking.

Journal of Microbiological Methods. **Twenty-first century methods for microbiological analysis of recreational and source waters.** List of recent articles related to testing, detection, and source tracking of microbial contaminants in a variety of environments. List was last updated July 17, 2021. Retrieved from https://www.sciencedirect.com/journal/journal-of-microbiological-methods/special-issue/10CPX4K3DTN

Lalor, Melissa and Pitt, Robert. (2015). **Use of Tracers to Identify Sources of Contamination in Dry Weather Flow.** Retrieved from https://www.riverkeeper.org/wp-content/uploads/2015/03/CWP_Use-of-Tracers-to-Identify-Sources-of-Contamination-in-Dry-Weather-Flow.pdf

- Overview of the use of chemical tracers to identify inappropriate discharges to urban stormwater systems. Includes a table relating possible tracers to sources.

Pitt, Robert & Chaturvedula, Soumya & Karri, Verra & Nara, Yukio. (2004). **Source Verification of Inappropriate Discharges to Storm Drain Systems.** Proceedings of the Water Environment Federation. 1192-1218. 10.2175/193864704784147089. Retrieved from https://accesswater.org/publications/-291085/source-verification-of-inappropriate-discharges-to-storm-drainage-systems

- Survey of stormwater outfalls to Cribbs Mill Creek in Tuscaloosa, Alabama. Non-biological chemical characteristics of samples including concentrations of ammonia, potassium, fluoride, and detergent were used in combination with modeling and a flow chart to identify the likely sources of pollution. Several samples were then analyzed further to verify the sources.
- Low-cost approach for non-biological tracers.

Staley ZR, Boyd RJ, Shum P, Edge TA. **Microbial Source Tracking Using Quantitative and Digital PCR To Identify Sources of Fecal Contamination in Stormwater, River Water, and Beach Water in a Great Lakes Area of Concern.** Appl Environ Microbiol. 2018 Oct 1;84(20):e01634-18. doi: 10.1128/AEM.01634-18. PMID: 30097445; PMCID: PMC6182909. Retrieved March 1, 2022 from https://pubmed.ncbi.nlm.nih.gov/30097445/

- PCR, including dPCR and qPCR, methods were used to measure fecal contamination in the Rouge River watershed and to measure human and gull-specific MST markers. These methods indicated high levels of both human and gull fecal contaminants with human levels higher during wet weather and gull contributions higher during dry weather. The digital PCR (dPCR) assay was found to be more sensitive to the human and gull contamination.

Southern California Coastal Water Research Project (SCCWRP) news article. **Effort Launched to Quantify Microfracture Leaks in Sewers.** Retrieved from https://www.sccwrp.org/news/effort-launched-to-quantify-microfracture-leaks-in-sewers/

- Development of technique to identify microfracture leaks in sanitary sewer piping. Purpose is to detect sources of human fecal contamination of regional waterways.

United States Environmental Protection Agency. (1999, September). **Storm Water Management Fact Sheet Visual Inspection**. National Service Center for Environmental Publications. Retrieved from https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=200044CU.txt

- EPA guidance document for conducting a visual inspection of stormwater discharges and surrounding areas to identify possible sources of pollution. This document is intended for site-specific uses as part of a SWPPP; however, the guidance included could be used for a larger scale visual inspection or windshield survey of a watershed.

Van De Werfhorst, L.C., Murray, J.L., Reynolds, S., Reynolds, K. and Holden, P.A. (2014). **Canine Scent Detection and Microbial Source Tracking of Human Waste Contamination in Storm Drains.** Water Environment Research, 86: 550-558. Retrieved from https://doi.org/10.2175/106143013X13807328848496

- Study conducted in Santa Barbara, CA sampling storm drain locations identified as having human fecal contamination through canine scent tracking. The locations the dogs indicated as positive for contamination were confirmed through testing. Human waste testing was also negative at locations where the dogs did not indicate a response. Overall, canine scent tracking was shown to be effective and useful for identifying and tracking human waste through storm drain networks.

Pathogen Management and Mitigation

Afrooz, A. N., Pitol, A. K., Kitt, D., & Boehm, A. B. (2018). **Role of microbial cell properties on bacterial pathogen and coliphage removal in biochar-modified stormwater biofilters.** Environmental Science: Water Research & Technology, 4(12), 2160-2169. Retrieved from https://pubs.rsc.org/en/content/articlelanding/2014/ew/c8ew00297e/unauth

- Bacterial removal in biochar-augmented biofilters was likely controlled by straining and hydrophobic interactions. Biochar-amended biofilters performed better than sand biofilters in removing the microorganisms from stormwater and removal of pathogenic bacteria was greater than that of FIB.

Ahmed, W., Hamilton, K., Toze, S., Cook, S., Page, D., (2019). **A review on microbial contaminants in stormwater runoff and outfalls: Potential health risks and mitigation strategies**. Prepared for the National Institute of Health. Retrieved April 19, 2022 from https://doi.org/10.1016/j.scitotenv.2019.07.055

- Review of fecal indicators, pathogens, and MST marker genes in urban stormwater. Key findings indicate that effective removal of indicators and pathogens can be achieved through water sensitive urban design or BMPs. QMRA is also discussed as it can be used to assess and mitigate health risks for stormwater reuse.

Bratieres, K., Fletcher, T. D., Deletic, A., Alcazar, L., Le Coustumer, S., & McCarthy, D. T. (2008, August). **Removal of nutrients, heavy metals and pathogens by stormwater biofilters.** In 11th International Conference on Urban Drainage. Retrieved from https://www.researchgate.net/publication/228476983_Removal_of_nutrients_heavy_metals_and_pathogens_by_stormwater_biofilters

- Large scale column study conducted in Melbourne, Australia to determine the effectiveness of biofilters for treatment of stormwater pollutants including nutrients, heavy metals, and pathogens. Pathogen-related findings were that biofilters consistently had a mean removal >80% during dry weather periods and >98% following wet periods.

Burns and McDonald Engineering Company. (2020). **Lambert Creek Treatment Wetland Pilot Project**. Prepared for Vadnais Lake Area Water Management Organization. Project No. 97161. Retrieved from https://www.vlawmo.org/files/5415/9741/0345/VLAWMO_Treatment_Wetland_Pilot_Project_-_Final_Report_-_07-28-20_-_FINAL_with_Attachments.pdf

- Project assessed pollutant removal (including pathogens) through Vertical Flow Bed cells contained in Whitaker Pond. VFB media consists of (from top to bottom): growth media, sorption media, sand, and gravel.
- Samples were collected at bottom of top three media layers. A 95% to 100% decrease in E coli concentrations was observed at base of sorption layer.

De Lambert, J. R., Walsh, J. F., Scher, D. P., Firnstahl, A. D., & Borchardt, M. A. (2021). **Microbial pathogens and contaminants of emerging concern in groundwater at an urban subsurface stormwater infiltration site**. *Science of the Total Environment*, *775*, 145738. Retrieved from https://doi.org/10.1016/j.scitotenv.2021.145738

- The reduction in number and concentrations of contaminants found in the monitoring well indicates that although geologically sensitive aquifers receiving urban stormwater effluent in the subsurface may be prone to contamination, those with a protective cap of fine-grained sediments are less vulnerable.
- Viruses and other pathogens, as well as other contaminants of emerging concern, were measured in stormwater and groundwater at an urban site containing a stormwater cistern and related subsurface infiltration gallery, three shallow lysimeter wells, and a monitoring well.
- The microbial and chemical contaminants present in urban stormwater were much lower in the water table monitoring well than the vadose zone lysimeters. There may be numerous causes for these reductions, but they are most likely related to transit across fine-grained sediments that separate the water table from the vadose zone at this location.

Feng, W., McCarthy, D. T., Henry, R., Zhang, X., Zhang, K., & Deletic, A. (2018). **Electrochemical oxidation for stormwater disinfection: How does real stormwater chemistry impact on pathogen removal and disinfection by-products level?** *Chemosphere*, *213*, 226-234. Retrieved from https://doi.org/10.1016/j.chemosphere.2018.09.038

- Results showed that total disinfection of indigenous Escherichia coli (E. coli), as well as three different stormwater pathogens (Enterococci, Campylobacter and C. perfringens) was achievable for all four tested stormwater samples within 30 min. Lower disinfection rates were observed in real stormwater when compared to synthetic stormwater. Stormwater chloride concentration was the only tested parameter that had significant impact on the treatment performance, with higher initial stormwater chloride concentration leading to an increased disinfection rate. Disinfection by-products in the treated stormwater were well below the Australian Drinking Water Guideline value for health, with its production level positively correlated to the pH values of stormwater.

Force, T., Wolosoff, S., & CDM Smith. (2020). **Middle Santa Ana River Bacteria Synoptic Study and TMDL Triennial Report**. Special Study Background. Retrieved from https://sawpa.org/wp-content/uploads/2020/05/Final-Synoptic-Study-Report_021020_BabcockLabQAQC-Report-Appended_051920.pdf

- Significant reduction in upper watershed dry weather flows resulted in indicator bacteria concentrations below water quality objectives in downstream receiving waters during dry weather conditions.
- Efforts to regulate septic systems and improved maintenance of sanitary collection systems resulted in lower (less frequent and smaller magnitude) indicators of human signals.

Grebel, J. E., Mohanty, S. K., Torkelson, A. A., Boehm, A. B., Higgins, C. P., Maxwell, R. M., ... & Sedlak, D. L. (2013). **Engineered infiltration systems for urban stormwater reclamation**. *Environmental Engineering Science*, *30*(8), 437-454. Retrieved from https://www.liebertpub.com/doi/full/10.1089/ees.2012.0312

- This article discusses chemical and biological contaminants of concern in urban stormwater and the mechanisms by which they are removed through porous media systems, including filtration, sorption, and chemical and biological transformation. Three strategies have been identified as opportunities to optimize treatment of stormwater more effectively: (1) choice of filtration media; (2) manipulation of system hydraulic behavior; and (3) manipulation of redox conditions.

Hipsey, Matthew R. & Brookes, Justin D. (2013). **Pathogen Management in Surface Waters: Practical Considerations for Reducing Public Health Risk**. Current Topics in Public Health. IntechOpen. Retrieved April 19, 2022 from https://www.intechopen.com/chapters/44591

- A framework for the reduction in risk due to pathogens in the water. The framework includes control measures for mitigating the fate and transport of pathogens, how to conduct a risk assessment to determine the impact on public health, and suggestions for monitoring and modeling as it applies to risk management.

Kurz, R. C. (1998). **Removal of microbial indicators from stormwater using sand filtration, wet detention, and alum treatment: best management practices** (Doctoral dissertation, University of South Florida). Retrieved from https://p2infohouse.org/ref/41/40254.pdf

- Study of stormwater BMPs for their ability to remove microbial pathogens. Removal efficiencies using sand filtration were generally high for turbidity, MS2, and beads (representing Cryptosporidium parvum) but not for total or fecal coliforms. Wet detention using the current regulatory standard of a 5-day bleed-down period provided consistently high removal efficiencies for fecal coliform bacteria. Overall, alum coagulation (dose = 10 mg/L) provided greatest removal efficiencies for total and fecal coliform bacteria, MS2 coliphage, and turbidity under semi-controlled conditions using jar tests.

Mehring, A. S., & Levin, L. A. (2015). **Potential roles of soil fauna in improving the efficiency of rain gardens used as natural stormwater treatment systems.** Journal of applied ecology, 52(6), 1445-1454. Retrieved from https://doi.org/10.1111/1365-2664.12525

- Review of the effectiveness of natural treatment systems such as rain gardens and bioswales and the role infiltration into soil plays in pathogen management is touched on however it is concluded that further study is needed to understand pathogen removal or transport through these BMPs.

Nieber, J. L., Arika, C., Lahti, L., Gulliver, J. S., & Weiss, P. T. (2014). **The impact of stormwater infiltration practices on groundwater quality.** Retrieved from https://conservancy.umn.edu/handle/11299/169456

- Monitoring of three Twin Cities area sites to assess the movement of pollutants of concern from infiltration system into groundwater.
- Pollutants of concern included chloride, nitrate, phosphorus, heavy metals, and petroleum.
- Literature search included summaries of studies that assessed the movement of pathogens through soils. Findings include:
  - Bacteria and viruses are not well contained in soils.
  - Highest concentration of bacteria are found when groundwater is near the land surface.
  - Bacteria survive longer in acidic soils with large amounts of organic matter, and typically will survive two to three months within the soils.
  - Groundwater contamination potential depends on the soil chemical properties, adsorption capability, ability of soil to strain the pathogens, and pathogen survival characteristics.
  - The risk of groundwater contamination by river water can increase during periods of surface flooding.

Paerl, H. (2014). **Mitigating Harmful Cyanobacterial Blooms in a Human- and Climatically-Impacted World.** Life, 4(4), 988–1012. https://doi.org/10.3390/life4040988

- Report summarizing approaches to mitigation for harmful cyanobacteria with considerations toward the impacts of climate change such as increased growth rates and nutrient thresholds.

Petterson, S. R., Mitchell, V. G., Davies, C. M., O'Connor, J., Kaucner, C., Roser, D., & Ashbolt, N. (2016). **Evaluation of three full-scale stormwater treatment systems with respect to water yield, pathogen removal efficacy and human health risk from faecal pathogens.** Science of the Total Environment, 543, 691-702. Retrieved from https://doi.org/10.1016/j.scitotenv.2015.11.056

- Study of stormwater harvesting systems in Melbourne, Australia. The systems were evaluated for pathogen removal and QMRA was used to determine potential human health risk. Finding included that: fecal contamination was site specific and variable, there was negligible removal of viruses during event conditions, and there was an elevated risk for zoonotic transmission in stormwater storage that provide habitat for waterfowl.

Schifman, L. A., Kasaraneni, V. K., Sullivan, R. K., Oyanedel-Craver, V., & Boving, T. B. (2016). **Bacteria removal from stormwater runoff using tree filters: a comparison of a conventional and an innovative system**. Water, 8(3), 76. Retrieved from https://doi.org/10.3390/w8030076

- Rhode Island study of two tree filter medias: sand/shale vs. sand/shale with red cedar wood chip layer. Bacteria removal as measured by *E. coli* concentrations in both filters met or outperformed RI bacteria standards of 60% removal.

Shirdashtzadeh, M., Chandrasena, G. I., Henry, R., & McCarthy, D. T. (2017). **Plants that can kill; improving E. coli removal in stormwater treatment systems using Australian plants with antibacterial activity.** Ecological Engineering, 107, 120-125. Retrieved from https://doi.org/10.1016/j.ecoleng.2017.07.009

- Study of 17 Australian native plants suitable for use in stormwater BMPs to determine if their antimicrobial properties have potential for reducing microbial pathogens in stormwater. Nine of the plants inhibited *E. coli* growth with the plant *Melaleuca ericifolia* being singled out for further study as it showed promising antibacterial activity.

Struck, S. D., Borst, M., & Selvakumar, A. (2005). **The Role of Stormwater Research in BMP Design—Pathogens and Regulatory Demands.** In Impacts of Global Climate Change (pp. 1-11). Retrieved from https://ascelibrary.org/doi/abs/10.1061/40792(173)220

- Evaluation of constructed wetlands and retention ponds found that these BMPs can lower microbial concentrations. Retention ponds have greater removal rates in June and September sample events. Further reduction may be limited by irreducible concentrations in runoff and/or sediments.

Tillman, L., Plevan, A., Conrad, P. (2011). **Effectiveness of Best Management Practices for Bacteria Removal, Developed for the Upper Mississippi River Bacteria TMDL.** Retrieved from https://www.pca.state.mn.us/sites/default/files/wq-iw8-08q.pdf

- Literature review focused on implementation strategies to improve water quality in the Upper Mississippi River Bacteria TMDL project area. A thorough review of common stormwater best management practices was conducted. Findings were that wetland treatment systems, wet retention ponds, filtration practices including filter strips, and limiting livestock in riparian areas were the most useful for reducing bacterial loads downstream.

Trojan, D. M., Gulliver, S. J., & Fairbairn, J. D. (2019). **Groundwater Impacts from Stormwater Infiltration Practices.** Encyclopedia of Water: Science, Technology, and Society.

- Little information exists on the fate and transport of pathogens through infiltration systems.

- BMP media that contains organic matter has higher bacteria removal rates as compared to media with little to no organic material.
- Underground infiltration systems are less effective in attenuating pathogens.
- Survival of pathogens in the groundwater is dependent of temperature, pH, and organic matter. Die-off of most microorganisms is typically rapid, with a three-order magnitude decrease within 100 days.

Wolfand, J. M., Bell, C. D., Boehm, A. B., Hogue, T. S., & Luthy, R. G. (2018). **Multiple pathways to bacterial load reduction by stormwater best management practices: Trade-offs in performance, volume, and treated area.** Environmental science & technology, 52(11), 6370-6379. Retrieved from https://pubs.acs.org/doi/abs/10.1021/acs.est.8b00408

- Simulation of 1,400 scenarios in highly urbanized, semi-arid watershed in Los Angeles. Looks at bacteria within various BMPs performance, % watershed, treatment volume and infiltration. Models used consisted of: H&H: EPA SWMM, BMP PERFORMANCE: EPA SUSTAIN, Pathogen: stoachistic model.

Youngblood, S., Vogel, J., Brown, G., Storm, D., McLemore, A., & Kandel, S. (2017). **Field studies of microbial removal from stormwater by bioretention cells with fly-ash amendment.** Water, 9(7), 526. Retrieved from https://doi.org/10.3390/w9070526

- Study of three bioretention cells with fly-ash amendments in Oklahoma for their microbial removal efficiency. Overall, the removal rates were found to be highly variable. The amendment of media with fly-ash appears to perform better than sand-only filter media based on results from other studies and may be an option for the improvement of microbial removal through stormwater BMPs.

Zhicong Wang, Dunhai Li, Hongjie Qin, Yinxia Li. (2012). **An integrated method for removal of harmful cyanobacterial blooms in eutrophic lakes, Environmental Pollution**. Volume 160, Pages 34-41, ISSN 0269-7491, https://doi.org/10.1016/j.envpol.2011.09.003

- Proposed two-step approach for the inactivation and removal of cyanobacteria in lakes using ferric sulfate and lake sediment clay.

COVID-19

Girón-Navarro R, Linares-Hernández I, Castillo-Suárez LA. **The impact of coronavirus SARS-CoV-2 (COVID-19) in water: potential risks.** Environ Sci Pollut Res Int. 2021 Oct;28(38):52651-52674. doi: 10.1007/s11356-021-16024-5. Epub 2021 Aug 27. PMID: 34453253; PMCID: PMC8397333. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8397333/

- Summary of research data on SARS-CoV-2 in water environments. Virus is removed from water in conventional wastewater facilities. The risk of contracting with untreated water is generally high, but lower in countries with treated wastewater. There is insufficient research on persistence and mobility of virus in polluted waters/sewage and on transmission via drinking water.

Gundy, P. M., Gerba, C. P., & Pepper, I. L. (2009). **Survival of Coronaviruses in Water and Wastewater.** Food and Environmental Virology, 1(1), 10. Retrieved from https://doi.org/10.1007/s12560-008-9001-6

- Inactivation of coronaviruses in the test water was highly dependent on temperature, level of organic matter, and presence of antagonistic bacteria. The time required for the virus titer to decrease 99.9% (T99.9) shows that in tap water, coronaviruses are inactivated faster in water at 23°C (10 days) than in water at 4°C (>100 days). Coronaviruses die off rapidly in wastewater, with T99.9 values of between 2 and 4 days. Poliovirus survived longer than coronaviruses in all test waters, except the 4°C tap water.

La Rosa G, Bonadonna L, Lucentini L, Kenmoe S, Suffredini E. **Coronavirus in water environments: Occurrence, persistence and concentration methods.** A scoping review. Water Res. 2020;179:115899. 2020 Retrieved from https://www.cebm.net/study/covid-19-coronaviruses-in-water-environments/

- Four studies looking at covid persistence in water environments. SARS-CoV detected in wastewater, sewage, and tap water for 2 days at 20°C (68°F) and 14 days at 4°C (39°F). No evidence that human CoV is present in surface water or transmitted via drinking water.

Paul, D., Kolar, P. & Hall, S.G. **A review of the impact of environmental factors on the fate and transport of coronaviruses in aqueous environments.** *npj Clean Water* 4, 7 (2021). Retrieved from https://doi.org/10.1038/s41545-020-00096-w

- The various environmental factors that impact the persistence of coronavirus in different water matrices include temperature, UV exposure, organic matter, disinfectants as well as adversarial microorganisms.

- The available data suggest that: (i) increasing temperature decreases the overall persistence of the virus; (ii) the presence of organic matter can increase the survivability of coronavirus; (iii) chlorine is the most effective and economic disinfectant; (iv) membrane bioreactors in wastewater treatment plants are hosts of competitive microorganisms that can inactivate coronaviruses; (v) ultraviolet irradiation is another effective option for virus inactivation.

Modeling Pathogens

Wagner, Richard A., Schmidt, Michael F., Wolosoff, S. (2020). **Stormwater, Watershed and Receiving Water Quality Modeling.** Model Selection. In Water Environment Federation (Ed.). WEF.

- Chapter of WEF's modeling guide focused on the process of selecting the appropriate model including selection criteria based on level of detail, important constituents and processes, features and capabilities, and appropriate scale.

USEPA. (2021). **Models for Predicting Beach Water Quality.** U.S. Environmental Protection Agency. Retrieved from https://www.epa.gov/beach-tech/models-predicting-beach-water-quality

- EPA web page providing resources for predictive beach water quality modeling including EPA guidance documents, links to related EPA research, and list of models supported by EPA.

USEPA. (2010, November 22). **Predictive Tools for Beach Notification Volume I: Review and Technical Protocol**. U.S. Environmental Protection Agency Office of Water and Office of Science and Technology. EPA-823-R-10-003. Retrieved from https://www.epa.gov/sites/default/files/2015-11/documents/predictive-tools-volume1.pdf

- Volume I provides background on the current predictive tools available and the concepts for developing predictive models for same-day beach notifications. Includes overviews of each predictive tool as well as the benefits and limitations of predictive tools.

Zepp, Richard G., et al. (2010, November 22). **Predictive Modeling at Beaches Volume II: Predictive Tools for Beach Notification.** U.S. Environmental Protection Agency National Exposure Research Laboratory. EPA-600-R-10-176. Retrieved from https://www.epa.gov/sites/default/files/2018-12/documents/predictive-modeling-beaches-volume2.pdf

- Volume II provides case studies from EPA research and in-depth discussion of the Virtual Beach (VB), a multiple linear regressing (MLR) predictive tool including and research surrounding its effectiveness at predicting exceedances. Findings concluded that models are more accurate for predicting non-exceedances than exceedances and model performance did not appear to be related to FIB density.

Additional Minnesota Information

MNDNR Watershed Health Assessment Framework (WHAF) Glossary.
https://www.dnr.state.mn.us/whaf/about/glossary.html

- Watershed health glossary.

- Does not contain definitions of bacteria, viruses, or pathogens.

MNDNR Watershed Health Assessment Framework (WHAF) References.
https://www.dnr.state.mn.us/whaf/about/references.html

- Water quality research.
- Contains bacteria research for Ag land, only.

MPCA Stormwater Wiki: Pathogen Types and Examples.
https://stormwater.pca.state.mn.us/index.php?title=Pathogen_types_and_examples

- Reports, templates, and fact sheets to assist with TMDL compliance.

MPCA Stormwater Wiki: Overview and Management Strategies for Bacteria in Stormwater.
https://stormwater.pca.state.mn.us/index.php?title=Overview_and_Management_strategies_for_bacteria_in_stormwater

- Source and concentration.
- Relationship between bacteria and pathogens in stormwater.
- Meeting bacteria water quality targets.
- Stormwater Management for Bacteria
    - *The treatment train approach for bacteria focuses on implementing the following hierarchy of practices: pollution prevention and source control, pretreatment for structural BMPs, infiltration, settling, filtration.*

MPCA Stormwater Wiki: Guidance for meeting bacteria TMDL MS4 permit requirements.
https://stormwater.pca.state.mn.us/index.php?title=Guidance_for_meeting_bacteria_TMDL_MS4_permit_requirements

- Inventory of potential areas and sources of bacteria.
- Maintain written plan to prioritize reduction activities.

MPCA Stormwater Wiki: Checklist for bacteria source inventory.
https://stormwater.pca.state.mn.us/index.php?title=File:Checklist_for_bacteria_source_inventory.xlsx

MPCA Stormwater Wiki: Support document for Checklist for bacteria source inventory.
https://stormwater.pca.state.mn.us/index.php?title=Support_document_for_Checklist_for_bacteria_source_inventory

MPCA Stormwater Wiki: Summary of TMDL requirements in stormwater permits.
https://stormwater.pca.state.mn.us/index.php?title=Summary_of_TMDL_requirements_in_stormwater_permits

MPCA Stormwater Wiki: Recommendations and guidance for utilizing monitoring to meet TMDL permit requirements.
https://stormwater.pca.state.mn.us/index.php?title=Recommendations_and_guidance_for_utilizing_monitoring_to_meet_TMDL_permit_requirements

MPCA Stormwater Wiki: 2020 MS4 General Permit TMDL Application.
https://stormwater.pca.state.mn.us/index.php?title=Annual_TMDL_forms_submitted_by_MS4_permittees

MPCA Stormwater Wiki: Guidance for completing the TMDL reporting form.
https://stormwater.pca.state.mn.us/index.php?title=Guidance_for_completing_the_TMDL_reporting_form

- *E. coli* and fecal coliform are category 1, qualitative reductions.

Urban Pathogen Sources

This graphic displays the most common sources of water borne pathogens in the urban environment. Water borne pathogens of concern are those which could cause human illness in recreational waters as well as those that cause water to be impaired, as defined in Minnesota by the Minnesota Pollution Control Agency (MPCA). A list of water borne pathogens of concern can be found here (Pathogens in Urban Water Resources). MPCA information on bacteria impairment can be found here (https://www.pca.state.mn.us/water/bacteria).

The common sources of water borne pathogens depicted on this graphic are organized into three categories. The source category, also called primary source, is the initial source of pathogen found in the urban water environment which originate from wildlife and human sources. Primary sources depicted include birds and waterfowl, rodents (beavers, chipmunks, gophers, mice, rats, squirrels, voles, woodchucks), urban wildlife (coyotes, deer, feral cats, fox, moles, raccoons), domestic pets, trash, organic waste, human waste in the environment (beaches, illegal discharge of waste from boats and recreational vehicles, homeless encampments, leaking septic systems, temporary toilets), and overflows from municipal sanitary sewer systems.

The reservoir category, also called secondary source, are sites that allow for the growth of pathogens. Reservoirs depicted on this graphic include decaying plants, exposed and eroding soils, organic matter at water edges, organic matter in stream and lake sediment, stormwater structures (vegetated filter strips, bioretention basins, infiltration structures, buried stormwater structures, stormwater ponds, street pavement and gutters, storm drain piping, blockages within storm drain piping).

The third category is called transport mechanism which involves the water flow that moves the pathogens from primary sources and reservoirs to downstream reservoirs and surface waters. Transport mechanisms depicted in this graphic include stream flows, flood flows, non-stormwater discharges to stormwater drains, gray water discharges from pools and hot tubs, over irrigation of lawns and gardens, power washing and other maintenance actions, and runoff from rain events.

Natural Background

	Pathogen Sources	Type
1	**Urban Wildlife**	
	Birds and Waterfowl	Primary Sources
	Rodents – beavers, chipmunks, gophers, mice, rats, squirrels, voles, woodchucks	Primary Sources
	Urban wildlife – coyotes, deer, feral cats, fox, moles, rabbits, racoons	Primary Sources
2	**Other Natural Sources**	
	Decaying plants	Reservoir
	Exposed/eroding soil	Reservoir
	Organic matter at lake/stream edge	Reservoir
	Organic matter in lake/stream sediment	Reservoir
	Stream and lake sediment	Reservoir
	Stream flow	Transport Mechanism
	Flood flows in flood plain	Transport Mechanism

Urban Watershed Sources

	Pathogen Sources	Type
3	**Watershed**	
	Domestic pets	Primary Sources
	Trash from garbage trucks/dumpsters/trash cans/litter, etc.	Primary Sources
	Non-plant based organic waste – compost/outdoor dining/grease bins	Primary Sources
4	**Human Sanitary Sources**	
	Bathing/beaches	Primary Sources
	Boats, illegal discharge of waste tanks	Primary Sources
	Homeless encampments	Primary Sources
	Leaking or failed septic systems	Primary Sources
	Temporary toilets	Primary Sources

Urban Infrastructure Sources

	Pathogen Sources	Type
5	**Municipal Sanitary Infrastructure**	
	Combined sewer outfalls	Primary Sources
	Sanitary sewer overflows	Primary Sources
	Exfiltration from leaky sanitary pipes	Primary Sources
6	**Dry Weather Sources**	
	Direct connections that discharge non-rainfall base flow	Transport Mechanism
	Dumping - including RV stations	Primary Sources
	Gray water/pools/hot tub discharge	Transport Mechanism
	Illegal sanitary connections	Primary Sources
	Lawn care practices (overirrigation)	Transport Mechanism
	Other sources of non-rainfall base flow	Transport Mechanism
	Street and stormwater maintenance	Transport Mechanism
7	**Wet Weather Sources**	
	Stormwater hotspots (including dog parks, plant nurseries, etc.)	Primary Sources
	Stormwater runoff	Transport Mechanism

MS4 Infrastructure

	Pathogen Sources	Type
8	**MS4 Infrastructure**	
	Pretreatment - above ground	
	Vegetated filter strips	Reservoir
	Bioretention basins	Reservoir
	Infiltration Best Managment Practices	
	Trench	Reservoir
	Dry well	Reservoir
	Underground infiltration	Reservoir
	Pretreatment - below ground	
	Inlet sumps	Reservoir
	Hydrodynamic devices	Reservoir
	Screening devices	Reservoir
	Settling tanks	Reservoir
	Filters	Reservoir
	Wet Detention BMPs	
	Ponds/wetlands	Reservoir
	Underground vaults (non-infiltration)	Reservoir

MS4 Infrastructure (cont.)

	Pathogen Sources	Type
8	**MS4 Infrastructure (cont.)**	
	Conveyance	
	Hard surfaces in convenyance systems (curb and gutters, storm drain piping, and other structures)	Reservoir
	Temporary ponding caused by blockages/poor maintenance	Reservoir
	Permanent ponding caused by misaligned inverts, depressions	Reservoir
	Erosion at outfalls caused by high flow velocity	Reservoir

Pathogen Identification, Investigation, and Mitigation Decision Tree

A

Are there PHYSICAL INDICATORS related to excessive pathogens or bacteria present in surface water?

MORE INFORMATION

- YES → Has there been a recent release of sanitary sewage that flowed into the storm drainage system that is greater than 5 gallons in volume? MORE INFORMATION
  - YES → GO TO EMERGENCY SPILL RESPONSE (NEXT PAGE)
  - NO → Is the indicator COLOR?
    - YES → Is color created by Cyanobacteria? Confirm by MPRB visual monitoring index. If positive for Cyanobacteria, collect sample and test for Microcystin toxin using ELISA test kit. Or CONFIRM BY MPCA SIMPLE NO COST TEST FOR BLUE-GREEN ALGAE
      - NO → Does color have a non-petroleum sheen? SHEEN MAY BE CAUSED BY PATHOGEN GO TO BOX B
    - NO → Is the indicator ODOR?
      - YES → Could odor be caused by Cyanobacteria?
        - YES → Is color created by Cyanobacteria? (see above)
        - NO → Is odor from petroleum source?
          - YES → Problem is not bacteria related. REPORT LARGE PETROLIUM SPILLS TO MN DUTY OFFICER
          - NO → **ODOR MAY BE FROM SEWAGE OR ILLICIT DISCHARGE. GO TO BOX F TO INVESTIGATE SOURCE**
      - NO → Is the indicator HUMAN or ANIMAL ILLNESS, HEALTH ADVISORY, and/or FREQUENT BEACH CLOSURES?
        - YES → IS ILLNESS RECREATIONAL WATER ILLNESS (RWI)?
          - YES → **REPORT SUSPECTED ILLNESS TO MN DEPT OF HEALTH. FOLLOW MDH GUIDANCE FOR NEXT STEPS**
          - NO → **GO TO BOX D, REVIEW DATA, AND ASSESS NEED FOR ONE-TIME SAMPLING TO DOCUMENT INCIDENT**
        - NO → **GO TO BOX B FOR NEXT STEP**
- NO → Box B

B

Is the waterbody listed as IMPAIRED FOR PATHOGEN?

MORE INFORMATION

- YES → Is there an approved TMDL PATHOGEN IMPLEMENTATION PLAN? *(REVIEW ALL BOXES)* MORE INFORMATION
  - NO → **CONSULT WITH MPCA ON STATUS OF IMPLEMENTATION PLAN. CONSIDER RISK ANALYSIS AND INVESTIGATION IN BOX D**
  - YES → Does the Implementation Plan require ongoing sampling and testing?
    - YES → **USE TOOLS PATHOGEN TESTING TECHNIQUES AND PATHOGEN SAMPLING AND MONITORING TECHNIQUES TO PLAN AND IMPLEMENT LONG-TERM MONITORING**
  - YES → Does the Implementation Plan require reduction in concentration of pathogens?
    - YES → **USE TOOL PATHOGEN MITIGATION TECHNIQUES TO SELECT & IMPLEMENT PATHOGEN MANAGEMENT TECHNIQUE(S)**
  - YES → Does the Implementation Plan require tracking the source(s) of pathogens?
    - YES → **USE TOOL PATHOGEN SOURCE IDENTIFICATION TECHNIQUES TO SELECT & IMPLEMENT SOURCE TRACKING**
  - YES → Does the Implementation Plan require annual reporting on progress of pathogen reduction?
    - YES → **USE TOOL PATHOGEN ANNUAL REPORTING REQUIREMENTS TO FIND INFORMATION REQUIRED FOR ANNUAL REPORT CONTENT**
- NO → Box C

C

Have basic PATHOGEN MANAGEMENT STRATEGIES been implemented?

- NO → Continue ongoing efforts to review and update existing ordinances, standards, and management practices to ensure a base level of pathogen management practices:
  - Ordinances that require proper management of animal and human wastes.
  - Enhanced street sweeping in catchment areas identified as contributing runoff to surface waters with excessive levels of pathogens
  - Enhanced inspection and enforcement to ensure proper handling and disposal of sanitary wastes not managed by sanitary collection system, including sanitary dump stations, portable toilets, homeless encampments, etc.
  - Establishment of IDDE program to aid in the identification of discharges to the stormwater drainage system that may contain and/or transport pathogens to surface waters.
  - YES / NO → **USE TOOL PATHOGEN MITIGATION TECHNIQUES TO SELECT & IMPLEMENT PATHOGEN MANAGEMENT TECHNIQUE(S)**
- YES → Box D

D

Has SAMPLING and TESTING been conducted in the past?

- YES → Is pathogen data collected as part of a TMDL Diagnostic Study or Implementation Plan?
  - YES → **GO TO BOX E FOR NEXT STEP**
  - NO → Is the problem LONG-TERM?
    - YES → **USE TOOLS PATHOGEN TESTING TECHNIQUES AND PATHOGEN SAMPLING AND MONITORING TECHNIQUES TO PLAN AND IMPLEMENT LONG-TERM MONITORING**
    - NO → **USE TOOLS PATHOGEN TESTING TECHNIQUES TO CONDUCT ONE-TIME SAMPLE AND LAB ANALYSIS TO DOCUMENT PATHOGEN INCIDENT**
- NO → Box E

E

Is PRIORITIZATION or a RISK ANALYSIS needed to prioritize next steps?

- YES → A prioritized implementation plan should be developed with consideration given to:
  - Highest priority for mitigation should be in catchment area(s) upstream of water recreational areas
  - Dry weather sources should be investigated and managed before wet weather sources
  - Initial controls should focus on potential human sources of pathogens
  - Source controls and transport source management should be implemented before installation/modification of structural controls
  - YES → **CONDUCT QMRA RISK ANALYSIS TOOL CONTAINED IN TOOL MODELS WITH APPLICATION FOR PATHOGENS**
- NO → Box F

F

Has a PATHOGEN SOURCE been IDENTIFIED? (review all boxes)

- NO → Has there been a recent sewage spill and/or do sanitary sewer records document location of SSO or CSO events in catchment area that is upstream of location
  - YES → **USE TOOL PATHOGEN MITIGATION TECHNIQUES TO SELECT & IMPLEMENT STRUCTURAL REHAB/ RETROFIT PATHOGEN MANAGEMENT TECHNIQUE(S) FOR SANITARY SEWERS**
- NO → Are there reservoirs in the stormwater drainage system within catchment area that is upstream of location of identified pathogen?
  - YES → **USE TOOL PATHOGEN MITIGATION TECHNIQUES TO SELECT & IMPLEMENT MAINTENANCE and/or STRUCTURAL REHAB/ RETROFIT PATHOGEN MANAGEMENT TECHNIQUE(S) FOR STORM DRAINAGE SYSTEMS**
- NO → Is there documentation of non-rainfall base flow from IDDE inspections within catchment area upstream of location of identified pathogen?
  - YES → **USE TOOL PATHOGEN MITIGATION TECHNIQUES TO SELECT & IMPLEMENT POLLUTION PREVENTION and/or MAINTENANCE PATHOGEN MANAGEMENT TECHNIQUE(S)**
- NO → Has an investigation of potential Pathogen Sources been conducted within catchment areas upstream of identified pathogen location?
  - YES → **USE TOOL PATHOGEN MITIGATION TECHNIQUES TO SELECT & IMPLEMENT POLLUTION PREVENTION and/or NATURAL RESOURCE MANAGEMENT PATHOGEN MANAGEMENT TECHNIQUE(S)**
- NO → Is there ongoing development/redevelopment or CIP project that proposes to install stormwater storage devices to comply with stormwater requirements?
  - YES → **USE TOOL PATHOGEN MITIGATION TECHNIQUES TO SELECT & IMPLEMENT BMP DESIGN ENHANCEMENT PATHOGEN MANAGEMENT TECHNIQUE(S)**
- NO → **USE TOOL PATHOGEN SOURCE IDENTIFICATION TECHNIQUES TO SELECT AND IMPLEMENT SOURCE TRACKING**
- YES → Box G

G

Have PATHOGEN MANAGEMENT TECHNIQUES selected from Pathogen Mitigation Techniques been implemented?

- YES → Has monitoring been conducted to confirm mitigation of excessive pathogens in surface water?
  - YES → **GO TO BOX I FOR TMDL OR MS4 REPORTING**
  - NO → **GO TO BOX D TO RE-INITIATE MONITORING**
- NO → Box H

H

Is there a need to PREDICT THE EXTENT AND MOVEMENT OF THE PATHOGEN and/or to SCREEN MITIGATION TECHNIQUE(S)?

- YES → **USE TOOL MODELS WITH APPLICATION FOR PATHOGENS TO SELECT MODEL**
- NO → Box I

I

Is there a TMDL or MS4 ANNUAL REPORTING REQUIREMENT?

- YES → **USE TOOL PATHOGEN ANNUAL REPORTING REQUIREMENTS TO FIND INFORMATION REQUIRED FOR ANNUAL REPORT CONTENT**

Pathogen Identification, Investigation, and Mitigation Decision Tree

Emergency Spill Response

Has the MN Duty Officer been notified?

NO → *Immediately contact* MN DUTY OFFICER
1-800-422-0798
The Duty Officer will request the following information:

- Caller name
- Date time and location of incident
- Telephone #
- Notification of local officials (fire, police)
- Materials and quantity of spill
- Incident location
- Responsible party name and phone number
- Surface waters and/or sanitary sewers impacted
- Current situation

YES ↓

Has Metropolitan Council been notified? (Twin Cities area, only)

NO → Report to MCES Interceptor Services
Regional Maintenance Dispatch: **651-602-4511**

YES ↓

Has a sample of the release been collected and analyzed by laboratory?

NO → Collect samples at each release location and analyze for:

- Fecal Coliform
- CBOD5
- Total Phosphorus
- E. Coli

YES ↓

Has clean-up been initiated?

NO →

1. **Contain spill**
   - Install spill containment barriers to prevent spill from being released to downstream storm drains and/or surface waters.
   - Install sandbags or other barriers within storm drain system if release has flowed into system.
   - Retain barriers until after all clean-up activities have been completed.
2. **Protect release area from public**
   - Install fencing in soil/grass areas that have public safety risk.
   - Close affected beaches for 72 hours.
3. **Clean released materials from grass/soil areas**
   - Cover with woodchips; or
   - Rake or till lime into soil or grass areas in areas that have public safety risk (lime should be applied only by experienced personnel). Wait 24 hours, then collect lime soil and dispose properly.
4. **Clean released materials from public infrastructure, including storm drainage system**
   - Remove and properly dispose all released materials from street, gutters, catch basins, and storm drains using sewer vacuum and/or jetting equipment.
   - Flush cleaned areas with mild bleach solution. Collect and dispose of bleach solution before discharge to surface waters.
   - Conduct additional flushing, as needed.
5. **Remind personnel on proper hygienic practices**
   - In the event of contact with release, bathe with soap and water.
   - Wash clothes thoroughly as soon as possible.

YES ↓

Has the public been notified?

NO → Follow MPCA wastewater release/bypass PROTOCOLS:

- Post signage at location of release and at areas where there is a public safety risk
- Notify downstream users, including beach managers, when event exceeds water quality standards

YES ↓

Has MPCA Release Report been prepared and submitted?

NO → DOWNLOAD REPORT

Pathogen Testing Techniques

This table contains a list of techniques to follow to detect and/or quantify pathogen levels. It is organized from simple to most complex. Links are provided for additional information.

Test Method [1]	Brief Description	Recommended Applications	Benefits	Limitations	Indicator of Pathogen	EPA or Standard Method (if applicable)	Time to Results	Sample Requirements	Detection Limits	Locally Available?	Case Studies and More Information
Established Methods											
Culture based (typically membrane filtration and liquid broth)	Method to allow pathogens to reproduce in a culture medium to detect and quantify the presence of the cultured pathogen.	Routine testing and monitoring	Well established, inexpensive, reliable, widely available	Delay between sampling and results – results may no longer be representative of the current levels	*E. coli*	EPA Method 1603	24-27 hours	100 mL	1 CFU/100 mL	Y	
					Enterococci	EPA Method 1106.1	24-52 hours	100 mL	1 CFU/100 mL	Y	
					Total Coliform and *E. coli*	EPA Method 1604	24 hours	100 mL	1 CFU/100 mL	Y	
					Enterovirus and Norovirus	EPA Method 1615	2 weeks	300 L	0.05 MPN/L	Y	
					Coliphage	EPA Method 1601	24 hours	100 mL or 1 L	1 PFU/100 mL	Y	
						EPA Method 1602	24 hours	100 mL	1 PFU/sample size	Y	
						EPA Method 1642	24 hours	2 L	1 PFU/sample size	Y	
ELISA	"Enzyme-linked immunosorbent assays" – relies on light absorption measurements of lysed cyanotoxins in a sample.	HAB monitoring	Does not require expensive equipment or extensive training, rapid results	Not variant or congener specific	Cyanotoxins	EPA Method 546	3-4 hours	100 mL	0.3 µg	Y	
Filtration/ Immunomagnetic Separation (IMS)/ Immunofluorescence Assay (FA)	Oocysts/cysts are concentrated through filtration, separated from other materials using IMS and fluorescing dye through FA is used for microscopic identification	Direct testing for common disease-causing pathogens. Testing in response to gastroenteritis outbreak.	EPA accepted method to detect cryptosporidium and Giardia. Direct detection of disease-causing protozoa.	Requires specialized microbiology lab, more costly than FIB tests	Cryptosporidium and Giardia	EPA Method 1623.1	~1 day	10-50 L	40 (oo)cysts/ 10 L	Y	
IDEXX-Colilert, Enterolert	Multiple well enzyme substrate test	Routine testing and monitoring, field testing	No dilution or other preparation required, easy to interpret results, widely available	Must read results within 24-48 hours, more expensive per test, doesn't differentiate between pathogenic vs. benign *E. coli*	Colilert Total Coliform and *E. coli*	SM 9223 B	24 hours	100 mL	1 organism/ 100 mL	Y	Use of IDEXX Colilert-18® and Quanti-Tray/2000 as a Rapid and Simple Enumeration Method for the Implementation of Recreational Water Monitoring and Notification Programs: Lake and Reservoir Management: Vol 21, No 1 (tandfonline.com)
					Enterolert – Enterococci	SM 9230	24 hours	100 mL	1 organism/ 100 mL	Y	
PCR Methods (i.e., TaqMan probe)	Method to extract, amplify, and detect (PCR) and/or quantify (qPCR) the DNA of a bacteria or virus	Supplementary testing, may be useful for quick results at recreational waters during critical seasons, testing for non-culturable pathogens and viruses	Fast results, works for bacteria and viruses that are not culturable, can be used to detect any pathogen of interest, small sample size requirement	Doesn't differentiate between viable and dead cells, more expensive per test than traditional culture methods	*E. coli*	Draft Method C	3-8 hours		1 cfy/100 mL	Y	Michigan EPA
					Bacteroides	EPA Method 1696 EPA Method 1697	3-8 hours	500 mL grab sample	0.32 copies/µL	Y	Chicago Beaches
					Enterococci	EPA Method 1609	3-8 hours	100 mL		Y	Essentials of Real-Time PCR | Thermo Fisher Scientific - US
					Enterovirus and Norovirus	EPA Method 1615	3-8 hours		2 genomic copies/L		EPA Guidance Document

Test Method [1]	Brief Description	Recommended Applications	Benefits	Limitations	Indicator of Pathogen	EPA or Standard Method (if applicable)	Time to Results	Sample Requirements	Detection Limits	Locally Available?	Case Studies and More Information
					Adenovirus, norovirum, hepatitis A and E	Emerging testing method – no applicable accepted method	3-8 hours		2 copies/μL of cDNA/DNA		
					Cryptosporidium, Giardia	Emerging testing method – no applicable accepted method	3-8 hours		1-10 oocyst and 5-50 cysts		
					Many others…	Emerging testing method – no applicable accepted method	3-8 hours		Varies	Y	
Emerging Research											
Biosensors	Field deployable devise used to detect presence/absence and/or concentration of a biological analyte (pathogen, in this case). Includes component recognizing the pathogen and produces and signal, signal transducer, and reader device.	Biosensors are not likely to be currently useful; however, this is a rapidly growing area of research that could be a game-changer for water quality monitoring in the future.	Field deployable, ongoing research into online sensors for monitoring water quality in real time, fast results	Emerging method, limited "real world" applications/case studies, limited number of pathogens/ indicators have been studies with these methods	Currently, methodologies have been researched for *E. coli*	Emerging testing method – no applicable accepted method	Minutes to hours	Varies	Varies	N	▪ A primer on emerging field-deployable synthetic biology tools for global water quality monitoring | npj Clean Water (nature.com) ▪ Multiplexed paper test strip for quantitative bacterial detection | SpringerLink ▪ Full article: Biosensors for on-line water quality monitoring – a review (tandfonline.com) ▪ Recent Progress on the Electrochemical Biosensing of Escherichia coli O157:H7: Material and Methods Overview - PMC (nih.gov)
DNA Sequencing Approaches (i.e., Pyrosequencing, Sanger sequencing)	Parallel DNA sequencing method relying on light detection (bioluminescence) when pyrophosphate is released	Research, detection of novel pathogens	Can detect novel pathogen, useful to determine diversity of bacterial and viral pathogens in environmental samples	Still exploratory – would need to be supplemented with more established methods, expensive and difficult to implement	Multiple	Emerging testing method - no applicable accepted method	Days to weeks	Varies	Varies	Sequencing options available through UMN Genomics Lab	▪ Viral metagenome analysis to guide human pathogen monitoring in environmental samples (nih.gov) ▪ Metagenomic Analysis of RNA Viruses in a Fresh Water Lake (nih.gov)
Microarrays (i.e., PhyloChip)	Array to detect DNA of multiple pathogens simultaneously	Microbial source tracking, in-depth water quality analyses, research	Ability to test for thousands of pathogens at the same time	High detection limits, requires analysis by outside lab, limited availability	Multiple	Emerging testing method – no applicable accepted method	A week or more	Varies, typically only requires a small sample size	Varies	N	▪ pandersen2010.pdf (windows.net) ▪ Berkeley Lab's PhyloChip Enables Tracking of Bacterial Dangers - Intellectual Property Office (lbl.gov) ▪ Microbial source tracking in impaired watersheds using PhyloChip and machine-learning classification - ScienceDirect

Notes:

[1] The MPCA requires certified laboratories, as accredited by the MN Department of Health, for stormwater testing for NPDES and/or TMDL compliance. The list of approved laboratories can be found at https://eldo.web.health.state.mn.us/public/accreditedlabs/labsearch.seam

Pathogen Sampling and Monitoring Techniques

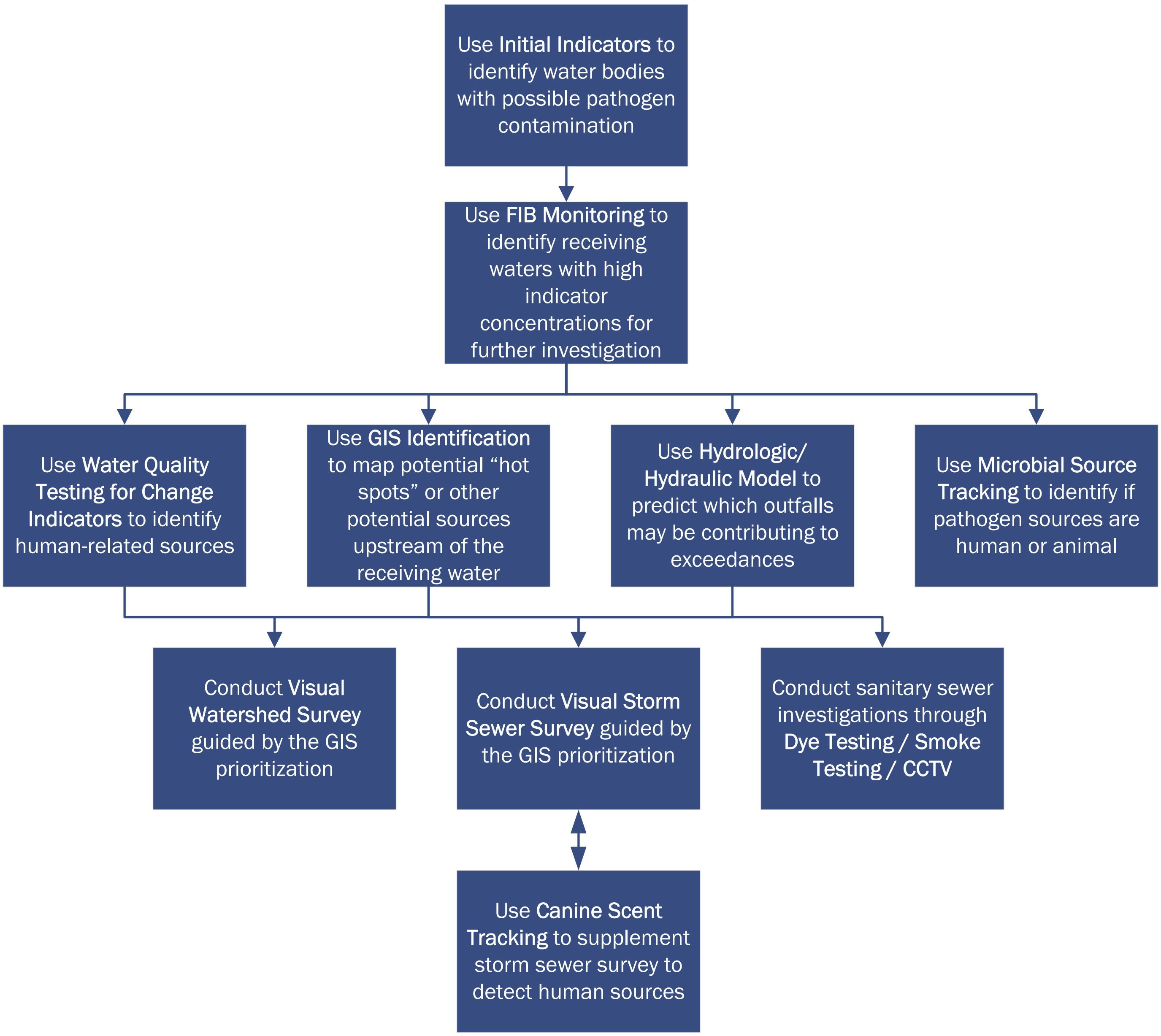
This table should be reviewed prior to initiation of field sampling to determine the presence and concentration of pathogens in the urban stormwater drainage systems. The organization of this table is based on the steps typically followed for general stormwater monitoring, as listed in the first column. The second column adds specific actions recommended when collecting samples for pathogen investigations.

General Stormwater Sampling Actions	Additional Actions Recommended for Pathogen Sampling
Step 1: Conduct Site Reconnaissance	
Review historic sampling plans and results	Check with local watershed organizations and MPCA to find relevant local pathogen studies. Review EPA TMDL studies for similar pathogen studies conducted in other states.
Review GIS data to identify potential sampling sites	Collect samples at historic sampling wherever possible. Identify sampling sites as close as feasible to suspected pathogen source. If possible, identify two sites upstream and downstream of suspected pathogen source.
Field visit proposed sampling sites	Confirm that site is accessible for grab samples.
Create map of selected sampling sites	Map should note the location of suspected pathogen source(s), if known.
Step 2: Create Standard Operating Procedure (SOP)	
Identify number of samples required	Follow MN requirements for TMDL sampling: MINIMUM 15 samples over two years with at least five samples per month for at least three months. RECOMMNEDED: Five samples per month for the period of April through October.
Identify additional field data	In addition to pathogen samples, field data should also document conditions that influence growth of pathogens in the environment: flow, pH, dissolved oxygen, temperature, conductivity, weather conditions, field observations at suspected pathogen source(s)
Identify testing parameters	When sampling for pathogens, also sample for: nutrients, organic carbon, turbidity, fluoride, potassium, surfactants, and optical brighteners.
Establish sample collection and handling protocols	Refer to EPA guide for drinking water sample collection for handling of pathogen samples. Water column samples should not disturb sediment.
Create equipment list	Include equipment to record flow, pH dissolved oxygen, temperature and conductivity. Sample bottles must remain sterile and sealed until sample collection. Sodium thiosulfate added to sample to neutralize chlorine residual (if expected). Pathogen samples must be placed on ice in cooler.
Create list of PPE for field staff	Additional PPE for microbial sample should include hand sanitizer, protective gloves, rubber boots, safety glasses, and spray bottles with diluted bleach solution.
Communicate with laboratory and establish sample collection requirements	Laboratory should advise on the number of samples required for each sampling location, as necessary for testing as well as quality control procedures. Laboratory may be able to prepare sterilized sample bottles with sodium thiosulfate or other additive as required for preservation.
Communicate with laboratory and establish delivery protocols	Laboratory must be able to process within six hours for public health sampling or up to 24 hours for other microbial testing purposes. Hold times longer than 24 hours may affect microbial concentrations.
Create field documentation worksheet	Use to document time, location, field data, sample collection, and laboratory delivery. Each sample location to be documented on a separate worksheet.
Create Quality Assurance Project Plan (QAPP)	Consult with laboratory on additional QAPP procedures, including additional samples, that are needed for pathogen analysis.
Create field SOP guide	Field reference guide should contain separate section on pathogen sampling requirements.
Step 3: Establish Testing Period	
Determine whether sampling is seasonal or single event	MPCA recommends that bacteria monitoring be conducted between April 1 and October 31.
Determine wet weather vs. dry weather	MPCA recommends sampling over different flow rates and weather conditions. Dry weather sampling for pathogens is appropriate for illicit discharge detection and elimination (IDDE) and best management practices (BMP) investigations.
Establish sampling season(s) and time period between sample events	Multiple sampling events are recommended for pathogen investigations because of seasonal variations in pathogen concentrations.

General Stormwater Sampling Actions	Additional Actions Recommended for Pathogen Sampling
Review time-of-day sample recommendations	Similar time-of-day sampling is recommended for multiple sampling events. For example, early morning samples typically have higher concentrations of pathogens.
Step 4: Verify Personnel Requirements	
Establish education and experience requirements for field personnel	Qualifications should include knowledge of sample sites, availability on short notice for wet weather sampling, knowledge of sample collection and handling protocols, ability to assess site conditions, and understanding of QA/QC techniques.
Provide field staff with annual review session of field requirements	Annual training for pathogen sampling should be based on SOP and should include actions specific to pathogen sampling, handling, and analysis; field protocols for pre-field check, sample collection, sample handling, laboratory information, documentation; safety and communication protocols, and emergency procedures.
Educate field staff on PPE requirements	Additional protection measures recommended for pathogen sampling include: Personal hygiene practices (limit exposure to open wounds, avoid hand contact with face, avoid eating/drinking while in field, promptly shower and wash clothing after sample collection). Use of hand sanitizer after sample collection is completed at each sample site. Use spray bottle with dilute bleach solution for immediate disinfection after accidental exposure.
Additional Information	
Burns & McDonnell Engineering Company. 2020. Lambert Creek Treatment Wetland Pilot Project. Prepared for Vadnais Lake Area Water Management Organization	https://www.vlawmo.org/files/5415/9741/0345/VLAWMO_Treatment_Wetland_Pilot_Project_-_Final_Report_-_07-28-20_-_FINAL_with_Attachments.pdf
Geosyntec Consultants, Wright Water Engineers, Urban Stormwater BMP Performance Monitoring, Prepared for USEPA, WERF, FHWA, ASCE, October 2009.	https://static1.squarespace.com/static/5f8dbde10268ab224c895ad7/t/604926dae8a36b0ee128f8ac/1615406817379/2009MonitoringManualSingleFile.pdf
MPCA, Total Maximum Daily Load (TMDL) Projects	https://www.pca.state.mn.us/water/total-maximum-daily-load-tmdl-projects
MPCA, Appendix D, Monitoring Requirements for MPCA Integrated Assessments	https://www.pca.state.mn.us/sites/default/files/wq-s1-15n.pdf
MPCA, Recommendations and Guidance for Utilizing Stream Monitoring to Meet TMDL Permit Requirements (web page)	https://stormwater.pca.state.mn.us/index.php?title=Recommendations_and_guidance_for_utilizing_stream_monitoring_to_meet_TMDL_permit_requirements#Bacteria_.28E._coli.29
MPCA, Industrial Stormwater Training, Monitoring Service Training (Webex)	https://www.pca.state.mn.us/water/industrial-stormwater-training
Packman, A. (2014). Pathogens in Urban Stormwater Systems.	https://www.asce-pgh.org/Resources/EWRI/Pathogens%20Paper%20August%202014.pdf
Standard Methods for the Examination of Wastewater	https://www.standardmethods.org/
USEPA QAPP Development Tool (Website)	https://www.epa.gov/quality/quality-assurance-project-plan-development-tool
USEPA National Pollutant Discharge Elimination System Stormwater Sampling Guidance Document, EPA 833-B-92-001	https://www3.epa.gov/npdes/pubs/owm0093.pdf
USEPA Quick Guide to Drinking Water Sample Collection	https://www.epa.gov/sites/default/files/2015-11/documents/drinking_water_sample_collection.pdf
USEPA Industrial Stormwater Monitoring and Sampling Guide, EPA 832-B-09-003	https://www.epa.gov/sites/default/files/2015-11/documents/msgp_monitoring_guide.pdf
USEPA Protocols for Developing Pathogen TMDLs, EPA 841-R-00-002, January 2001	https://nepis.epa.gov/Exe/ZyPDF.cgi/20004QSZ.PDF?Dockey=20004QSZ.PDF

Pathogen Source Identification Techniques

This flow chart is designed to provide guidance and show possible steps for tracking and identifying pathogen sources in an urban watershed. See the additional information in the table below for additional detail on each of these techniques. This chart provides a broad look at all possible techniques, however not all techniques will need to be applied in all situations.



Pathogen Source Identification Techniques

Tool (listed simple to complex)	Human Source	Animal Source	Point Source	Non-Point Source	Brief Description of Method and Purpose	Advantages	Disadvantages	Possible Sources Identified by Method	Links to Information and Case Studies
Initial Indicator	X	X	X	X	Color, odor, surfactants, sheen observed in waterbody	Initial indicators can alert water resource managers that investigation of presence and source of pathogens should be implemented.	Indicators may be caused by pollutants that are not pathogenic, such as excessive nutrients, illicit discharges, or spills.	Indicators are used to identify that a problem is present but cannot be used to identify the specific source.	See Pathogen Identification, Investigation, and Mitigation Decision Tree for additional detail on actions related to visual indicators.
FIB Monitoring	X	X	X	X	Testing for fecal indicator bacteria (FIB) to identify receiving waters with significant contamination for further investigation.	Low-cost monitoring for establishing baseline and locations of concern. Can be used to determine spatial and temporal trends.	Does not identify the source of contamination so this is only a starting point for source tracking.	Prioritizes waterbodies or areas of concern for further study through the methods below.	See Pathogen Sampling and Monitoring Techniques for detailed monitoring checklist and Pathogen Testing Techniques for testing methods.
Visual Watershed Survey	X	X	X		Visual survey of key locations in contributing watershed to identify possible sources of pathogens.	Easy and inexpensive to conduct, doesn't require advanced training, can eliminate low-hanging fruit.	Only useful for locating visible, at-grade contributions, impossible to survey entire contributing watershed.	Poor waste management (trash, organic waste, pet waste, homeless encampments, etc.), above-grade structural sources, natural background sources.	Document Display | NEPIS | US EPA WTW_TrainingManualJune2011.docx (live.com)
Visual Storm Sewer Survey / IDDE Tracking	X	X	X		Use of visual observations, test kits, and pole cameras to track the source of non-stormwater sources of pollutants in stormwater drainage network.	Utilizes IDDE information developed by MS4s as part of NPDES stormwater permit requirements.	Must be conducted by field staff that have confined space training. Test kits typically will identify a specific pathogen, such as E coli. Test kits are limited to sites where water is flowing and/or ponding.	Non-stormwater flows, in-pipe collection areas, and underground BMPs.	https://stormwater.pca.state.mn.us/index.php?title=MCM_3_Illicit_Discharge_Detection_and_Elimination
GIS Identification / Prioritization	X	X	X		Mapping of storm drain and sewer pipe networks, known sources or "hot spots", known IDDE, locations with likelihood of pathogen contributions (dog parks, dump stations, etc.), and FIB monitoring locations and results to look for spatial trends and relationships.	Allows for planning and identifying areas of concern for further investigation. Provides a broad overview of entire pipe system or watershed. Mapping of FIB monitoring results with infrastructure and land use can identify possible relationships.	Pipe network and land use GIS may be outdated or incorrect, only identifies likely locations for further investigation.	None directly - may lead to further investigation for cross connections, IDDE, sewage leaks, and visual surveys.	https://www.metrogis.org/projects/stormsewers.aspx
Dye-testing / Smoke Testing / CCTV	X		X		Use of dye, smoke, or CCTV to inspect the sanitary sewer for leaks or illegal connections and identify locations where wastewater may be leaking into storm drains or waterbodies.	Useful for identification of illicit connections, cross connections with sanitary sewer, or leaking wastewater.	Time consuming to cover large areas, environmental factors can impact results, public notice required for smoke testing, only useful for sewage sources.	Sewer leaks or cross connections, illicit connections.	Illicit Discharge Detection and Elimination (IDDE) Guidance Manual: Chapter 13: Tracking Discharges To A Source (epa.gov)
Canine Scent Tracking	X		X		Use of trained sewage sniffing dogs to survey storm drains and alert to the presence of human fecal waste.	Ability to survey storm sewer infrastructure with real-time results and can easily chase contamination source up branches of network to locate sources.	Requires specially trained dogs and handlers (may not be widely available and is more expensive to conduct).	Human fecal contamination in storm sewer infrastructure from IDDE, sanitary sewer leaks and surcharges or cross connections.	Canine Scent Detection and Microbial Source Tracking of Human Waste Contamination in Storm Drains - Van De Werfhorst - 2014 - Water Environment Research - Wiley Online Library
Hydrologic / Hydraulic Modeling	X	X	X	X	Modeling of flow patterns in lakes and streams can be used to identify the contributions of stormwater outfalls to beaches or recreational areas.	Useful for identifying which outfalls may be contributing to beach exceedances to narrow source investigation.	Large amount of background and calibration data is needed to create a model with enough definition to be useful.	Wet-weather stormwater outfall contributions to lakes or streams.	See Models with Applications for Pathogens for modeling methods and information.

Tool (listed simple to complex)	Human Source	Animal Source	Point Source	Non-Point Source	Brief Description of Method and Purpose	Advantages	Disadvantages	Possible Sources Identified by Method	Links to Information and Case Studies
Water Quality Testing for Change Indicators	X		X	X	Testing of outfalls and manholes for chemical markers associated with different water sources (for example, higher conductivities or metals present in industrial waste or caffeine and cotinine present in human waste).	Narrows down contributing sources to outfalls.	Contaminant sources identified may not be a source of pathogens.	Industrial waste, potable water, wash or laundry water, spring water, irrigation, sewage.	(PDF) Source Verification of Inappropriate Discharges to Storm Drain Systems (researchgate.net) Article 125: Use of Tracers to Identify Sources of Contamination in Dry Weather Flow (riverkeeper.org)
Microbial Source Tracking (MST)	X	X	X	X	Use of molecular methods and DNA markers to determine if sources of fecal contamination are human or animal (including species specific markers).	Knowing if human fecal contamination is occurring informs further investigation and effective management techniques.	Most likely requires working with outside laboratories to conduct analyses, high testing costs.	Identification of non-human fecal waste (i.e., dog, cattle, bird, gull).	Microbial Source Tracking Using Quantitative and Digital PCR To Identify Sources of Fecal Contamination in Stormwater, River Water, and Beach Water in a Great Lakes Area of Concern - PubMed (nih.gov) Document Display | NEPIS | US EPA Using Microbial Source Tracking to Identify Pollution Sources in Pathogen Impaired Embayments in Long Island, New York | U.S. Geological Survey (usgs.gov)

For more information:

Griffith, John F., Layton, Blythe A., Boehm, Alexandria B., Holden, Patricia A., Jay, Jennifer A., Hagedorn, Charles, McGee, Charles D., Weisberg, Stephen B. (2013, December). The California Microbial Source Identification Manual: A Tiered Approach to Identifying Fecal Pollution Sources to Beaches. Southern California Coastal Water Research Project, Technical Report 804. sipp_manual.pdf (ca.gov)

Chapter 5 of Clary, J., Pitt, R., & Steets, B. (2014). Pathogens in Urban Stormwater Systems. American Society of Civil Engineers Environmental and Water Resources Institute. Pathogens in Urban Stormwater Systems (asce-pgh.org)

Models with Applications for Pathogens

The table below lists models that are either designed specifically to predict the growth or movement of pathogens or have a sub-routine that may be used to predict the growth or movement of pathogens. This list contains both open-source models and models that must be purchased. As with all modeling projects, it is recommended that a modeling professional be consulted prior to selecting a model from this list.

Model Name	Publisher	Type (predictive, data source, etc.)	Designed for (beaches, watersheds, BMPs, lakes, etc.)	Applications	Input	Output	Key Features (mapping, data vis, plotting, etc.)	Complexity	Open-source/ Subscription/ One-Time Cost	System Requirements	Links to model and more information, training, etc.
AT2K/ PlantMap2K	Tufts University	Spreadsheet based 1D lateral benthic algae model	Algae modeling in streams – growth and transport	Benthic algae concentrations in streams/rivers	QUAL2K model output for water column, stream cross section, light parameters, bottom-algae stoichiometry and kinetic parameters, biomass measurements at various locations across stream width	Cross section average, extent of channel width where plant density standard is exceeded, depth beyond which exceedances do not occur. Plot of depth profile and profile of average daily bottom-algae biomass.	Excel workbook interface	Easy	Open source	Excel or other spreadsheet editing software with macro capabilities	QUAL2K Homepage
AEM3D (formerly ELCOM-CAEDYM)	Centre for Water Research, University of Western Australia (now HydroNumerics)	Spatially resolved, coupled hydrodynamic-ecological model	Scientists, academics, consultants	Simulating pathogens in surface waters that are subjected to environmental and anthropogenic forces	Climate data, lake bed surface, stream flow, stream concentrations and/or mass	Lake concentrations and/or mass, 3D variations in lake water concentrations at hourly or daily time scale	Flexible configuration for modeling processes of interest or within limits of available data	Advanced	Annual license	Windows 64-bit, Linus, or OSX operating system	https://www.hydronumerics.com.au/software/aquatic-ecosystem-model-3d USE OF ELCOM AND CAEDYM FOR WATER QUALITY SIMULATION IN BOULDER BASIN (d3pcsg2wjq9izr.cloudfront.net)
AQUATOX	EPA	Simulation, predictive, process-based	Aquatic ecosystems (plants, invertebrates, fish) including lakes, ponds, reservoirs, rivers, streams)	Developing nutrient targets. Predicting effects of climate changes, pesticides, and land use changes.	Environmental Data: ▪ Loadings to the waterbody ▪ General site characteristics Biological and Chemical Parameters ▪ Biological characteristics ▪ Chemical characteristics of any organic toxicant *Includes data libraries *can link to BASINS	Time-varying biomass of the various plants and animal, chemical concentrations in water, and concentrations of the organic toxicant in water, organic sediments, and biota	Powerful graphic capability, export to Excel	Moderate	Open source	Minimum: Windows 98, 2000, NT, or XP; 1 GB RAM; 100 MB free disk space Recommended: Pentium PC, 2.0 GHz or higher; Windows 2000, XP, or Vista; Windows 7 or 8; 4 GB RAM; 1 GB free disk space	AQUATOX 3.1 Download Page | US EPA AQUATOX Training Workshops | US EPA
BASINS	EPA	Environmental analysis system	Development of TMDLs, watershed-based, integrating point and non-point sources	Mapping potential pathogen sources, including both point and non-point sources, within a watershed	Internal databases provide basic inputs which can be supplemented with user-provided datasets. Base cartographic data. Environmental background data. Environmental monitoring data. Point sources/loading data.	GIS format for displaying results, Watershed Characterization Reports, Climate Assessment	Includes plug-ins for SWAT, AQUATOX, WASP, and SWMM models; can be used on a variety of scales; compatible with ArcGIS	Moderate	Open source	Minimum: Windows XP or greater, 1 GHx process, 2 GB disk space, 512 MB RAM, and 2 GB of page space, 16-bit color, 1024x768 resolution Preferred: 2 GHz processor, 10 GB hard disk, 1 GB RAM + 2 GB page space, 32-bit color, 1600x1200 resolution	BASINS Download and Installation | US EPA https://www.epa.gov/ceam/basins-user-information-and-guidance

Model Name	Publisher	Type (predictive, data source, etc.)	Designed for (beaches, watersheds, BMPs, lakes, etc.)	Applications	Input	Output	Key Features (mapping, data vis, plotting, etc.)	Complexity	Open-source/ Subscription/ One-Time Cost	System Requirements	Links to model and more information, training, etc.
DELFT3D	Deltares	Hydrodynamic simulations and particle tracking. Simulates either 2D or 3D flows	Particle tracking. Initially developed for simulation of deltas. Can also be used in coastal, estuary, river, and urban environments.	Transport of bacteria	Hydrologic and hydraulic inputs, climatological inputs, plus water quality parameters	Map or grid files of particle concentrations	Data can be exported to Google Earth for data visualization. User-friendly interface. Capable of modeling sediment transport and hydraulic interactions between storms, waves, flows, and water levels.	Advanced	One-time purchase, open source version also available	Windows 10 or CentOS6 Minimum: 1.5 GHz, 2 GB RAM, 10 GB disk space Preferred: 3 GHz processor, 4 GB RAM, 100 GB disk space	https://oss.deltares.nl/ https://www.deltares.nl/en/software/delft3d-4-suite/
QUAL2K	Tufts University	Spreadsheet based 1D river and stream water quality model used to compute distribution of biomass in rivers	Stream modeling including fate and transport of water quality parameters	Pathogen concentration and transport in streams	Stream hydraulic characteristics	Temperature, water quality kinetics, heat, mass	Excel workbook interface	Easy	Open source	Excel or other spreadsheet editing software with macro capabilities	QUAL2K Homepage
SWAT (Soil & Water Assessment Tool)	Texas A&M / EPA	Watershed scale semi-distributed, physically based hydrologic model	Estimating the long-term impact of land management practices on runoff, sediment loads, and loss of nutrients at different scales	Non-point source pollution and land use impacts on groundwater and surface water quantity and quality from changes in land management	Watershed dimensions, climate data (precipitation, temperature, solar radiation, humidity, wind speed), hydrologic information, sediment data, nutrient loading, pesticides, bacteria in soil/runoff, water quality data, land cover, channels/lakes/ponds characteristics and routing, point sources	Watershed average annual, monthly, or daily loadings for the hydrologic response units to streams or other waterbodies	Very involved user group for technical support and guidance	Advanced	Open source	Windows, Linus, or OS operating system, QGIS (open source GIS platform)	SWAT | Soil & Water Assessment Tool (tamu.edu)
SWMM	EPA (versions available from Innovyze and PCSWMM, as well)	Dynamic rainfall-runoff model	Urban watershed modeling, non-point source pollutant loadings, evaluating BMP impacts	Urban watershed with both storm sewer infrastructure and runoff contributions	Storm sewer infrastructure (commercial versions support importing from GIS) including stormwater BMPs/LID controls, pervious/ impervious areas and land use, rainfall data, TIN surface (if modeling overland runoff flow), pollutant buildup and wash off parameters and inflows	Summary table including pollutant loads, time-series graph of pollutant concentrations at any point in watershed	Can be combined with BASINS, GIS compatibility, commercial versions have 1D/2D modeling capabilities, can model non-point source pollution loadings, add-in available for climate projections	Moderate	Open source version available from EPA, commercial versions also available for annual fee	32- or 64-bit Windows	SWAT | Soil & Water Assessment Tool (tamu.edu) SWMM5 modeling with PCSWMM Sanitary, Storm and Flood Modeling Software | XPSWMM (innovyze.com)

Model Name	Publisher	Type (predictive, data source, etc.)	Designed for (beaches, watersheds, BMPs, lakes, etc.)	Applications	Input	Output	Key Features (mapping, data vis, plotting, etc.)	Complexity	Open-source/ Subscription/ One-Time Cost	System Requirements	Links to model and more information, training, etc.
Virtual Beach (VB)	EPA	Site-specific statistic predictive model	Beach managers	Prediction of pathogen indicator levels at beach sites	Indicator pathogen concentration (E. coli, enterococci) Independent variables include turbidity, visibility, dry bulb, wet bulb, dew point, relative humidity, station pressure, precipitation, wind speed, current, and wave data	Predicted pathogen concentration	Integrated mapping, data import from Excel, multiple modeling methods, decomposition of wind and current speeds into onshore and offshore components, direct link to USGS EnDDaT system, data validation	Easy	Open source	Windows OS with DotNet Framework 4.0, internet connection, 2 GB RAM or better, 140 MB disk space for VB and 170 MG for DotNet Framework	Virtual Beach (VB) | US EPA
WASP8 (Water Quality Analysis Simulation Program)	EPA	Dynamic compartment-modeling program	Development of TMDLs		Time series data *can link to hydrodynamic and sediment transport models	Spatial grid and x/y plots of predicted concentrations	1D, 2D, and 3D system investigation, variety of pollutant types	Advanced	Open source	64-bit Windows 7 or higher, Mac OSX, Linux Ubuntu	https://www.epa.gov/ceam/wasp8-download WASP Model Tutorials | US EPA
Not models but helpful information											
CyAN HAB forecasting app	EPA	Cyanobacterial bloom satellite data	Water quality managers to aid in decision making	Regular monitoring of waterbodies for initial screening and locating areas of concern for sampling or other investigation	Local of waterbody (must be one square kilometer or greater)	Cyanobacterial bloom satellite date	Mobile app Easy to use, customizable interface, can compare multiple waterbodies at once	Easy	Open source	Android devices using version 4.2-9.0 (API levls 18-26)	Cyanobacteria Assessment Network Application (CyAN app) | US EPA
QMRA (Quantitative Microbial Risk Assessment)	N/A	Risk analysis methodology	Practitioners responsible for risk management	Determining risks associated with pathogen exposures	Dose response analysis: how adverse effects are related to level of exposure with pathogen Exposure assessment: how exposures to the pathogen occur in the environment and calculating the amount, frequency, and length of time of exposure	Risk characterization: magnitude of risk, uncertainty, and variability which can inform risk management decisions	Dose-response equations are available online	Moderate	N/A	N/A	Quantitative Microbial Risk Assessment Basics - EH: Minnesota Department of Health (state.mn.us) QMRA (qmrawiki.org)
WATERS (Watershed Assessment, Tracking, and Environmental Results System)	EPA	Database	Environmental professionals and interested citizens	Database to find data for model inputs	Information available through the WATERS includes designated use of waterbody, water quality monitoring results, assessments of water quality, causes and sources of impaired waters, public beach closures, and locations of discharges. (Not a model itself but good contributing information)		Includes web service and mapping service	Easy	Open source	Mapping tool requires ESRI ArcMap 9.3.1 or greater	

Pathogen Mitigation Techniques

This table allows users to focus on specific pathogen mitigation techniques that are best suited to a specific pathogen source. Users are encouraged to use the links provided to learn more about the effectiveness and engineering criteria necessary for a specific mitigation technique.

			Natural Background Sources									Urban Watershed Sources								Urban Infrastructural Sources																	
			Urban			Other Natural Resources						Watershed			Human Sanitary					Municipal			IDDE								Wet Weather		MS4 Infrastructure				
Management Category	Technique	Description	Birds and waterfowl	Rodents – beavers, chipmunks, gophers, mice, rats, squirrels, voles, woodchucks	Urban wildlife – coyotes, deer, feral cats, fox, moles, rabbits, racoons	Decaying plants (on pervious or impervious surfaces)	Exposed/eroding soil	Organic matter at lake/stream edge	Organic matter in lake/stream sediment	Stream flow	Flood flows in floodplain	Domestic pets	Trash from garbage trucks/dumpsters/trash cans/litter, etc.	Non-plant based organic waste: compost/outdoor dining/grease bins	Bathing/beaches	Boats, illegal discharge from waste tanks	Homeless encampments	Leaking or failed septic systems	Temporary toilets	Combined sewer overflows	Sanitary sewer overflows	Exfiltration from leaky sanitary pipes	Direct connections that discharge non-rainfall base flow	Dumping – including RV stations	Gray water/pools/hot tubs	Illegal sanitary connections	Improper disposal, littering, and/or inadequate cleanup of human wat (including soild diapers or vomit in open trash containers)	Lawn care practices (over irrigation)	Other sources of nonOrainfall base flow	Street and stormwater maintenance, improper disposal of leachates, litter, and sediment	Stormwater hotspots (including dog parks, plant nurseries, etc.)	Stormwater runoff	Pre-treatment (above ground)	Infiltration of best management practices	Pre-treatment (below ground)	Wet detention best management practices	Stormwater conveyance
Natural Resource Management [1]	Streambank buffers	Natural vegetative buffer designed to slow rate of overland flow to maximize infiltration of runoff from natural areas of excess pathogen loads to surface waters	X	X	X	X	X	X	X		X																										
Natural Resource Management [2]	Shoreline/ streambank erosion repair	Riprap, native plantings, and other measures that prevent shoreline/streambank erosion					X	X	X	X	X																										
Natural Resource Management [3]	Beach use management	Pre-established testing, beach closure, beach opening procedures to follow in the event of pathogen contamination													X	X	X	X	X	X	X	X	X	X	X	X	X										
Natural Resource Management [4]	Beach maintenance	Beach grooming, trash and litter controls, temporary toilet siting, pet policies, etc.				X							X		X				X																		
Natural Resource Management [4]	Deterrence/ dispersion/ removal/ chemical controls	Use of sound, light, sprinklers, predators (dogs, etc.), or chemicals for the purpose of controlling birds or wildlife in areas of excessing pathogen loads to surface water. Consultation with expert advised.	X	X	X																																
Natural Resource Management [4]	Habitat alteration/ control of natural food source	Alteration of vegetation, installation of fencing and/or installation of other features for the purpose of controlling birds and wildlife in areas that generate excessive pathogen loads to surface waters. Consultation with expert advised.	X	X	X																																

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Maintenance Activities [5]	Sweeping and trash collection	Increased frequency of sweeping and/or trash collection in areas identified as a potential source or transport of pathogens				X	X		X			X	X	X													X				X						
Maintenance Activities [6]	Storm drainage system inspection and maintenance	Inspection of stormwater drainage piping to locate and maintain areas of clogs or misaligned inverts that have created standing water in areas identified as potential sources of pathogens.																																			X
Maintenance Activities [7]	Sanitary collection system inspection and maintenance	Adoption of CMOM (Capacity, Management, Operations, and Maintenance) practices for the purpose of SSO prevention through scheduled inspection, cleaning, and other preventive maintenance practices, especially in locations where SSO events have occurred.																		X	X	X															
Maintenance Activities [5]	Increased frequency of BMP sediment removal	Increased frequency of floating debris and sediment removal from structural BMPs to prevent the excessive growth of biofilms.							X																					X	X		X	X	X	X	
Maintenance Activities [6]	Proper disposal of leachates, vegetation debris, and sediments	Implementation of policies, practices, and staff education on proper disposal of leachates and sediments from structural BMP maintenance. Goal is prevention of disposal of pathogen laden materials into surface waters. Disposal of leachates into sanitary sewer may require permit.							X																					X	X		X	X	X	X	

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Pollution Prevention [6]	Education	Signage, websites, advertisements, articles, etc. to educate and change behaviors of residents, businesses, and park uses that collectively can reduce pathogen inputs through improved pollution prevention practices.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Pollution Prevention [5]	Good housekeeping practices/ ordinances/ inspection/ enforcement	Adoption of ordinances, increased frequency of inspection, and strict enforcement of IDDE controls that focus on source control and transport control. May include elimination of non-stormwater discharges, increased level of maintenance in stormwater hotspots with significant organic wastes (restaurant dumpsters, garden nurseries, etc.), and adoption of practices for the proper location of temporary toilets in areas identified as potential sources of pathogens.				X	X		X			X	X	X		X	X	X	X				X	X	X	X	X	X	X	X	X						
Pollution Prevention [5]	New impervious surface controls	Adoption of ordinances and other development controls that minimize impervious surfaces and maximize stormwater infiltration for the purpose of minimizing the transport of pathogens.								X	X																		X			X	X					X

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Structural Rehabilitation/ Retrofit [6]	Sanitary sewer rehabilitation	Inspection, rehabilitation, and/or increased capacity of sanitary sewers in areas where exfiltration, SSO, or CSO has been identified as a source of pathogens.																		X	X	X															
Structural Rehabilitation/ Retrofit [6]	Inlet/outlet modifications	Structural modification within stormwater retention BMP for the purpose of lengthening flow path, minimizing resuspension of sediment, and/or extending detention time for the purpose of enhancing pathogen die-off. May also be for the purpose of managing runoff velocities to prevent erosion.					X		X	X																						X	X	X	X	X	X
Structural Rehabilitation/ Retrofit [6]	Hydraulic retrofit	Removal of feature within structural stormwater conveyance and/or structural BMP that is found to host pathogen. Includes removal of structural features in outfalls, conveyance systems, and structural BMPs that create incidental ponding areas that harbor bacteria.																														X					X
Structural Rehabilitation/ Retrofit [6]	Media filters retrofit	Addition of media filters or change of media within existing filter in structural stormwater BMPs to enhance pathogen die-off or sorption within BMPs.																															X	X	X	X	

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BMP Design Enhancements [6]	Enhanced water storage and sediment storage	Lengthening retention to allow additional storage time to maximize exposure of sunlight to enhance natural pathogen die-off. Enhancement of sediment storage should be considered in BMPs that experience significant sediment resuspension.																																		X	
BMP Design Enhancements [6]	Increased volume of infiltration	Increased infiltration in structural infiltration BMPs for the purpose of minimizing runoff to control the transport of pathogens.																														X		X			X
BMP Design Enhancements [6]	Installation of biofilters	Biofilters, including biochar filters, typically have smaller pore size than sand filters that can be sufficient to capture larger bacteria. The materials in bio-style filters have surfaces that enhance pathogen attachment and die-off.																															X	X	X	X	
BMP Design Enhancements [6]	Greater vertical separation between BMP and groundwater	Increased depth of soil or media below stormwater BMP and groundwater will increase pathogen filtration and create conditions for pathogen die-off in drinking water protection areas and other locations where groundwater is sensitive to pathogen contamination.																															X	X	X	X	
Other [6]	Disinfection	Installation of disinfection devices (UV light irradiation, ozonation, peracetic acid, chlorine). Best used in location with low flows. Not widely used in stormwater application.																													X	X					
Other [6]	Low flow diversion	Diversion of pathogen laden runoff away from recreational and other sensitive areas.																					X					X	X								X

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Unit Processes [6]	Natural inactivation	Die-off caused by exposure to sunlight, temperature, and/or drying/desiccation.																															X	X			
Unit Processes [6]	Predation	Introduction of predatory microorganisms, including protozoa.																															X		X	X	
Unit Processes [6]	Sorption	Bonding of microorganisms to the surface of particles.																															X	X		X	
Unit Processes [6]	Chemical inactivation	Use of antimicrobial agent that will inactivate bacteria.																															X		X	X	
Unit Processes [6]	Filtration and sedimentation	Removal of particles from water column to remove bacteria that have attached to particles.																															X	X	X	X	

Notes:

Additional information can be found at:

[1] https://www.fs.usda.gov/nac/buffers/guidelines/1_water_quality/11.html

[2] https://www.lrc.usace.army.mil/Portals/36/docs/regulatory/pdf/StrmManual.pdf

[3] https://www.ncbi.nlm.nih.gov/books/NBK572636/

[4] https://wildlifecontroltraining.com/training/wildlife-control-methods/

[5] https://stormwater.pca.state.mn.us/index.php?title=Overview_and_management_strategies_for_bacteria_in_stormwater

[6] https://www.asce-pgh.org/Resources/EWRI/Pathogens%20Paper%20August%202014.pdf

[7] https://www3.epa.gov/npdes/pubs/cmom_guide_for_collection_systems.pdf

Pathogen Annual Reporting Requirements

Minneapolis’ current National Pollutant Discharge Elimination System (NPDES) permit does not contain specific reporting requirements for pathogens, specifically *E. coli* and fecal coliform. However, the permit does not require annual reports on compliance with TMDL implementation plans, including any plans that mitigate pathogens. As of 2022, there are no bacteria or *E. coli* waste load allocation (WLA) requirements for any surface waters that receive runoff from the Minneapolis stormwater drainage system. The reporting requirements listed below are for general total maximum daily load (TMDL) compliance in the event that any future TMDL plan will require actions by Minneapolis or by any other Minnesota municipal separate storm sewer systems (MS4) community.

Reporting Requirements	Description	Tool Reference	Link
Minneapolis TMDL Annual Reporting Requirements			
V.C.1.f Addressed TMDL compliance at annual public meeting	Annual public meeting notice must contain proposed modifications to TMDL minimum control measures	N/A	https://www2.minneapolismn.gov/media/content-assets/www2-documents/department/NPDES-Phase-I-Permit.pdf
V.C.8 Select and implement a program of appropriate BMPs and measurable MCM-specific goals including schedules to meet time frames for WLAs	Review adequacy of stormwater management plan (SMP) to meet TMDL WLA	Pathogen Identification, Investigation, and Mitigation Decision Tree	
	Estimate loading calculations according to permit requirements and compare to WLA for impaired waterbody	Pathogen Sampling and Monitoring Techniques	
		Models with Applications for Pathogens	
	Modify SMP as necessary to meet WLA requirements	Pathogen Source Identification Techniques	
		Pathogen Mitigation Techniques	
MS4 General Permit Annual Reporting			
MS4 General Permit Section 22	Actions required to meet applicable WLAs for bacteria, chloride, and temperature (see Minn Rule 7090)	N/A	https://www.pca.state.mn.us/sites/default/files/wq-strm4-94.pdf
Section 22.3	Permittee must maintain written or mapped inventory of potential areas and sources of bacteria with each annual report	Urban Pathogen Sources	
		Pathogen Source Identification Techniques	
Section 22.4	Permittee must maintain written plan to prioritize reduction activities to address the areas and sources identified in the inventory with each annual report	Models with Applications for Pathogens	
		Pathogen Mitigation Techniques	