Colorado *E. coli* Toolbox

A Practical Guide for Colorado MS4s Version 2

June 2026 (original July 2016)

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Colorado *E. coli* Toolbox: A Practical Guide for Colorado MS4s (Version 2)

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Prepared for
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The intent of this Toolbox is to provide a concise, easy-to-read reference for use in urban areas in Colorado. Thus, more detailed technical analysis supporting the condensed discussion in this Toolbox can be obtained from the following sources, which provide some of the technical underpinnings of portions of this Toolbox.

Urban Water Resources Research Council of the Environmental and Water Resources Institute of the American Society of Civil Engineers. (2014). *Pathogens in Urban Stormwater Systems*. Eds. Clary, J., Steets, B., and Pitt, R. Prepared with support from the Mile High Flood District and the Urban Watersheds Research Institute. August.

International Stormwater BMP Database, including various statistical summaries such as International Stormwater BMP Database: 2020 Summary Statistics prepared by Clary, J., Jones, J., Leisenring, M., Hobson, P., and Strecker, E. for The Water Research Foundation (WRF): Alexandria, VA. Current project co-sponsors include ASCE-EWRI, WRF, MHFD and Villanova University. https://bmpdatabase.org/

U.S. Environmental Protection Agency. (2012). *Recreational Water Quality Criteria*. Office of Water 820-F-12-058. http://water.epa.gov/scitech/swguidance/standards/criteria/health/recreation/

Center for Watershed Protection and R. Pitt. (2004). *Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessments*. Center for Watershed Protection, Ellicott City, MD, and University of Alabama, Tuscaloosa, AL. https://www.epa.gov/sites/default/files/2015-11/documents/idde_manualwithappendices.pdf

City of Santa Barbara, Creeks Division, in Partnership with University of California, Santa Barbara. (2012). *Tools for Tracking Human Fecal Pollution in Urban Storm Drains, Creeks, and Beaches*. September 1, 2012.

Griffith, J.F., Layton, B.A., Boehm, A.B., Holden, P.A., Jay, J.A., Hagedorn, C., McGee, C.D., and S.B. Weisberg. (2013). *The California Microbial Source Identification Manual: A Tiered Approach to Identifying Fecal Pollution Sources to Beaches.* Technical Report 804 - December 2013. Prepared for the Southern California Coastal Water Research Project. Accessible at: http://www.waterboards.ca.gov/board_info/agendas/2014/jan/012114_11_804_sipp_mst_manual.pdf

Acronyms and Abbreviations

ARP	advance restoration project
BMP	best management practice (also known as stormwater control practice)
CCTV	closed circuit television
CDC	Centers for Disease Control
CDPS	Colorado Discharge Permit System
cfu	colony forming units
CIP	capital improvement program
Commission	Colorado Water Quality Control Commission
CPW	Colorado Parks and Wildlife
CSO	combined sewer overflow
ddPCR	digital droplet quantitative polymerase chain reaction
Division	Colorado Water Quality Control Division
DSV	discharger specific variance
EPA	U.S. Environmental Protection Agency
FIB	fecal indicator bacteria
GIS	geographic information system
IDDE	illicit discharge detection and elimination
LA	load allocation
M&E	monitoring and evaluation
MEP	maximum extent practicable
MHFD	Mile High Flood District
mL	milliliters
MOS	margin of safety
MPN	most probable number
MS4	municipal separate storm sewer system
MST	microbial source tracking
NEEAR	National Epidemiological and Environmental Assessment of Recreational Water
NPDES	National Pollutant Discharge Elimination System
NSE	natural source exclusion
NSQD	National Stormwater Quality Database
PCR	polymerase chain reaction
QMRA	quantitative microbial risk assessment
WWTP	wastewater treatment plant
qPCR	quantitative polymerase chain reaction
RWQC	Recreational Water Quality Criteria
SCCWRP	Southern California Coastal Water Research Project
SOP	standard operating procedure
SSO	sanitary sewer overflow
STV	statistical threshold value
TIL	tolerable illness level
TMDL	total maximum daily load
UAA	use attainability analysis
USDCM	Urban Storm Drainage and Flood Control Manual
USGS	U.S. Geological Survey
UV	ultraviolet
WHO	World Health Organization
WLA	wasteload allocation

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EXECUTIVE SUMMARY

The purpose of this Colorado *E. coli* Toolbox is to provide a consolidated resource to support local governments with Municipal Separate Storm Sewer System (MS4) permits working to reduce *E. coli* loading to impaired waterbodies in Colorado. As of 2026, approximately 105 stream segments in Colorado are identified as impaired or in need of additional monitoring and evaluation due to elevated *E. coli* concentrations relative to recreational water quality standards. This Toolbox provides a concise overview of regulations driving Total Maximum Daily Loads (TMDLs) and MS4 permit conditions and focuses on approaches to understanding sources of *E. coli*, potential non-structural and structural best management practices (BMPs) to reduce *E. coli* loading, and regulatory alternatives.

Pathogens (disease-causing organisms) are impractical to monitor directly, so fecal indicator bacteria (FIB) are used as a surrogate to indicate risk of gastrointestinal illness in place of direct measurement of pathogens. Although there are limitations with use of *E. coli* for this purpose, the U.S. Environmental Protection Agency (EPA 2012) concluded that *E. coli* (or enterococcus) were the best currently available indicators appropriate for use in nationally applicable recreational criteria. When communicating with the public, it is often important to clarify that the FIB called *E. coli* are not equivalent to the pathogenic strain of *E. coli* (O157:H7) that the public may be familiar with due to highly publicized foodborne illness outbreaks.

Most streams in Colorado's urban areas are assigned "existing primary contact" recreation standards. Primary contact recreation is defined as "recreational activities where the ingestion of small quantities of water is likely to occur. Such activities include but are not limited to swimming, rafting, kayaking, tubing, windsurfing, water-skiing, and frequent water play by children" (WQCC 2012). Colorado's primary contact standard of 126 colony forming units per 100 milliliters (cfu/100 mL) for *E. coli* is expressed as a not-to-be-exceeded geometric mean value, which is consistent with EPA's 2012 Recreational Water Quality Criteria and corresponds to an allowable swimmer illness rate of 36 illnesses per 1,000 exposures. Although a wide range of trends can occur for *E. coli*, a common trend in warm-water Colorado streams is elevated *E. coli* during the summer and/or early fall months and attainment of the standard during the winter.

As of early 2026, the Water Quality Control Division (Division) has finalized seven *E. coli* TMDLs in Colorado, including four segments in the South Platte River Basin, Wildhorse Creek in the Arkansas River Basin and two segments in the Grand Valley that are tributary to the Lower Colorado River. Each of these TMDLs includes unique aspects, although basic requirements for EPA-approvable TMDLs are included in each. The Division has prioritized completion of additional *E. coli* TMDLs as a high priority on its near-term planning horizon.

Sources of pathogens and FIB in MS4s and receiving waters vary widely, originating from both non-human and human sources. Representative sources of FIB in urbanized areas in Colorado may include sewer leaks into and illicit connections to storm drain systems (e.g., sanitary sewer connections to the storm drain), SSOs (sanitary sewer overflows), wet weather (stormwater) discharges from MS4s (which mobilize and convey sources deposited on land surfaces), illicit discharges to storm drain systems (e.g., recreational vehicle dumping), failing or improperly located onsite wastewater treatment systems (septic systems), wastewater treatment plants (if not meeting discharge permit limits), urban wildlife, domestic pets, agriculture, and other sources. Allowed discharges to MS4s such as irrigation runoff and uncontaminated groundwater discharges may also transport FIB originating from other sources. It is beneficial for MS4 permittees to have a broad understanding of the diverse sources of *E. coli* that may contribute to waterbody impairments; however, MS4 permittees are only responsible for controlling sources contributed through their MS4. In addition to fecal sources, non-fecal sources or reservoirs of FIB exist. These include sediments in receiving waters, biofilms in storm drains and waterbody substrate/sediments, and naturalized FIB associated within plants and soil. Although agricultural sources are not the focus of this Toolbox, both livestock and manure management can be sources of FIB in watersheds where MS4 permittees are working toward watershed-scale solutions.

Although some FIB sources can be controlled to an appreciable extent (e.g., wastewater discharges, sanitary sewer leaks, illicit connections), other sources are much more difficult to control. These diffuse, ubiquitous, and often mobile sources include anthropogenic (e.g., unsheltered populations) as well as non-anthropogenic sources such as wildlife (e.g., raccoons, beavers, and birds). Furthermore, not all sources present the same public health threat; human fecal sources present a much higher illness risk than most non-human and non-fecal sources. Properly accounting for and identifying potential sources in a particular area are the first steps in working toward minimizing FIB and pathogen contributions from controllable sources and protecting public health.

Monitoring strategies to characterize local sources of FIB can range from simple and relatively inexpensive sample collection and analysis of FIB and basic water quality parameters to higher cost microbial source tracking (MST) approaches relying on advanced molecular methods. It is recommended that entities with wasteload allocations in *E. coli* TMDLs begin with simple methods to identify and prioritize anthropogenic FIB sources in their drainage areas and collection systems and then target source control strategies to address these. Monitoring and source tracking techniques selected may be limited by budget constraints, regulatory drivers, and available technical expertise. Although monitoring and investigation can be costly, these costs are typically much less than the cost of structural stormwater control measure (SCM) implementation. It is typically worthwhile to invest in a well-designed monitoring program that enables well-supported identification of sources to determine source controls and, where necessary, structural SCMs that effectively target highest priority (or highest risk) sources. This approach is expected to provide the greatest likelihood of achieving meaningful contributions to public health protection and recreational beneficial use restoration. Monitoring programs should utilize adaptive management principles, evolving over time as new information becomes available.

The foundation of *E. coli* load reduction plans is source controls, which are non-structural measures (behaviors) that help to reduce the *E. coli* sources and/or flow sources that are transporting *E. coli* to the storm drainage systems. Effective implementation of source control practices typically involves coordination with multiple local government departments, including sanitary sewer collection system owners/operators. Interdepartmental and interjurisdictional coordination and collaboration are essential to achieving meaningful pathogen and FIB reduction.

SCMs, also referred to as permanent post-construction best management practices (BMPs), are key tools to help reduce *E. coli* loading in urban runoff. Options include flow-through and volume reduction-based treatment controls. Existing performance data indicate that passive (i.e., non-disinfection) SCMs are unlikely to consistently achieve primary contact limits in treated effluent; therefore, volume reduction-based SCMs are an important structural control strategy for achieving bacteria load reductions. Green infrastructure approaches should be considered because they encourage infiltration of stormwater and reduce dry weather flows. Treatment SCMs with performance data indicating the potential ability to reduce *E. coli* concentrations include retention (wet) ponds, media filters, bioretention facilities and subsurface flow wetlands. Site-specific constraints, cost and sustainability (ability to maintain performance over time) will also affect selection of SCMs that are suitable for any particular site. Active treatment, such as ultraviolet (UV) disinfection and diversion of dry-weather low flows to the sanitary sewer system, are generally a last resort for controlling *E. coli* discharges to receiving waters, due to their high cost and other factors.

In some urban areas across the United States, multi-million or billion-dollar MS4 implementation plans have been developed to address FIB TMDLs; thus, substantial benefits may be gained by well-developed and clearly targeted special studies prior to embarking on expensive capital improvement programs. For example, EPA's 2012 Recreational Water Quality Criteria recognize the need for and allow the development of site-specific standards based on demonstration that local illness risks are low (due to the predominance of non-human sources). Meanwhile, MST techniques have become better validated, standardized, commercialized, and familiar/acceptable to state and federal water quality regulators over the past few years. Therefore, use of MST has become more common, including for the use of risk-based analysis. Experience is still being developed for use of tools such as Quantitative Microbial Risk Assessment (QMRA) to modify water quality standards (or discharger-specific variances) after human sources are demonstrated to be absent or mostly absent.

1 Introduction

1.1 Purpose of this Toolbox

As of 2026, approximately 105 stream segments in Colorado are identified as impaired or in need of additional monitoring and evaluation due to elevated *E. coli* concentrations relative to recreational water quality standards. For streams identified as impaired on Colorado's "303(d) List," typically the next step is development of a total maximum daily load (TMDL), which determines the load reductions needed to attain recreational water quality standards. As of 2026, there are seven completed *E. coli* TMDLs in Colorado with more than a dozen TMDLs prioritized for development through 2028. In urban areas, municipal separate storm sewer systems (MS4s) subject to Colorado Discharge Permit System (CDPS) permits may have additional permit requirements to reduce *E. coli* loading as a result of these TMDLs.

The purpose of this Toolbox is to provide a consolidated resource to support local governments with MS4s working to reduce *E. coli* loading to impaired waterbodies. Although the issue of *E. coli* impairment in urban areas is complex, this Toolbox has been kept as simple as possible with the intention of providing readers with a broad range of backgrounds a resource to develop a general understanding of the issues and to provide tools that may be useful for reducing *E. coli* loads from urban areas. This Toolbox is organized into six chapters including:

- Introduction: this chapter provides a basic overview of recreational water quality criteria and use impairment, Colorado's approach to bacteria TMDLs, and a basic overview of considerations for building an *E. coli* control program in the context of MS4 permits.

- Finding the Sources: the key to success in reducing *E. coli* loading to streams is understanding and identifying the sources of FIB loading. This chapter provides an overview of source identification techniques that a local government may want to consider for developing a better understanding of sources.

- Developing a Control Strategy: controlling bacteria loads in urban areas can be both complex and expensive. There is not a "one size fits all" solution for attaining recreational water quality criteria in urban areas. This chapter provides general guidance on how to develop a control strategy to progress from control of dry weather sources then wet weather sources, focusing first on human-related sources of bacteria loading.

- Source Control Practices: source control practices are the foundation of *E. coli* load reduction strategies. This chapter provides a description of source control practices that communities should consider for reducing *E. coli* loading.

- Structural Control Measures: structural stormwater control measures (SCMs), also known as best management practices (BMPs), can reduce dry weather and wet weather loading to streams. Ideally, for dry weather discharges from MS4s, source controls are the primary solution; however, some structural controls can be used for dry weather flows, typically as a last resort. For wet weather flows, Mile High Flood District's (MHFD) *Urban Storm Drainage Criteria Manual (Volume 3)* is a key source of design information for structural SCMs suitable for use in Colorado's urban areas. This chapter provides additional information on performance expectations for SCMs and techniques that help to enhance their performance.

- Adaptive Management Prioritizing Human Health: Although Colorado's recreational use criteria focus strictly on attainment of numeric standards for *E. coli* regardless of source, local governments and public health agencies should use adaptive management principles to prioritize control of sources posing the greatest human health risk in areas where actual recreation use occurs.

- Regulatory Alternatives: Colorado's Basic Standards and Methodologies for Surface Water (Regulation 31) define how water quality standards are adopted in Colorado, allowing development of site-specific standards and discharger-specific variances (DSVs) under certain conditions. Additionally, in its 2012 Recreational Water Quality Criteria update, the U.S. Environmental Protection Agency (EPA) outlined three options for alternative or site-specific standards for recreational water quality. Communities where these alternatives may be most viable are those where human sources of bacteria have been mostly controlled. In 2024, EPA released Technical Support Materials describing these options.

1.2 Colorado Recreational Water Quality Criteria and Recreational Use Impairment

The Colorado Water Quality Control Commission (WQCC) establishes water quality standards to protect designated uses for streams and lakes in Colorado. These standards are reviewed on a routine basis and modified based on changes in federal and state regulations and other factors. Colorado streams are classified according to whether primary contact is present, potentially present, not present or undetermined. Practically speaking, unless a fence is in place to preclude access, streams in urban areas are assigned primary contact recreation standards.

Difference between Fecal Indicator Bacteria (FIB) and Pathogens

Fecal matter often contains pathogens, which are disease-causing organisms. Because of impracticality of testing for many pathogens associated with fecal waste, fecal indicator bacteria or "FIB" are used as indicators of fecal contamination. The FIB currently recommended by EPA include *Escherichia coli* (*E. coli*) and/or enterococcus. Historically, fecal coliform bacteria were also recommended indicators. FIB are not necessarily disease-causing and may be present due to non-fecal sources such as decaying plant matter and other environmental sources.

Determination of impairment of a waterbody for recreational use depends on the recreational use classification assigned to a waterbody and assessment of available *E. coli* data following the most current version of Colorado's 303(d) Listing Methodology, which is updated biennially. Consistent with EPA's 2012 Recreational Water Quality Criteria (EPA 2012), Colorado uses *Escherichia coli* (*E. coli*) as the indicator of potential fecal contamination of waterbodies. Pathogens (disease-causing organisms) are impractical to monitor directly, so fecal indicator bacteria (FIB) are used as a surrogate to indicate risk of gastrointestinal illness in place of direct measurement of pathogens. Although there are a number of limitations with use of *E. coli* for this purpose, EPA (2012) concluded that *E. coli* (or enterococcus) were the best currently available indicators appropriate for use in nationally-applicable recreation criteria.[1] When communicating with the public, it is often important to clarify that *E. coli* in the context of FIB are not equivalent to the pathogenic strain

[1] EPA's 2012 Recreational Water Quality Criteria include some provisions that allow for use of alternative indicators, provided that equivalent protection of human health is provided. From a practical perspective, significant epidemiological and/or risk-based verification of alternative indicators typically would be required for such a standard to be adopted. See Section 7 for additional discussion and nuances.

of *E. coli* (O157:H7) that the public may be familiar with due to highly publicized foodborne illness outbreaks.

Water quality standards are expressed in terms of 1) magnitude (numeric value), 2) duration over which the standard is assessed, and 3) frequency of allowed exceedances. In Colorado, the numeric values for *E. coli* allowed in a waterbody depend on the assigned use, which includes existing (E) primary contact recreation, potential (P) primary contact recreation (within the next 20 years), not (N) primary contact, and unclassified (U) recreational use. Most streams in urban areas are assigned existing primary contact recreation standards. Primary contact recreation is defined as "recreational activities where the ingestion of small quantities of water is likely to occur. Such activities include but are not limited to swimming, rafting, kayaking, tubing, windsurfing, water-skiing, and frequent water play by children" (WQCC 2012). Many urban streams in Colorado have limited flows that preclude swimming and boating; however, if the public can access the stream for activities such as wading and water play by children, then a primary contact recreational use is typically assigned. Table 1 summarizes the numeric values associated with Colorado's currently applicable recreational water quality criteria. These standards are assessed using static bimonthly intervals of January-February, March-April, May-June, July-August, September-October, and November-December.

Table 1. Recreational Water Quality Criteria for Colorado[2]

Use Classification	Description	Standard for *E. coli* (cfu/100 mL)[1]
Class E: Existing Primary Contact	These surface waters are used for primary contact recreation or have been used for such activities since November 28, 1975.	126
Class P: Potential Primary Contact	These surface waters have the potential to be used for primary contact recreation. This classification is assigned to water segments for which no use attainability analysis has been performed demonstrating that a recreation class N classification is appropriate, if a reasonable level of inquiry has failed to identify any existing primary contact uses of the water segment, or where the conclusion of a use attainability analysis is that primary contact uses may potentially occur in the segment, but there are no existing primary contact uses.	205
Class N: Not Primary Contact	These surface waters are not suitable or intended to become suitable for primary contact recreation uses. This classification is applied only where a use attainability analysis demonstrates that there is not a reasonable likelihood that primary contact uses will occur in the water segment(s) in question within the next 20-year period.	630
Class U: Undetermined	These are surface waters whose quality is to be protected at the same level as existing primary contact use waters, but for which there has not been a reasonable level of inquiry about existing recreational uses and no recreation use attainability analysis has been completed. This is the default classification until inquiry or analysis demonstrates that another classification is appropriate.	126

[1]Expressed as a two-month geometric mean in units of colony forming units (cfu) per 100 milliliters. IDEXX test methods reporting *E. coli* in units of most probable number per 100 milliliters (MPN/100 mL) can be compared directly to the cfu/100 mL standard.

As described in the 2026 Listing Methodology (Division 2024), the *E. coli* standard is expressed as the geometric mean of samples collected within a two-month period. To evaluate this two-month criterion, the Division calculates the geometric mean for all *E. coli* data collected within static two-month periods. The static two-month periods are January and February, March and April, and so on through November and December. If samples are available for only one of the months in the period (e.g., samples available from March but not April), the geometric mean for that period is based solely on samples collected during that month. If the geometric mean *E. coli* value exceeds the relevant numeric criterion during any bimonthly assessment period, then the stream is considered to be impaired for recreational use. When calculating the geometric mean, values lower than the detection limit are replaced with 1 and values

[2] Colorado's primary contact standard of 126 cfu/100 mL expressed as a not to be exceeded geometric mean value is consistent with EPA's 2012 Recreational Water Quality Criteria and corresponds to an allowable swimmer illness rate of 36 illnesses per 1,000 exposures. EPA's updated criteria also recommend some additional provisions such as a 30-day assessment period (Colorado uses fixed two-month periods) and adoption of an additional Statistical Threshold Value (STV) not to be exceeded in more than 10% of samples. For *E. coli*, the STV value would be 410 cfu/100 mL if adopted in the future in Colorado.

above the upper quantification limit (e.g., 2,419.6 MPN/100 mL) are replaced with the upper quantification limit. The Division also applies "bias correction" techniques for multiple samples collected on the same date at the same site, portion or segment by taking the geometric mean of those samples and treating the geometric mean as a single sample.

The 2026 Listing Methodology (Division 2024) utilizes the following approach for evaluating *E. coli* data during two-month assessment periods (e.g., May-June, July-August):

- Data sets of five or more samples with a geometric mean concentration above the stream standard are added to the 303(d) List as impaired.
- Data sets with two, three or four samples during the assessment period that indicate impairment of the *E. coli* standard are placed on the Monitoring and Evaluation List. (Note: as a practical matter, many voluntary monitoring programs conduct monthly sampling, so it is common for data sets to have fewer than 5 samples in a two-month assessment interval.)
- Segments with *E. coli* data sets with four samples where there is "overwhelming evidence" of non-attainment are placed on the 303(d) List.

To remove a segment from the 303(d) List, the geometric mean for at least one two-month period that includes at least five samples from the most recent two years of available data in the period of record must demonstrate attainment. To remove a segment from the M&E List, the geometric mean for at least one two-month period that includes at least two samples from the most recent two years of available data in the period of record must demonstrate attainment. For both 303(d) and M&E delistings, the two-month period must fall within the same season as the period that originally triggered the listing. In addition, all other two-month periods from the most recent two years must demonstrate attainment, regardless of sample size (Division 2024).

Although some states (particularly "Beach Act" states) also incorporate a "single sample maximum" standard or a "statistical threshold value" standard, Colorado standards are only based on the geometric mean. However, Colorado has a "Natural Swimming Area" regulation (5 CCR 1003-5) that requires a swim beach to be closed and a public health notice posted if a single *E. coli* sample exceeds 235 cfu/100 mL. The swimming area must remain closed until sample results indicate that *E. coli* levels have returned below 235 cfu/100 mL. A natural swimming area is defined as a designated portion of a natural or impounded body of water in which the designated portion is devoted to swimming, recreative bathing, or wading and for which an individual is charged a fee for the use of such area for such purposes (Division 2015). Most designated natural swimming areas in Colorado are at lakes and reservoirs in state parks. Areas that are free to use, such as Confluence Park near downtown Denver, do not meet the definition of a natural swimming area.[3]

[3] For more information on Swim Beach monitoring, see [Swim beach monitoring | Colorado Department of Public Health and Environment].

1.3 Colorado's Approach to *E. coli* TMDLs

As of 2026, the Division has finalized seven *E. coli* TMDLs in Colorado, including four segments in the South Platte River Basin including Segments 14 and 15 of the South Platte River, Boulder Creek Segment 2b, Big Dry Creek Segment 1, Wildhorse Creek in the Arkansas River Basin and two segments in the Grand Valley that are tributary to the Lower Colorado River. Each of these TMDLs includes unique aspects, although basic requirements for EPA-approvable TMDLs are included in each. To understand Colorado's approach to TMDLs, it is important to be aware of Colorado's TMDL prioritization process, the basic components of a TMDL, integration of TMDL-related requirements into MS4 permits and alternatives to TMDLs, as briefly described further below.

1.3.1 TMDL Prioritization Process

In 2025, CDPHE updated its Colorado TMDL Prioritization Framework describing its general strategy for prioritizing TMDLs and Advanced Restoration Plans (ARPs) for 2024-2032 (CDPHE 2025). Thirteen segments impaired for *E. coli* are included on this list with up to three additional segments included. CDPHE submits its commitments to TMDL and ARP development to EPA every two years. CDPHE's rationale for prioritizing these *E. coli* TMDLs aligns with these objectives:

- Protect public health, especially in shallow urban streams where children play.
- Align with department goals for environmental justice by addressing water quality impairments in areas with disproportionately impacted communities.
- Keep pace with state-scale priorities and goals that support strategic growth.

Additionally, other considerations include identification by the Commission as high priority, opportunities to combine *E. coli* in a TMDL for another pollutant, and location in a sub-basin with no TMDLs to date.

The Division's prioritization process has evolved over time, building on EPA's "National Long-Term Vision for the Clean Water Act Section 303(d) Program" (EPA 2013). EPA's goals include prioritization, engagement, integration, protection, alternative approaches and assessment. The Division's current process invites stakeholder input to recommend candidate water for prioritization as well as for delayed prioritization. See the Division's website for the most current TMDL priorities (https://www.colorado.gov/pacific/cdphe/tmdl-prioritization).

1.3.2 Basic Components of a TMDL

A TMDL is a calculation of the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards, and an allocation of that amount to the pollutant's sources. TMDLs consider both volume of discharge and pollutant concentration to calculate pollutant loads. The basic components of a TMDL include: wasteload allocations (WLAs) for point sources, load allocations (LAs) for non-point sources, and a margin of safety (MOS). A Reserve (RES) allocation may also be allocated to allow capacity for addition of new discharges. Wastewater treatment plant (WWTP) discharges and MS4s are considered point source discharges, with TMDL-related wasteload reductions enforceable under CDPS permit requirements. For non-point sources, load allocations are implemented on a voluntary basis. The basic formula for a TMDL is expressed as:

$$TMDL = \Sigma WLA + \Sigma LA + RES + MOS$$

Where:

WLA = the sum of wasteload allocations (point sources such as permitted wastewater and stormwater discharges)

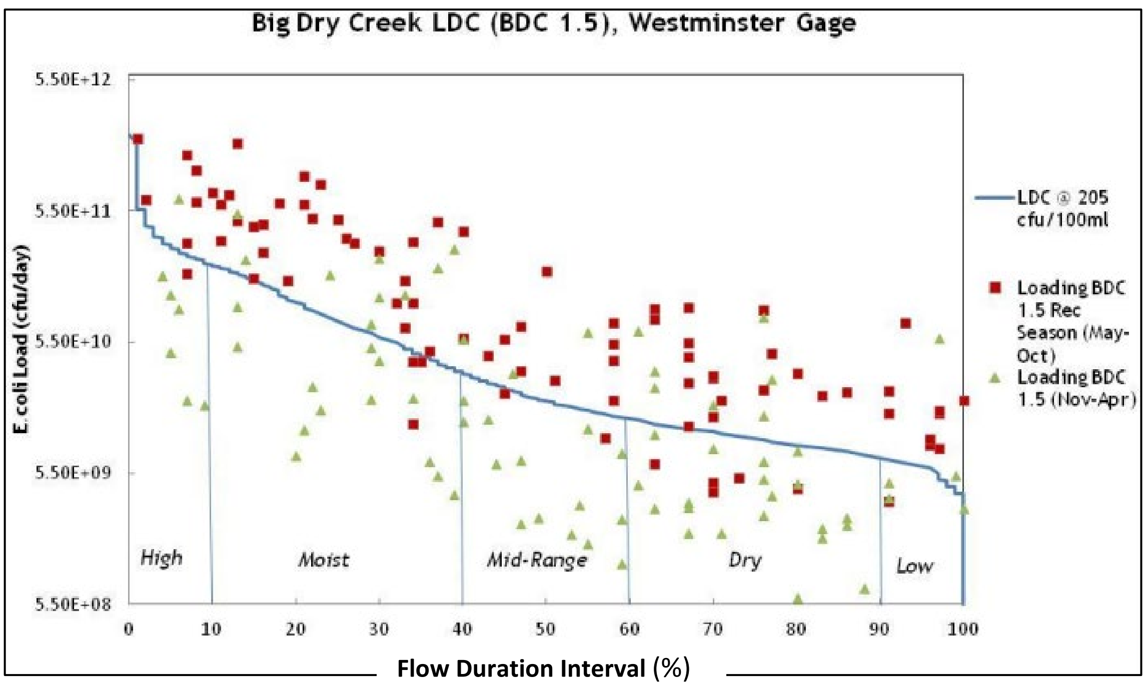
LA= the sum of load allocations (nonpoint sources and background)

RES= reserve load allocations for new development/new discharges

MOS= the margin of safety (typically 10%)

Colorado allows a variety of approaches for development of TMDLs. The most common basic approach is the use of Load Duration Curves (Figure 1), which can be completed using a spreadsheet. For guidance on Load Duration Curves, see *An Approach for the Development of TMDLs Using Load Duration Curves* (EPA 2007). Colorado State University's "eRAMS" Comprehensive Flow Analysis tools (CSU One Water Solutions, updated 2020) also allow simple development of load duration curves (see https://erams.com/documentation/flow-analysis/). Examples of TMDLs completed for *E. coli* in Colorado can be accessed at: https://www.colorado.gov/pacific/cdphe/total-maximum-daily-loads-tmdls. Also see *Protocol for Developing Pathogen TMDLs* (EPA 2001) for more information on the process applicable to *E. coli* TMDLs.

Figure 1. Example Load Duration Curve from Big Dry Creek Segment 1 TMDL: Upper Watershed Portion



Graph Description: The blue line represents the allowable load (flow x water quality standard). Instream loads above that line exceed the allowable load. In this case, fewer exceedances occur during winter months with nearly all recreation season loads exceeding the allowable load. Exceedances occur during both high flow and low flow conditions.

It is generally in the best interest of a community or MS4 permittee anticipating a TMDL to develop a robust data set that can be used to refine the understanding of the source(s) of FIB and conditions under which elevated bacteria occur. Collection of *E. coli* samples is relatively low cost and can be used to bracket reaches of stream where additional source characterization is needed or to limit the portion of the segment identified as impaired included in the TMDL. Over the last decade, use of commercial and other laboratories to conduct microbial source identification using molecular methods allowing enumeration of fecal source-specific DNA has become more reliable and accessible to more communities (i.e., does not require a research laboratory). Although such molecular analyses are relatively expensive (e.g., several hundred dollars per test per sample versus less than $30 per *E. coli* sample), quantitative information related to fecal sources can be useful for crafting more equitable TMDLs and for identifying potential solutions for controlling high priority fecal waste sources. (Note: the highest priority sources for protection of human health may not necessarily coincide with the highest *E. coli* concentrations.) As a medium-cost approach, *E. coli* analyses can be combined with other "flow fingerprinting" techniques to determine sources of flows associated with elevated *E. coli* (CWP and Pitt 2004).

Regardless of the approach selected within the monitoring constraints of a local government, it is well worth the upfront effort to obtain robust monitoring data prior to planning capital improvements or intensive maintenance programs and implementing other programs to reduce *E. coli.* Monitoring programs are typically on a scale of tens of thousands of dollars (or several hundred thousand dollars for large/advanced programs), whereas capital investments are often in terms of millions of dollars. For example, urban case studies in various parts of the country indicate that implementation of *E. coli* TMDL implementation plans or load reduction plans may have costs on the order of $1 to 9 million per square mile of tributary urban area (UWRRC 2014; unadjusted to 2026 dollars).

1.3.3 Integration of Wasteload Allocations into Stormwater Permits

At the time that this Toolbox was updated, requirements for MS4 permits discharging to stream segments with TMDL requirements were changing and becoming more rigorous in response to EPA's directive to include "clear, specific and measurable" requirements in MS4 permits. The Division's MS4 permit website should be visited for the most currently applicable requirements, which vary by permit (https://www.colorado.gov/pacific/cdphe/wq-municipal-ms4-permits).

If an approved bacteria TMDL includes a wasteload allocation and associated wasteload reduction target for an MS4, the MS4 permit will include multiple requirements related to activities such as public education and outreach, source identification, implementation of control measures, monitoring, and additional reporting requirements. Some of these requirements may be practices that MS4s are already implementing under MS4 permit requirements minimum measures" including: Public Education and Outreach, Public Involvement/Participation, Illicit Discharge Detection and Elimination, Construction Site Stormwater Runoff Control, Post-Construction Management, and Pollution Prevention/Good Housekeeping. The Division will amend the permittee's certification if necessary to address additional reporting or documentation requirements to demonstrate compliance with the WLA (Division 2016).

Generally, monitoring requirements in permits focus on the recreational season timeframe of May through October. The most common monitoring requirement is dry weather outfall investigation and sampling. The threshold to be considered a flowing outfall for purposes of sampling in CDPHE-issued MS4 permits is 5 gallons per minute (gpm). Various reporting requirements also apply to document these activities and monitoring results. Monitoring is discussed further in Section 2.3.

Although implementation of numeric effluent limits at end of pipe is allowed in MS4 permits, to date, this approach has not been implemented in Colorado other than in the Denver MS4 permit (due to the unique characteristics of the Segment 14 TMDL) and is not required by EPA. A shortcoming of a numeric effluent limits approach is that some of the most effective strategies for reducing *E. coli* loads include volume reduction, which are not necessarily reflected on a concentration basis.

At a national level, recent litigation reaching the Supreme Court related to San Francisco's MS4/CSO National Pollutant Discharge Elimination System (NPDES) permits has further defined what MS4s can be held responsible for regarding TMDLs in MS4 permits. Specifically, the U.S. Supreme Court issued a final decision on March 4, 2025, reversing the Ninth Circuit and holding that the Clean Water Act does not allow EPA to impose generic receiving water ("end result") requirements in NPDES permits. The ruling has significant implications for bacteria TMDL implementation in permits because it clarified that EPA cannot impose generic receiving water ("end result") requirements in NPDES permits. The ruling clarified that EPA cannot:

- Hold an MS4 or CSO liable solely because ambient bacteria standards are exceeded.
- Enforce permits where compliance depends on factors outside the permittee's control.
- Rely on narrative "cause or contribute" language without defined limits or actions.

Implications for what permits must include are that the <u>permit</u> must now:

- Regulate what is discharged, not ambient receiving water conditions.
- Include clear, enforceable effluent limits, BMP requirements, or implementation actions.
- Preserve the "permit shield" for compliant MS4s (meaning that if an MS4 is complying with its permit requirements, then it is considered in compliance).

The Court explicitly recognized that bacteria water quality outcomes are often outside MS4 control, stating that permittees cannot be punished for other upstream sources, wildlife and sediments and regional hydrology factors. Conversely, permits need to clearly state requirements, consistent with the "clear, specific and measurable" direction set by EPA. As a result of this litigation, permit requirements in California are evolving to approaches that shift from "outcome-based compliance to action-based compliance" with representative permit conditions including:

- Defined BMP menus
- Implementation plans tied to TMDL WLAs
- Milestones and schedules of compliance
- Demonstration of progress in lieu of numeric end-of-pipe limits

In summary, the general shift in permit language as a result of the Supreme Court decision is expected to be toward reasonable enforceable actions rather than instream ambient exceedances. In general, the Supreme Court decision is aligned with increasing recognition that bacteria loading originates from multiple sources, can be weather-driven, and may be outside of an MS4's operational control. In

Colorado, ongoing MS4 permit renewals incorporate many of these principles and focus on “clear, specific and measurable” requirements.

1.3.4 Alternatives to TMDLs

As described in CDPHE’s Final TMDL Prioritization Framework (CDPHE 2025), CPDHE has the option of developing an “Advance Restoration Plan” (ARP) for impaired waters instead of a TMDL. An ARP is a near-term plan to achieve water quality standards in an impaired water body. States have the option of adopting an ARP “in advance” of developing a TMDL. Impaired waters with an ARP remain on the 303(d) list. If the ARP does not result in attainment of water quality standards, then a TMDL is still required (CDPHE 2025). The only ARP under consideration in Colorado at the time of this 2025 update was for selenium on the Lower Arkansas Segment 1c. Previously this approach had been considered for *E. coli* on Lower Bear Creek but was abandoned.

The primary benefit of this approach, also known as Category 5r, is that it allows resources to be applied directly to reducing loading under this “straight to implementation” approach, rather than for development of the TMDL, which can be a time-consuming, lengthy and expensive process. For MS4 permittees, an added benefit is that the actions implemented are not integrated into MS4 permit requirements while the alternative approach is being implemented. Good candidates for this alternative approach are watersheds where a local government or watershed organization has the ability to implement actions needed to reduce *E. coli* loading and where there is a reasonable expectation that the stream standard could be achieved within the designated timeframe.

EPA's Expectations for Elements in Alternative Restoration Approach Plans
(Source: EPA 2015, Best-Wong Memorandum to EPA Regions)

- Identification of specific impaired water segments or waters addressed by the alternative restoration approach, and identification of all sources contributing to the impairment.
- Analysis to support the implementation of the alternative restoration approach is expected to achieve Water Quality Standards (WQS).
- An Action Plan or Implementation Plan to document: a) the actions to address all sources—both point and nonpoint sources, as appropriate—necessary to achieve WQS (this may include: commitments to adjust permit limits when permits are re-issued or a list of nonpoint source conservation practices or BMPs to be implemented, as part of the alternative restoration approach); and, b) a schedule of actions designed to meet WQS with clear milestones and dates, which includes interim milestones and target dates with clear deliverables.
- Identification of available funding opportunities to implement the alternative restoration plan.
- Identification of all parties committed, and/or additional parties needed, to take actions that are expected to meet WQS.
- An estimate or projection of the time when WQS will be met.
- Plans for effectiveness monitoring to: demonstrate progress made toward achieving WQS following implementation; identify needed improvement for adaptive management as the project progresses; and evaluate the success of actions and outcome.
- Commitment to periodically evaluate the alternative restoration approach to determine if it is on track to be more immediately beneficial or practicable in achieving WQS than pursuing the TMDL approach in the near-term, and if the impaired water should be assigned a higher priority for TMDL development.

1.4 Building a Program to Address *E. coli* TMDLs and MS4 Permit Requirements

Most of the remainder of this Toolbox focuses on tools that MS4s can use to build a program to address *E. coli* TMDLs. The starting place for each MS4 differs based on experience factors such as the existing baseline information, extent of understanding of how and where the MS4 contributes to elevated instream *E. coli*, experience of in-house staff, scale of the MS4 (e.g., a few outfalls to hundreds of outfalls), and other factors. Addressing MS4 permit requirements is an iterative, long-term endeavor. A brief overview of the phases of an MS4 program addressing an *E. coli* TMDL is generally described below, with each component described in more detail in the remainder of this Toolbox.

1.4.1 Getting Started and Understanding the Problem

An early-stage *E. coli* control program begins with getting organized, getting the right people to the table, compiling information to form hypotheses about potential sources, and formulating a plan. Representative activities include:

- Identify who needs to be involved – stakeholder engagement. One of the most important aspects of formulating and implementing an effective plan to reduce *E. coli* loading is to get the right people to the table. This includes individuals who have knowledge of watershed conditions, those who are already implementing controls that may help to reduce *E. coli*, and those who are affected by the *E. coli* impairment, as a few examples. Figure 2 identifies potential partners who may be able to support TMDL development and implementation.

- Develop or retrieve relevant GIS mapping/inventory (e.g., outfalls, storm network, key features).
- Begin or continue public education and outreach (e.g., website/social media on pet waste).
- Conduct illicit discharge detection and elimination (IDDE)/dry weather screening (*E. coli* grab samples/flow estimates) to identify outfalls of concern and develop hypotheses for potential sources.
- Continue program requirements for post-construction and good housekeeping control measures to minimize wet weather contributions of *E. coli*.
- Develop a follow-up plan based on the findings of the first few years of effort. The follow-up plan may need to be prioritized and phased depending on the number of stormwater outfalls requiring follow-up.

Figure 2. Partners for Development of Effective *E. coli* Load Reduction Strategies

1.4.2 Mid-program: Sources and Abatement

A mid-stage *E. coli* control program can last for many years as MS4s systematically work through source identification and abatement. Representative activities include:

- Continue IDDE/source investigation (MST markers, if feasible). This may involve phased storm sewershed prioritization (Figure 3) focusing on areas of highest potential human health risk first (see Section 2). Once a problem outfall is identified, it may take several months of in-network sampling to isolate the contributing area for further investigation using CCTV, smoke test, dye test and other techniques.
- Implement targeted source control BMPs (e.g., install pet waste cans, geese deterrents, restaurant outreach).
- Coordinate with sanitary utilities for repair of aging sanitary infrastructure (if applicable) – this may require a multi-year Capital Improvement Program (CIP), interdepartmental process, depending on the extent of repair costs.
- Continue public education and outreach (e.g., pet waste messaging, recreator health signage). Tailor public messaging to include information and understanding gained through baseline monitoring and source investigations.
- Continue post-construction and good housekeeping MCMs.
- Implement an adaptive management approach by reviewing what is and is not working, both in terms of monitoring, source controls and treatment, then revise the program to focus on effective actions.

Figure 3. City of Boulder Example Process for Phased Sewershed Management Plan Development

1.4.3 Mature Program

A mature program may have reached a point that controllable MS4-related sources of *E. coli* during dry weather are addressed. In other cases, a mature program may still be working its way through "sewershed plans" for multiple outfalls. Increasingly, there is recognition regarding what MS4s can and cannot control in terms of *E. coli* loading. It is possible that a mature program has controlled dry weather *E. coli*, maintains a routine infrastructure maintenance and repair program, implements and maintains SCMs, and implements public education and outreach, yet the receiving water still exceeds *E. coli* standards. Practices for mature programs may include:

- Ongoing Implementation: Continue what's working from prior phases.
- Adaptive Management: Review program components and revise as needed to focus on the most effective practices and filling information gaps needed to inform new actions.
- Innovation: Once the "standard" tools and techniques have been implemented, the MS4 permittee may want to consider special studies to better understand bacteria sources, retrofits of existing SCMs, pilot projects and other similar activities.
- Proposing Alternative Standards Protective of Human Health: If human sources have been controlled, then characterization of best attainable receiving water conditions and pursuit of site-specific standards utilizing use attainability analysis and other approaches identified by EPA may be an appropriate step. See discussion in Section 7.3 for EPA (2024) guidance.

2 Finding the Source(s) of *E. coli*

The starting point for effective *E. coli* load reduction is developing a reasonable understanding of the sources of *E. coli* in the watershed, as well as understanding sources of flows transporting *E. coli* to receiving waters. This chapter provides a summary of common sources in urban areas, followed by guidance on source identification approaches. It can be challenging to identify sources and the actual risk to human health associated with the elevated *E. coli*. As one example, a stream segment could be impaired due to a persistent year-round source of *E. coli* associated with leaking sanitary sewer infrastructure or illegal sanitary-storm drain connections, posing a clear human health risk. As another example, a stream could exceed the standard due to birds nesting on bridges (Sejkora et al. 2011; Pendergrass et al. 2013, 2015). The human health risk from scenarios such as these would be expected to differ (Schoen and Ashbolt 2010, Soller et al. 2010b) as would the expected abatement actions, reinforcing the importance of understanding FIB sources.

2.1 Common Sources in Urban Areas

In order to develop an effective plan for managing and reducing FIB in urbanized areas, it is first necessary to identify the likely sources and associated transport pathways to receiving waters. Effectively targeting source controls requires substantial information about the land uses and activities within the watershed. Sources of pathogens and FIB in MS4s and receiving waters vary widely, originating from both non-human and human sources. Representative sources of FIB in urbanized areas in Colorado may include SSOs (sanitary sewer overflows), wet weather (stormwater) discharges from MS4s, illicit connections to storm drain systems (e.g., sanitary sewer connections to the storm drain), illicit discharges to storm drain systems (e.g., power washing bird droppings), failing or improperly located onsite wastewater treatment systems (septic systems), wastewater treatment plants (if not meeting discharge permit limits), urban wildlife, domestic pets, agriculture, and other sources. Allowed discharges to MS4s such as irrigation runoff and uncontaminated groundwater discharges may also transport FIB originating from other sources. From a regulatory perspective, MS4 permittees are not required to address all of these sources (e.g., non-point sources); however, it is beneficial for MS4 permittees to have a broad understanding of the diverse sources of FIB that may be present in impaired waterbodies that receive discharges from the MS4. Table 2 provides a summary of potential FIB sources that communities should consider, depending on the conditions potentially present in a watershed.

Although agricultural sources are not the focus of this Toolbox, both livestock and manure management can be agricultural sources of FIB in watersheds where MS4 permittees are working toward watershed-scale solutions. Secondary sources of persistent FIB include sediments in receiving waters, biofilms in storm drains and waterbody substrate/sediments, and naturalized FIB associated with plants and soil (Ahmed et al. 2019, Francy et al. 2003, Ran et al. 2013, Byapanahalli et al. 2012, McCarthy 2009, Ellis et al. 1998, Ishii and Sadowsky 2008, among others).

Although some of these sources can be controlled to an appreciable extent (e.g., wastewater discharges, sanitary sewer leaks, illicit connections), other sources are much more difficult to control. These diffuse and often mobile sources include wildlife such as raccoons, beavers, birds, etc., as well as environmental sources, such as the biofilms and sediments that provide a stable habitat for these organisms to persist and reproduce. Properly accounting for and identifying potential sources in a particular area are the first steps in working toward minimizing FIB contributions from controllable sources.

Table 2. Potential Sources of FIB in Urbanized Areas and Adjoining Watersheds

General Category	Source/Activity
Municipal Sanitary Infrastructure (piped)	Sanitary sewer overflows (SSOs)
	Leaky sanitary sewer pipes (Exfiltration) (see Sercu et al. 2011)
	Illicit Sanitary Connections to MS4
	WWTPs (if inadequate treatment or upsets)
MS4 Infrastructure	Illegal dumping
	Illicit sanitary connections to MS4 (*also listed above*)
	Leaky sewer pipes (exfiltration) (*also listed above*)
	Biofilms/regrowth
	Decaying plant matter, litter and sediment in the storm drain system (catch basins)
Other Human Sanitary Sources (some also attract urban wildlife)	Leaky or failing septic systems
	Encampments
	Porta-Potties
	Dumpsters (e.g., diapers, pet waste, urban wildlife)
	Swimmers/bathers, boaters, trail users (e.g., hikers, runners)
	RVs (mobile)
	Trash cans
	Garbage trucks
Domestic Pets	Dogs, cats, etc.
Urban Wildlife (naturally occurring and human attracted)	Rodents/vectors (rats, raccoons, squirrels, opossums)
	Birds (gulls, geese, ducks, pigeons, swallows, etc.)
	Open space (coyotes, foxes, beavers, feral cats, etc.)
Other Urban Sources (including areas that attract vectors)	Landfills
	Food processing facilities
	Outdoor dining
	Restaurant grease bins
	Bars/stairwells (washdown areas)
	Green waste, compost/mulch
	Animal-related facilities (e.g., pet boarding, zoos, off-leash parks)
Urban Non-stormwater Discharges (potentially mobilizing surface-deposited FIB)	Power washing
	Excessive irrigation/overspray & irrigation ditch return flows
	Car washing
	Pools/hot tubs
	Sump pumps/groundwater dewatering
	Reclaimed water/graywater (if not properly managed)
Agricultural Sources (potentially including ranchettes within MS4 boundaries or areas in urban growth boundaries)	Livestock, manure storage
	Livestock, pasture
	Livestock, corrals
	Livestock, confined animal feeding operations (CAFO) (NPDES-regulated)
	Manure spreading, pastures/crops
	Municipal biosolids re-use
	Reclaimed water (if not properly managed)
	Irrigation tailwater
	Slaughterhouses (NPDES-regulated)
Natural Open Space/Forested Areas	Wildlife populations
	Grazing
	Natural area parks, off-leash areas
Other Naturalized Sources	Decaying plants/algae, sand, soil (naturalized FIB), sediment

Note: this table is a Colorado adaptation of work by San Diego County (Armand Ruby Consulting 2011).

2.2 PRIORITIZING SOURCES FOR INVESTIGATION

2.2.1 General Considerations

Given the many sources of FIB in urban areas and some of the challenges associated with definitively determining sources, it is helpful to develop a source prioritization process. Such processes should consider factors such as:

- Human health risk
- Magnitude of loading
- Geographical distribution relative to recreational use locations
- Controllability/ability to implement/ability to leverage other planned projects
- Frequency of standards exceedances[4]

When source identification is prioritized with these considerations in mind, then resources for source identification can be allocated to identify sources with high risk to human health, higher loads, close proximity to actively used recreation areas, sources that could reasonably be controlled if identified, and sources that cause frequent exceedances of standards.

An area of evolving research relates to use of HF183 (human fecal DNA marker) risk-based thresholds (RBTs) to prioritize actions and follow-up investigations based on published Quantitative Microbial Risk Assessment (QMRA) calculations for recreational exposure to untreated sewage. Because HF183 does not have a stream standard, MS4s can use a risk-based threshold for HF183 to make risk-based decisions about highest priority follow-up investigations and abatement efforts. A common range of HF183

Quantitative Microbial Risk Assessment (QMRA)

QMRA is a science-based framework used to estimate the probability of human infection or illness resulting from exposure to pathogenic microorganisms in surface waters. QMRA links measured or modeled pathogen concentrations in rivers, streams, or receiving waters to human health outcomes associated with activities such as primary contact recreation. The approach follows four core steps—hazard identification, exposure assessment, dose–response assessment, and risk characterization—allowing environmental data to be translated directly into estimates of health risk (U.S. EPA 2014; WHO 2016).

QMRA has been widely applied by EPA and others to support risk-based water quality criteria, including the development of recreational water quality criteria and alternative criteria where fecal contamination sources vary spatially or temporally. Work by Soller et al. (2014) demonstrated that pathogen risk in streams is not necessarily proportional to fecal indicator bacteria concentrations and that fecal source type and hydrologic conditions strongly influence instream health risk. As a result, QMRA provides a transparent and defensible tool for evaluating site-specific instream conditions, assessing management scenarios, and supporting risk-based decision making where traditional indicator-only approaches may be insufficient (Soller et al. 2014; U.S. EPA 2025).

[4] List adopted from the Source Prioritization Process prepared by Armand Ruby Consulting (2011) for the San Diego County MS4 co-permittees.

thresholds used to prioritize actions at stormwater outfalls is 500 to 1,000 copies/100 mL (Boehm et al. 2015, Boehm et al. 2019, Orange County MS4 Permittees 2020, HRSD 2017). Some recent research led by SCCWRP suggests lower HF183 thresholds (e.g., 100 copies/100 mL) may be relevant during wet weather for instream (receiving water) concentrations in relation to human health risk when recreating (Lowry et al. 2026), even though higher thresholds are used for outfall screening. Ongoing evaluation of this information in terms of management implications continues in Southern California (Steele 2025). Also, practical considerations are relevant such as decreased recreation during storm events.

It may be beneficial for MS4 managers to explore how other ongoing programs or projects can be leveraged. For example, communities could use drainageway and storm drain outfall inspection and maintenance efforts to meet Community Rating System (https://www.fema.gov/vi/floodplain-management/community-rating-system) requirements for flood insurance and outfall reconnaissance for illicit discharges could be conducted at the same time. Similarly, local governments may also have capital improvement projects planned that allow opportunistic integration of stormwater quality features (e.g., inlet retrofits to incorporate forebays, implementation of curbside bioretention in conjunction with road repaving or bike lane work). Several examples of source prioritization process case studies follow.

2.2.2 Case Studies

Since original publication of the Colorado *E. coli* Toolbox, various case studies are available related to how communities prioritize follow-up and mitigation of potential *E. coli* sources. Several examples are provided below from various parts of the country.

2.2.2.1 San Diego County Prioritization Process

San Diego County developed a consensus-based source prioritization process that leverages local knowledge and provides a framework potentially adaptable to other communities. The process was developed by a work group of San Diego County MS4 co-permittees and their consultants in 2011-2012 (Armand Ruby Consulting 2011) and used to target source control efforts in multiple watersheds across the county. The source prioritization process evolved from work group meetings that initially focused on developing conceptual models for bacteria sources, fate and transport, along with a literature review. Based on the conceptual models and literature review results, the work group focused on developing a process for prioritizing bacteria sources within watersheds. As a starting point, the conceptual models recognized two overarching, categorical distinctions:

- Wet weather vs. dry weather conditions
- Watersheds (including MS4s, creek and river systems) vs. lagoons (including beaches)

Second, the work group recognized that bacteria sources should be identified by their relationship to human activity and established the following broad categories for bacteria sources:

- Human origin (i.e., from the human body)
- Anthropogenic, non-human origin (resulting from human activities, but not the human body)
- Non-anthropogenic origin (independent of human activity)

Building on these initial frameworks, the work group developed a rating system using a spreadsheet tool to prioritize efforts. In its initial meetings, the work group produced a lengthy list of potential bacteria sources, which was used to inform construction of the conceptual model diagrams. The source list was sub-divided into the three main source type categories (human, anthropogenic non-human, non-anthropogenic). Only sources with a potential pathway into an MS4 or a receiving water (e.g., creek, river, lagoon, or ocean) were included on the list. The potential sources were further aggregated according to common characteristics. The draft lists of sources were then incorporated into conceptual model diagrams. To support the goal of reducing discharges of pollutants in urban runoff to the maximum extent practicable (MEP), the work group agreed it was important to prioritize sources for further investigation regarding possible application of BMPs (either source controls or local/regional treatment controls).

The work group agreed that prioritization criteria ought to include additional factors other than simply magnitude alone. Temporal variation (dry vs. wet weather) was identified as a top-level consideration and led to a decision that the prioritization process would be performed separately for dry weather and wet weather sources. Table 3 lists factors considered in the source prioritization process, aggregated under the following general themes described in Section 2.2.1 (Human Health Risk, Magnitude, Geographical Distribution, Controllability/Ability to Implement, Frequency of Exceedances).

From this exercise, a quantitative ranking scheme was developed for the relative scoring and ranking of sources within a given watershed. The five themes listed above were identified as the factors that would be used in the scoring matrix that was developed into a spreadsheet tool, with example output provided in Table 4. Human health risk and magnitude were identified as the most important of the five thematic factors for bacteria source prioritization. Within the scoring scheme, these two factors were given the highest weight, with possible score ranges of 1-10. The other three factors (geographical distribution, controllability, and frequency) were allocated possible score ranges of 1-5. Because of the primary importance of the source type (human, anthropogenic non-human, non-anthropogenic), this factor was given the role of then providing an overall weighting for the source score. The weighting factors for this tool were:

- x 5 for human sources (bacteria derived from the human body)
- x 3 for anthropogenic (resulting from human activity), non-human sources
- x 1 for non-anthropogenic (natural) sources
- x 0 for sources with no apparent transport mechanism from source to MS4 or receiving waters

Table 3. Factors Considered in a Source Prioritization Process

(Adapted from San Diego Co-permittees, as summarized by Armand Ruby Consulting 2011)

SOURCE CATEGORIES
TEMPORAL/FLOW CONDITION
Temporal distribution of sources: wet weather vs. dry weather
PRIORITIZATION CRITERIA HUMAN HEALTH RISK
Potential for human pathogens to be present
Potential for human exposure
Dose
MAGNITUDE
Concentration and/or loading
Frequency of occurrence
Variability
GEOGRAPHICAL
Spatial distribution of sources: discrete locations (can map location) or spread out or distributed (e.g., pet waste, soil)
Proximity to Primary Contact Recreational Uses
Proximity to MS4 impermeable surfaces
Land uses, hydrology, soil types, population (design parameters)
Redevelopment opportunities
Ease of transport pathway to receiving waters
CONTROLLABILITY/IMPLEMENTABILITY
Cost, social impact, technological barriers, organizational barriers
Challenge of changing behavior/culturally
How many application sites for BMPs
Repetitive nature of behavioral changes
POTENTIAL BENEFITS
Ability to maximize human health improvement
Potential for multiple (secondary/additional) benefits
Other water quality issues
Other benefits (e.g., flood control)
Ability to target underlying water quality issues
Consideration of the benefits of source activities (e.g., flood control)
TECHNICAL/DESIGN
Structural: siting, costs, maintenance
Site-specific flow conditions
WWTP capacity for low-flow dry weather diversions
ORGANIZATIONAL
Regulatory imperative
Code barriers, conflicts w/state-federal regulations
Political opposition/pushback; public support/lack
Organizational ease of implementation
Benefit to public (per cost)
FREQUENCY of STANDARD EXCEEDANCES

Table 4. Example Ranking of Weighted Scores for FIB Sources under Dry Weather Conditions Using San Diego Spreadsheet Tool as Applied to the San Diego River
(Source: San Diego Co-permittees, as summarized by Armand Ruby Consulting 2011)

Rank	Human Waste	Dry Score		Rank	Anthropogenic Non-human *(continued)*	Dry Score
1	Sanitary sewer overflows (SSOs)	105		10	MS4s Infrastructure - Biofilm/Regrowth	33
2	Encampments	105		11	Reclaimed Water	30
3	Leaky Sewer Pipes (Exfiltration)	100		12	Green Waste	27
4	Bathers	95		13	Litter	27
5	Boaters	95		14	Outdoor Dining/ Fast Food	27
6	RVs (mobile)	85		15	Grease Bins	24
7	Porta-Potties	80		16	Soil	18
8	Dumpsters	64		17	Livestock	0
9	Trash cans	64		18	Manure Re-use Non-Ag	0
10	Garbage trucks	60		19	Landfills	0
11	Illegal Dumping	56		20	Livestock	0
12	Leaky or Failing Septic Systems	55		21	Manure Re-use	0
13	Illicit Connections	55		22	Irrigation Tailwater	0
14	Illegal Discharges	40		23	Soil and Decaying Plant Matter	0
15	Gray Water Discharges	40		24	Food Processing	0
16	Pools	36		25	Bio-Tech Manure Management	0
17	Hot Tubs	36			**Non-anthropogenic**	
18	Biosolids Re-use	0		1	Wildlife (Birds and Others)	18
19	Landfills	0		2	Wrack line (Flies, Decaying Plants)	18
	Anthropogenic Non-human			3	Plants	16
1	Pets	72		4	Algae	16
2	Rodents (Mice, Rats), Rabbits, etc.	54		5	Soil	9
3	Birds (Gulls, Pigeons, etc.)	54				
4	Garbage Trucks	42				
5	Dumpsters	36				
6	Trash Cans	36				
7	Manure/Compost	33				
8	Vectors	33				
9	Wash water	33				

2.2.2.2 North Carolina: Using MST and GIS to Prioritize Infrastructure Repairs

A University of North Carolina study of the Town Creek Estuary in Beaufort, North Carolina, applied a combined framework of FIB data, molecular MST markers, and GIS-based infrastructure information to rank potential fecal contamination sources. This multipronged method enabled identification of high-priority areas for remediation by linking MST (HF183) signals to local infrastructure vulnerabilities. The study demonstrated how MST can be operationalized for municipal decision-making, infrastructure prioritization, and targeted water-quality interventions (Hynes et al. 2024). This case study supports the inclusion of both traditional water quality measurements and local infrastructure data to support the current need for municipalities to identify, prioritize, and remediate failing infrastructure (Hynes et al. 2024).

Figure 4. Study Area Map for Town Creek Estuary, Beaufort, NC

(Source: Hynes et al. 2024)

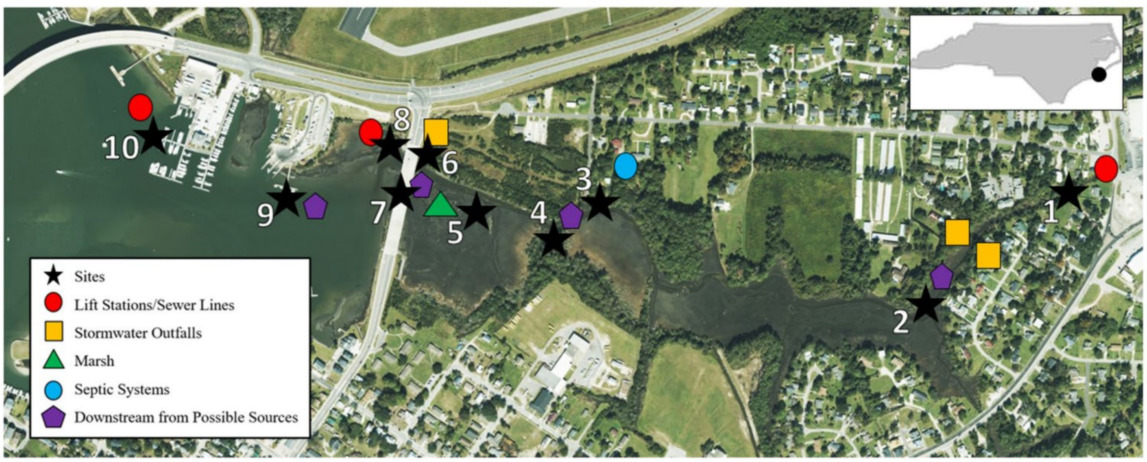


Fig 1. A map of Town Creek Estuary in Beaufort, NC, with the sampling sites denoted with a black star icon. Lift stations and nearby sewer infrastructure are denoted by a red circle icon; stormwater outfalls are denoted by a yellow square icon; marsh is denoted by a green triangle icon; septic systems are denoted by a blue circle icon; and areas downstream from possible major sources of contamination are denoted by a purple trapezoid icon.

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The Town of Beaufort provided shapefiles of the sewer and stormwater infrastructure with attribute information including each pipe's diameter, length, material, and date of construction. The attribute tables also included the location and date of construction of nearby lift stations and stormwater outfalls. Two models were developed to rank potential sources of fecal contamination: an equal weight model and a variable weight model. Six parameters were included from each site: mean *E. coli* concentration, mean enterococcus concentration, mean HF183 concentration, percentage of pipes in a 400-m radius made of vitrified clay, percentage of pipes in a 400-m radius over 50 years of age, and the inverse of the distance to the nearest stormwater pipe in a 400-m radius. The parameters were ranked at each site, with 10 being the highest concentration, percentage, or inverse distance of the parameter and 1 being the lowest. For the equal weighting model, each parameter was given equal weight, thus the overall site ranking was based on the total sum of the rank of each parameter at each site.

For the variable weighting model, empirical knowledge was used to weight parameters on a scale of 1 to 6 based on whether the parameter indicated the presence of fecal contamination (e.g., FIB, HF183). The highest weight was 6, based on whether the presence of the parameter indicated the presence of human fecal contamination. If a parameter had an equal likelihood of indicating the presence of fecal contamination as another parameter, it was given the same weight and the values of subsequent weights were adjusted accordingly.

By ranking the study sites based on surrounding infrastructure and average FIB and HF183 concentrations, several sites were determined to be most at risk for contributing fecal contamination and were prioritized for review and mitigation.

2.2.2.3 Comprehensive Human Waste Source Reduction Strategy, Orange County, California

This Comprehensive Human Waste Source Reduction Strategy (CHWSRS) Work Plan (Orange County, California, MS4 Permittees 2020) was developed to help guide Orange County, California, stakeholder efforts to address pathogen health risk in the South Orange County Watershed Management Area (SOC WMA). The SOC WMA Water Quality Improvement Plan (WQIP) identified Pathogen Health Risk as a High Priority Water Quality Condition and required the development of a Work Plan. The WQIP is unique in that it explicitly focuses on reducing human health risk at recreational beaches, rather than the traditional focus on FIB levels. Although elevated FIB concentrations may indicate higher potential for human health risks, it is the exposure to pathogens (microorganisms known to cause disease) that can cause illness in recreational water users and threaten or impair beneficial uses.

This Work Plan was developed to focus on reducing human health risk by identifying and eliminating sources of human waste to the MS4, which discharges to the recreational beach areas, through targeted monitoring investigations and abatement actions. While natural sources are expected to contribute to bacterial exceedances, identifying and eliminating human sources is critical to protecting public health. Also, it is widely known that natural sources present a much lower risk to human health and can be difficult (or infeasible) to control. This Work Plan was, therefore, designed to maximize the efficient use of limited resources by focusing on reducing sources of human waste, facilitating collaboration among stakeholders, streamlining and integrating efforts across agencies, and supporting decision-making based on the latest scientific advancements in microbial source tracking. In addition, a summary of current bacteria and human waste abatement strategies was included, as well as potential new and enhanced strategies that could be considered in the future to assist with targeting and reducing sources of human waste.

The CHWSRS utilized a screening threshold of 1,000 copies/100 mL for the human DNA marker HF183 to prioritize outfall investigations, described as follows:

> Based on recommendations from the [CHWSRS] Science Team, the HF183 data analysis was based on an action level of 1,000 copies/100 ml, which represents the density corresponding to the median illness risk of 30 illnesses[5] per 1,000 recreators for sewage contamination of age 2.5 days (Boehm et al., 2018). Receiving waters were considered low risk if zero percent of HF183 samples were >1,000 copies/100mL. If a receiving water was considered at low risk based on this analysis, the associated catchments were assigned the lowest priority. This does not mean follow-up actions will never be pursued within these catchments; however, source investigation and abatement actions would likely be more effective by focusing on higher priority areas.

[5] Colorado adopted EPA's 126 MPN/100 mL standard for *E. coli*, which corresponds to a higher allowable illness rate of 36 illnesses per 1,000 exposures.

2.2.2.4 Hampton Roads, Virginia

Hampton Roads Sanitation District (HRSD) has been using HF183 as the primary human-specific MST marker in HRSD's regional collection-system sewage leak investigations since 2014 across a 120+ square mile area. HF183 is used to distinguish human sewage from non-human fecal sources in surface waters, stormwater systems, and beach monitoring programs in collaboration with Virginia Department of Health. When beaches exceed enterococcus criteria, HRSD analyzes those samples for HF183 using ddPCR to confirm whether human sewage is the contributing source. Positive results above the assay detection limit are interpreted as recent human fecal contamination.

HRSD uses HF183 extensively for dry weather stormwater investigations to locate sewer exfiltration and infrastructure failures. Their process includes starting downstream and sampling upstream following the gradient of HF183 detections, combining this information with GIS information on likely sewer defects for targeted repairs. Multiple sampling rounds increase confidence in the results. Similar to the CHSA threshold, HRSD used an action level of ~1000 copies/100 mL as a flag for significant human contributions. HRSD uses 4200 copies/100 mL as a recreational risk benchmark (based on QMRA by Boehm et al., 2015) For comparison, HF183 in Hampton Roads raw sewage typically ranges from 10^7–10^8 copies/100 mL, providing a local reference condition for sewage (HRSD 2017).

Some of the benefits of this approach include:

- Up to 90% reduction in inspection areas by using MST-first approaches, which provides cost savings.
- Post-repair HF183 reductions of 90–99% confirm successful elimination of human sewage sources.
- Improved risk communication because HF183 helps distinguish human vs. wildlife vs. pet sources, allowing proper management actions.

2.3 Source Identification Methods and Monitoring Considerations

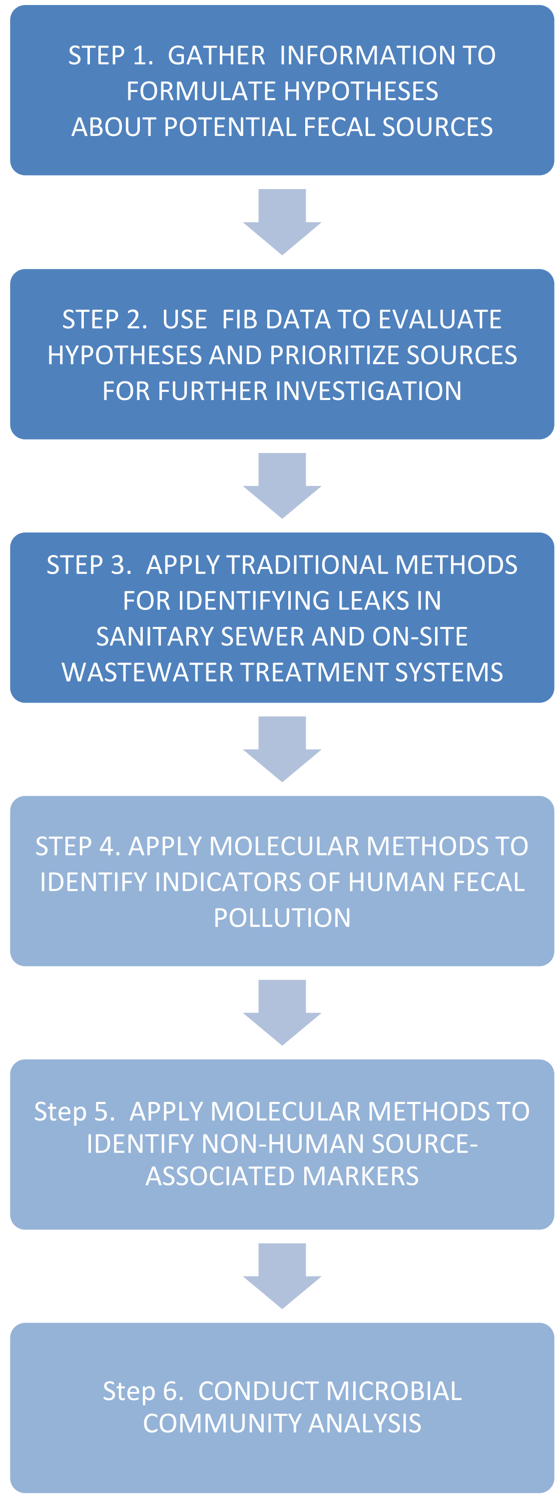
Monitoring strategies to develop an understanding of the sources of FIB can range from simple and relatively inexpensive sample collection and analysis of FIB and basic water quality parameters to more complex microbial source tracking (MST) approaches relying on advanced molecular methods. It is recommended that entities facing *E. coli* TMDLs begin with simple methods to identify and prioritize reaches of the receiving water of concern and then evaluate prioritized reaches based on local infrastructure conditions. If sources cannot be identified through these inexpensive measures, then the use of advanced methods may be warranted, providing additional benefits in terms of determining sources contributing FIB and pathogens to identified critical reaches. Monitoring and source tracking techniques selected may also be affected by budget constraints, regulatory drivers, and available technical expertise.

In urban areas, initial data collection efforts for FIB-impaired streams typically include instream synoptic sampling combined with dry weather screening of storm drain outfalls to identify potential illicit connections to storm drains (CWP and Pitt 2004). Griffith et al. (2013) recommend a six-step process, as summarized in Figure 5. Using this approach, a community would only advance to subsequent steps if the previous step did not provide adequate information to identify sources of FIB pollution with a level of confidence needed to develop management strategies to either reduce FIB or support an alternative regulatory resolution. Steps 1-3 are expected to be feasible in most communities, whereas steps 4-6 represent increasing costs that may or may not be justified, depending on the particular watershed. This section provides an overview of monitoring and source tracking strategies that can be used by local governments, including a variety of methods suitable for a range of budgets and technical expertise. A limited discussion of emerging, advanced techniques is also provided, along with recommended references for more in-depth information.

2.3.1 Basic FIB Monitoring in Impaired Waters

Guidance for basis FIB monitoring is divided into two sections. The first focuses on general guidance and the second focuses on common questions regarding the number of samples needed to assess statistical differences in FIB either at outfalls or in impaired waters.

Figure 5. Six-Step Process of Microbial Source Identification
(Source: Recommendations by Griffith et al. 2013, as presented in UWRRC 2014)



2.3.1.1 General Guidance

The starting point for assessing sources of fecal contamination in receiving waters is to collect basic FIB data to determine which portions of the waterbody have elevated FIB and under what conditions (e.g., summer/winter, wet/dry weather). FIB tests are low-cost and can be conducted in-house by most municipal laboratories. One of the keys to an effective FIB monitoring program is to collect samples with adequate spatial and temporal resolution to target stream reaches where FIB targets are exceeded and to identify where significant FIB loading may be occurring. Synoptic sampling of streams, where an upstream to downstream set of locations is sampled on the same day, is preferred. Both instream sources (such as contaminated sediment resuspension) and watershed sources need to be considered.

Considerations when collecting and interpreting FIB data include:

- Select initial sampling locations to evaluate potential FIB sources. Directly sampling runoff from potential sources allows for the identification of contributing sources or "hot spots" with a minimum number of required samples. Locations may also be selected to bracket potential sources. Examples might include above and below WWTP discharges, off-leash dog parks, areas with heavy bird usage, sewer line crossings of streams, encampments, aging sanitary sewers in proximity to storm drains, etc.

- Extreme variations in FIB concentrations can occur at the same location over relatively short time periods, so multiple samples over time are needed to begin to develop an understanding of potential trends and sources.

- Time of day of sample collection can affect FIB concentrations due to inactivation from natural UV light, flow variations that will affect the transport of bacteria discharged upstream through a sampled reach, and discharge variations of bacteria from potential sources. Early morning samples typically have the highest FIB concentrations.

- Seasonal variations in FIB are common, so erroneous conclusions may be drawn if adequate seasonal representation is not provided (e.g., a stream sampled in winter may meet stream standards, whereas a stream sampled in August may not meet standards). Sampling during dry and wet weather will likely also result in quite different results. When evaluating trends over time, comparable seasonal representation should be present in long-term data sets. An understanding of local hydrologic influences is important, including considerations such as spring runoff from snowmelt, irrigation diversions and return flows, reservoir releases and other factors that significantly affect local hydrology and sources of water comprising streamflows in streams.

- FIB can persist or grow in the environment, so elevated FIB concentrations do not necessarily represent recent fecal contamination. This is particularly true of organic-rich, moist, dark environments such as sediments, decaying organic litter and biofilms. Scour of contaminated sediment and substrate pore water are also known FIB sources.

- Unless exceptionally high, FIB concentrations typically do not provide information on the source of the contamination, so additional investigations or source tracking techniques are often needed to follow up on initial analyses to identify sources.

- When collecting instream samples, be sure not to disturb stream sediment during sample collection. For example, collect the water sample first and then perform flow measurements.

- It can be valuable to collect sediment samples to help determine if sediment resuspension may be contributing to elevated FIB in the water column.

- FIB results are often above or below the analytical quantification range (e.g., <1 or >2,419.6) MPN/100 mL), causing difficulties in data interpretation and statistical analyses. When sewage input is suspected, FIB tests should be conducted at several dilutions, including very high dilutions so that concentrations approaching those found in wastewater influent can be quantified (City of Santa Barbara 2012). Consult with the laboratory prior to finalizing the chain of custody to ensure an adequate range of quantification for FIB.

For standard operating procedures for FIB sample collection, see Standard Methods (APHA 2012) and CWP and Pitt (2004). Sample bottles appropriate to the analytical method should be used and samples should be kept cool (4°C) and quickly transported to the laboratory (6 hours is usually noted as a targeted time period between sample collection and receipt of samples by the lab).[6] In addition to FIB analyses, it is also often helpful to include analysis for other water quality parameters that may help to identify ("fingerprint") human sewage sources and/or conditions that may be contributing FIB growth and persistence in the environment or that can indicate different sources of water contributing to an outfall. Table 5 lists these parameters; most of these analyses can be conducted in municipal laboratories. Field data, including flow measurements or estimates, are recommended for all sample locations. Some or all of the additionally suggested water quality parameters should be considered based on the objectives of the sampling program since they may assist in identification of sources of discharges from an MS4. (See additional discussion in Section 2.3.3.1, Figure 7.) While no single parameter in Table 5 is a perfectly reliable indicator of sewage contamination, a suite of these parameters may provide an initial weight of evidence to identify potential sources or to identify where more advanced molecular methods should be used to confirm sewage contamination. For outfall monitoring programs that plan to utilize human DNA fecal markers (e.g., HF183), then supplemental analyses may be redundant.

[6] Some exceptions apply to the 6-hour hold time, depending on the use of the samples. See UWRRC (2014) for a more detailed discussion of allowance of longer hold times for stormwater sampling purposes.

Table 5. Field and Analytical Parameters for Consideration in Basic FIB Outfall Sampling Programs

Field Data	Basic Analytical Parameters
• Flow (estimate or measurement) • pH • Temperature • Conductivity • Dissolved oxygen (useful instream; less useful for outfalls) • Turbidity (optional) • Color (at outfalls) • Weather conditions • Field observation of sources • Narrative flow condition (e.g., spring runoff, storm flows, reservoir releases)	**Fecal Indicator Bacteria** • *E. coli* **Supplemental Analytes (optional)** • Nutrients[2] (e.g., ammonia,[1] nitrate/nitrite, total Kjeldahl nitrogen, total phosphorus, orthophosphate) • Organic carbon (total and dissolved)[2] • Fluoride[1] (useful for identifying tap water) • Potassium[1] (ammonia/potassium ratio >1 suggests wastewater) • Boron (>0.35 mg/L suggests wastewater) • Hardness • Detergents/Surfactants (typically MBAS)[1,3] • Optical brighteners (or fluorescence)[1]

[1]These may be sampled instream, at outfalls, or both as part of flow fingerprinting related to sources. See discussion Section 2.3.3.1 for additional information on why various analytes are recommended.
[2]Analytes that have been correlated to elevated FIB in some studies.
[3]Methyl Blue Active Substances (MBAS). Involves hazardous reagents.

2.3.1.2 Statistical Analysis Considerations for Sample Sizes for FIB Studies

Due to very high variability of results in FIB data sets, discerning statistically significant trends with acceptable levels of power and confidence is typically not possible without relatively large data sets.[7] Burton and Pitt (2002) and Pitt (2006) provide detailed discussions related to statistical analysis of water quality monitoring, with Figure 6 providing a graph that can be used to estimate the number of sample pairs needed to detect statistically significant differences based on coefficient of variation for the data set and the magnitude of the difference. As a general rule of thumb, 20-30 sample pairs would be needed to detect a meaningful (~2×) difference in *E. coli* stormwater concentrations; substantially more are needed for smaller effects (e.g., a 10-20% change). Applying the information in Figure 6, assuming lognormally distributed *E. coli* concentrations with a $\log_{10}$ standard deviation of 0.7, approximately 34 paired samples are required for normally distributed *E. coli* concentrations with a $\log_{10}$ standard deviation of 0.7, approximately 34 paired samples are required to detect a 0.3 $\log_{10}$ (two-fold) change at $\alpha = 0.05$ and 80% power. For assumptions differing from those in Figure 6, Burton and Pitt prepared a series of graphs that can be used to estimate the number of samples needed to determine statistically significant changes that are accessible in Stormwater Monitoring Guidance prepared for the International Stormwater BMP Database (Geosyntec and Wright Water Engineers [WWE] 2009) or Burton and Pitt (2002). As an example, using the same assumptions, but omitting the power variable, the calculation changes to 15 sample pairs.

Table 6 provides simplified rule of thumb estimates on sample pairs needed. The bottom line is that more samples are needed for FIB for rigorous statistical analysis than for more conservative pollutants

[7] For additional guidance on the number of sampling events needed, useful references include Burton and Pitt (2002) and Chapter 6 of UWRRC (2014).

such as phosphorus. In cases where a major source of FIB loading is identified and corrected resulting in large order of magnitude changes, fewer samples are needed, whereas many more samples would be needed to support statements such as “a 20% reduction in FIB” occurred.

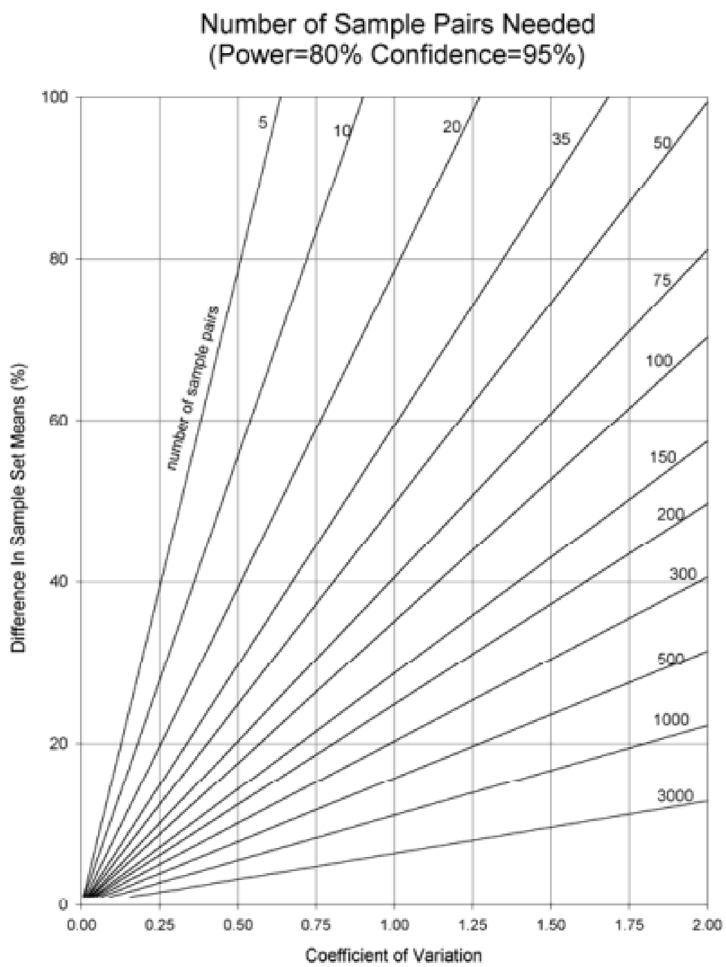
Pragmatically speaking, it is often impractical for MS4s to collect the ideal number of samples for FIB and “weight of evidence” considerations ultimately need to be taken into consideration when undertaking outfall screening. For example, where two independent samples at an outfall indicate non detect or very low *E. coli* concentrations and no corroborating indicators are present, additional screening may not be beneficial. Conversely, if two high concentrations are detected, additional sampling and screening should be pursued.

For MS4 permit compliance and/or Regulation 93 assessments, the number of samples required is specified in the permit or listing methodology. Collection of five samples in a two-month period to calculate a geometric mean is typically the minimum needed for compliance determinations. (See discussion in Section 1.2.)

Table 6. Rule of Thumb Sample Sizes for Determining Detectable Differences
(Derived from Burton and Pitt [2002])

Detectable difference (log10 scale)	Approx. concentration change	Typical paired samples needed
0.5 log10	~3× difference	10–15
0.3 log10	~2× difference	**20–30**
0.2 log10	~1.6× difference	35–50
<0.2 log10	Subtle change	>50

Figure 6. Sample Effort Needed for Paired Testing
(Original Source: Pitt and Parmer 1995)



2.3.2 Source Tracking Toolbox

Once basic monitoring has been conducted to bracket areas of concern instream, then there are many techniques that communities can use to explore and identify sources of elevated FIB in receiving waters. The selection of techniques should be based on initial hypotheses formed from basic FIB monitoring and in most urban areas should include basic dry weather screening of outfalls in stream reaches with elevated FIB. Some of these methods have been available for 20-30 years or more (e.g., Pitt et al. 1993, CWP and Pitt 2004), whereas others include recently published methods that integrate significant advances in microbial source tracking over the last 10-15 years (e.g., Griffith et al. 2013). There are strengths and limitations of both the older and more recent approaches, and each community will need to balance their source tracking objectives with available budget and technical resources. A common sequence of steps utilized by communities such as Boulder, Denver and Fort Collins that may be useful for communities beginning *E. coli* source investigations includes:

1. **Define and map locations of all outfalls draining to the impaired waterway.**
2. **Determine which outfalls are a part of the MS4 by assessing the ownership and flow contributions of the upstream drainage network.**
3. **Conduct initial dry weather outfall screening.** This field reconnaissance effort should characterize all outfalls along the impaired waterway and could be split into different field visits or combined for efficiency to collect the following information:
    - Document or verify physical characteristics of the outfall (pipe size and type). (Ideally, existing utility asset management system data can be loaded into a GIS-based field application like ArcGIS Field Maps enabling verification.)
    - Observe and document evidence of illicit connections (odor, staining, or evidence of sanitary waste).
    - Estimate dry weather outfall flow rate.
    - Collect initial sample for *E. coli* analysis if outfall is flowing.
4. **Conduct follow-up sampling to prioritize outfalls for further source identification based on estimated dry weather *E. coli* loading.** See MS4 permit requirements for required sample numbers, but typically at least 5 samples should be taken for outfalls with dry weather flow rates over 5 gpm. (For non-permit driven efforts, some variation in number of samples can be justified if the first few samples are consistently very high or very low.)
5. **Conduct initial follow-up source investigation at prioritized outfalls to identify whether human sources of FIB are expected to significantly contribute to *E. coli*.** This is commonly done using the HF183 human marker, but other methods can also be used as listed in Table 7. For labor efficiency, such samples may also be collected concurrently with FIB in Step 4.
6. **Create an outfall inventory that integrates collected information.** The outfall inventory could include metrics such as drainage area, land use, physical characteristics of the pipe, above-ground observations and collected monitoring results. Using this inventory, prioritize outfalls for more detailed source investigation, prioritizing human sources.
7. **Map Upstream Pipe Network and Sewershed Characteristics:** Such mapping includes sewershed boundaries, upstream storm network, sanitary and storm networks in the

sewershed, and storm and sanitary condition assessment information available from utility departments. Integrate with GIS and asset management tools for ongoing use in a manner that avoids data loss over time.

8. **Conduct Follow-up Sampling at Outfall and In-network**. At this step, a range of tools can be used to better understand where potential *E. coli* sources are entering the storm network. A variety of tools such as MST markers, flow fingerprinting/chemical tracers, and other tools in Table 7 can be used. For this step, follow-up investigations may need to be phased over a period of years since in-network investigations are often time-intensive and require staff and cooperation from multiple departments or organizations (e.g., a special district operates the sanitary sewer and a county operates the MS4).

Table 7 provides a summary or toolbox of potential source tracking methods, ranging from simple to complex. This table integrates findings from earlier EPA-sponsored work by the Center for Watershed Protection and Pitt (2004) titled *Illicit Discharge Detection and Elimination Manual* and two recently developed key references on source identification approaches that incorporate use of molecular methods. The two latter references include *The California Microbial Source Identification Manual: A Tiered Approach to Identifying Fecal Pollution Sources to Beaches* (Griffith et al. 2013*)* and *Tools for Tracking Human Fecal Pollution in Urban Storm Drains, Creeks, and Beaches* (City of Santa Barbara 2012a&b). The primary purpose of the tools in Table 7 is to identify signals of human waste in streams and storm drains and track these signals to their sources. Several of these techniques are discussed in more detail later in this chapter, but the toolbox of methods is addressed first because monitoring programs should ideally be designed considering the big picture of how a study could evolve to more advanced techniques if simple techniques are unable to identify the source of contamination (i.e., move forward sequentially).

Lastly, budget-related decisions on source tracking approach should consider the benefits that a well formulated source tracking program may provide relative to the projected costs of the actions specified in TMDL implementation plans. In some communities nationally, multi-million or billion dollar implementation plans have been developed to address FIB impairments; thus, substantial benefits may be gained by a well-developed and clearly targeted monitoring program. In some cases, definitively eliminating human sources may enable some regulatory relief for the MS4 permittee. Although this type of relief has not been evaluated in Colorado to date, EPA's Quantitative Microbial Risk Assessment (QMRA)-based option for site-specific standards becomes an option when human sources are largely ruled out (See Section 7.3.2.) In some states such as California, regulatory options based on "natural source exclusions" and reference watershed conditions are also available to dischargers when certain conditions are met.

Table 7. Source Tracking Tools

(Modeled after Tools *for Tracking Human Fecal Pollution in Urban Storm Drains, Creeks, and Beaches*, City of Santa Barbara 2012a&b; supplemented by Pitt et al. 1993, Center for Watershed Protection and Pitt 2004)

Tool	Best Use	Caveats and Challenges	Cost
Visual Surveys of Potential Sources	Encampments, sites with frequent daytime use, under bridges, obvious contamination associated with inappropriate discharges.	Feces often contained in newspaper or plastic bags.	$
GIS	Essential for planning and analyzing data in relation to infrastructure. Useful prior to initial field investigations, as well as for targeting areas for more detailed investigations.	Requires accurate data for both storm drains and sanitary sewers, including pipe materials, elevations and inverts, rehabilitation dates, NASSCO condition ratings, etc., where available.	$
Dry Weather Outfall Screening (Basic IDDE)	Identification of flowing outfalls for water quality sampling, along with physical observations (odor, color, floatables, deposits, stains).	Dry weather flows can originate from both contaminated and uncontaminated sources.	$
FIB (*E. coli*) Sampling	Basic indicator of potential fecal contamination tied to regulatory receiving water limits.	Recommended along with additional chemical or molecular tests. Urban wildlife (e.g., raccoons) may be sources. Biofilms and sediment sources may also contribute to elevated FIB. Extensive sampling required to account for variable results.	$
Human-specific waste markers (e.g., HF183, HumM2)	Best tool for quantifying inputs of human waste. Best for sampling in storm drain outfalls or major nodes in storm drain network. Can be used in streams if no WWTP discharges upstream.	Plan repeated sampling to account for variable results. Requires more expertise and cost. Reclaimed wastewater (both discharges to streams and used in irrigation) may interfere with results.	$$$
Chemical Indicators (Basic Flow Fingerprinting/ Non-human Chemistry)	Finding illicit connections. Good for understanding nutrient inputs from any type of illicit connection. Example indicators include detergents, fluoride, ammonia, and potassium. Others may also be useful.	May not identify direct human deposition (e.g., unsheltered individuals) and small sewage leaks that are significantly diluted by other flows. Background signal of urban runoff can make fingerprinting sewage difficult in some urban areas. Plan repeated sampling to account for variable results.	$
Chemical Indicators (Advanced Markers of Human Waste)	Finding sewage leaks. Advanced analyses may include sucralose, caffeine, and cotinine. May be useful as additional indicators where reclaimed water is present.	Some advanced chemical indicators may be present in the environment from surface deposition, rather than sewage sources (e.g., dumping coffee down storm drains). Plan repeated sampling to account for variable results.	$$$

Tool	Best Use	Caveats and Challenges	Cost
eDNA	Identifying presence or absence of various sources such as humans, birds and mammals in a waterbody. May be useful for an initial screening step in identifying wildlife sources without approved test methods.	Does not differentiate fecal contamination from general source presence (e.g., skin cells, hair included in results). Not comparable to HF183 results. Typically requires follow-up sampling with other methods to identify fecal sources and provide reliable quantitative data.	$
CCTV (Closed Circuit Television) of Storm Drains	Best for use where sampling data suggests sustained input of sewage.	Most operators are trained for sanitary sewer pipe inspection and may seek to clean the lines first. Plan to guide operators to slow down, look carefully at leaks, and do not clean the lines first (in order to see solids on bottom of storm drain).	$$
Basic Dye Test	Best for testing laterals or fixtures feeding a single illicit connection that has been observed by CCTV.	Use bright green dye and a UV light to look for dye in storm drains. Usually applied after an illicit connection or leak is suspected.	$
Dye with Rhodamine Probe	Best for testing suspected sewage infiltration to storm drains when persistent human-waste markers are found w/out observing solids such as toilet paper.	A fluorometer is used to detect much lower concentrations of dye compared to visual testing. Wet weather runoff may create a false positive signal. Usually applied after an illicit connection or leak is suspected.	$$
Smoke Test	Best for limited geographic areas with strong evidence for direct connections (e.g., toilet paper).	Difficult in large pipes and densely populated areas. Usually applied after an illicit connection or leak is suspected.	$$
Electric Current Flow Method	The method uses the variation of electric current flow through the pipe wall to locate defects that are potential water leakage paths either into or out of the pipe.	See ASTM F2550 – 13. Applies only to electrically non-conducting pipes w/ diameters of 3 to 60 in.	ND
Automated continuous flow gauges and autosamplers	Best for outfalls with evidence of higher flows (wet walls, signs of water flowing into creek channel). Supports load estimation.	Check specs carefully to find flow gauges suitable for dry weather flows. Requires confined space entry in most cases. Typically requires experienced staff, frequent field checks and significant maintenance. May be affected by vandalism, sediment accumulation, and floods.	$$ (initial)
Temperature Probes	Can be placed in storm drain outfalls to further verify certain types of suspected illegal connections (e.g., flushing/showering patterns).	Does not identify where the illegal connection is located. More useful in smaller drainage areas.	$

Tool	Best Use	Caveats and Challenges	Cost
Canine Scent Tracking (not commonly used)	Best for use when real time results are desired, such as working up storm drain networks with many branches. Also when broad spatial coverage is sought.	Canines may respond to non-human illicit connections, due to training with detergents. Poor sensitivity and specificity. Requires specially trained canines with trained staff.	$
Microbial Community Approach, e.g., Phylochip, Next Generation Sequencing (NGS)	Best for sampling along a gradient of suspected inputs, (e.g., to test if septage is entering a creek). May provide ability to discern human sources (i.e., sewage vs septage) or identify animal sources for which markers have not been developed or for groundwater, due to low detection thresholds.	Research base has increased in recent years. Still being proven under field conditions. Results are not conducive to simple interpretation by a nontechnical audience. Requires more expertise and cost. This work would typically be conducted by qualified university researchers. (Emerging Advanced Technique)	$$$$

Notes: Cost—increasing $ indicates more expensive techniques. ND = not determined.

2.3.3 Dry Weather Outfall Screening

Dry weather screening is one of the most important tools available to municipal stormwater managers. Identification and removal of illicit discharges and illegal connections may be the single most important action that municipal stormwater managers can take to reduce human sources of contamination. This step is particularly important for MS4s who are beginning a source investigation program.

The Center for Watershed Protection and Pitt (2004) prepared *Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessments* under EPA funding to provide guidance to communities in developing effective management programs and field guidance to reduce illicit discharges. The approximately 200-page manual provides detailed guidance for those embarking on dry weather surveys. The discussion which follows provides a significantly condensed version of steps required to conduct an Outfall Reconnaissance Inventory (ORI) and some aspects of indicator monitoring. ORI field forms, which have been effectively used by many communities, are provided in Appendix D of the Center for Watershed Protection and Pitt (2004) manual (accessible at: http://www.epa.gov/npdes/pubs/idde_manualwithappendices.pdf). The minimum list of monitoring parameters for use in dry weather screening includes flow rate (estimated or measured), water temperature, the regulated FIB parameter, and pH. If a flow-fingerprinting approach is being used, then additional recommended parameters for source fingerprinting include ammonia and potassium (for calculating ammonia/potassium ratios), fluoride, phosphorus, surfactants and/or optical brighteners (as summarized in Table 5). Many municipalities with *E. coli* TMDLs choose to proceed with human DNA markers (e.g., HF183) microbial source tracking techniques instead of the flow fingerprinting approach because they more directly quantify human fecal contamination; however, commercial laboratory fees for DNA markers can be substantial so some MS4s with access to an internal municipal laboratory may still choose to use these supplemental parameters. The basic steps for an outfall reconnaissance inventory recommended by CWP and Pitt (2004) are similar to those introduced in Section 2.3.2 and include:

1. **Collect background data**. At a minimum, this includes an initial map of storm drain outfalls. Other useful information, when available, can include more detailed sanitary and storm drain infrastructure mapping, age-related and maintenance information for the storm and sanitary sewer system, citizen complaints, known hotspots draining to the outfall and other information. As GIS is increasingly used by local governments in many urban areas, a significant amount of

information can be compiled prior to fieldwork. Ideally, the "storm drainshed" and tributary land use should be shown on maps to support field investigations.

2. **Define outfall and sewershed characteristics**. This includes information on the size and pipe material of the outfall, ownership and maintenance definitions, upstream pipe network and land ownership, and other relevant information. Many communities have GIS or asset databases that can be used to support organizing an outfall inventory framework.

3. **Conduct quantitative characterization of outfall flows.** This includes estimates of flow rates and documentation of outfalls without dry weather flow. For techniques useful for measuring or estimating flow rates, see Center for Watershed Protection and Pitt (2004). (Many municipalities combine steps 3 and 5, proceeding with *E. coli* sample collection at outfalls with flows >5 gpm on the initial field visit.)

4. **Assess and document physical indicators for flowing outfalls.** Examples of physical indicators of potential FIB contamination include odor, staining, and evidence of sanitary waste (e.g., feces, toilet paper).

5. **Assess and document physical indicators for non-flowing outfalls.** Visual indicators present at non-flowing outfalls imply intermittent inappropriate discharges, although water samples for analyses may not be available.

6. **Complete initial outfall designation and follow-up sampling actions.** Based on the initial screening activities, flowing outfalls (for practical purposes, the Division defines flowing outfalls as > 5 gallons per minute) with indicators of potential FIB contamination should be sampled several times. If an outfall is identified as possibly contaminated, additional sampling and investigations are conducted along the main storm drainage system to isolate the likely reaches of contamination to narrow the watershed investigations to identify the sources. Several different sampling approaches can be used at this stage, including a chemical tracer approach (discussed below), molecular methods (e.g., HF183 human waste DNA marker), and use of advanced chemical markers.

Prior to discussing various approaches for dry weather investigations, general guidance on dry weather sample collection is important. As is the case with instream sampling, the timing of sample collection from outfalls can affect their results. Center for Watershed Protection and Pitt (2004) provide these recommendations regarding timing of sample collection:

- Sample in the late fall/early spring because outfalls are easiest to spot during leaf-off or dormant vegetation conditions. For *E. coli*, CDPHE targets the May to October sampling, so May or October can be ideal. In Colorado, irrigation runoff is less prevalent before May and after September. Small outfalls draining streamside businesses may be problematic as they are not likely identified on city drainage maps but have been found to be more frequently contaminated than large outfalls in some parts of the country.

- Sample after a dry period of at least 48 hours (trace rainfall activity may be acceptable depending on the size of the watershed). Periods of regional high groundwater should also be included during surveys to identify possible groundwater intrusion sources.

- Sample in the early morning/late afternoon, when practical. Checking outfalls when people are home may increase the chances of catching an inappropriate connection (e.g., flushing, showering).Avoid conditions during snowmelt and/or if salt has been applied to the road system draining to the outfalls. Also note that some tests (e.g., ammonia, chlorine) are affected by cold temperatures or confounded by the presence of salt.

Following initial identification of flowing outfalls and initial FIB sampling, several different source tracking approaches may be used when elevated *E. coli* is present at flowing outfalls. (Note: The presence of a flowing outfall during dry weather does not necessarily mean that pollution is present since uncontaminated groundwater and irrigation-related dry weather flow sources are common in Colorado.) Examples of several approaches that have been used successfully in various locations follow.

2.3.3.1 Flow Fingerprinting/Chemical Tracer Methodologies[8]

A chemical tracer methodology can be used to conduct a mass balance of dry weather flows at an outfall or in a drainage system to identify and quantify the flow sources, including sanitary sewage. It is not specifically used to directly identify the sources of FIB, but the presence of wastewaters and other flows that may be contaminated with FIB. An investigation of non-stormwater discharges into storm drainage needs to proceed along a hierarchy of procedures and locations, progressing from exploratory techniques to confirmatory procedures. The methodology briefly summarized here was developed over many years for the EPA and verified in numerous communities (CWP and Pitt 2004). This procedure recognizes that limited resources are available to municipalities and makes maximum use of information typically available, particularly for communities that do not have budget for a study utilizing human DNA markers (e.g., HF183) to identify sewage.

The purpose of the investigative procedures is to separate storm drain outfalls having dry weather discharges into at least three general categories (with a known level of confidence) to identify which outfalls (and drainage areas) need further analyses and investigations. These categories are outfalls affected by non-stormwater discharges from: (1) pathogenic or toxic pollutant sources, (2) nuisance and/or aquatic life-threatening pollutant sources, and (3) unpolluted water sources. The pathogenic and toxic pollutant source category would be considered the highest priority due to potential human health impacts or significant impacts on receiving water organisms. Nuisance and aquatic life-threatening pollutant sources may include laundry wastes, landscaping irrigation runoff, automobile washing, construction site dewatering, and washing of ready-mix concrete trucks. These pollutants can cause excessive algal growth, tastes and odors in downstream water supplies, offensive coarse solids and floatables, and highly colored, turbid or odorous waters. Clean water discharged through stormwater outfalls can originate from natural springs feeding urban creeks that have been converted to storm drains, infiltrating groundwater, infiltrating domestic water from water line leaks, etc.

Ideal tracers should have the following characteristics:

- Significant differences in concentration between possible pollutant sources;
- Small variations in concentrations within each likely pollutant source category;

[8] The discussion in this section was prepared by Dr. Robert Pitt for use in *Pathogens in Urban Stormwater Systems* (UWRRC 2014) building upon discussions in CWP and Pitt (2004). For more detailed discussion and additional examples, see those reports.

- Conservative behavior (i.e., no significant concentration change due to physical, chemical or biological processes); and

- Ease of measurement with adequate detection limits, good sensitivity and repeatability.

Samples are collected from all flowing outfalls using the procedures described by CWP and Pitt (2004). That report also has detailed guidance on ancillary observations while in the field. The surveys should be repeated several times during the first year as intermittent flows may change seasonally. After potentially problematic outfalls are identified, similar sampling and analyses is conducted at various manhole locations in a drainage system to isolate the reach where the problem flows are entering the drainage system.

Several options can be used to evaluate the collected screening data. A flow chart method (shown as Figure 7) is simple to use and has been shown to be quite accurate. It is also possible to estimate the outfall source flow components using a set of simultaneous chemical mass balance equations. Once problem outfalls are identified, these fingerprinting techniques can be applied to the contributing storm drain system to further focus source identification and correction measures, as illustrated in Figure 8. Hand-held probes for constituents such as ammonia, fluorimeters and other test kits are commercially available that can provide real-time measurements that may be useful in such investigations. For more information on these techniques see UWRRC (2014) or CWP and Pitt (2004).

Figure 7. Flow Chart to Identify Most Likely Significant Flow Component Contributing to Elevated FIB
(Source: Shergill and Pitt 2004, modifies Pitt et al. 1993)

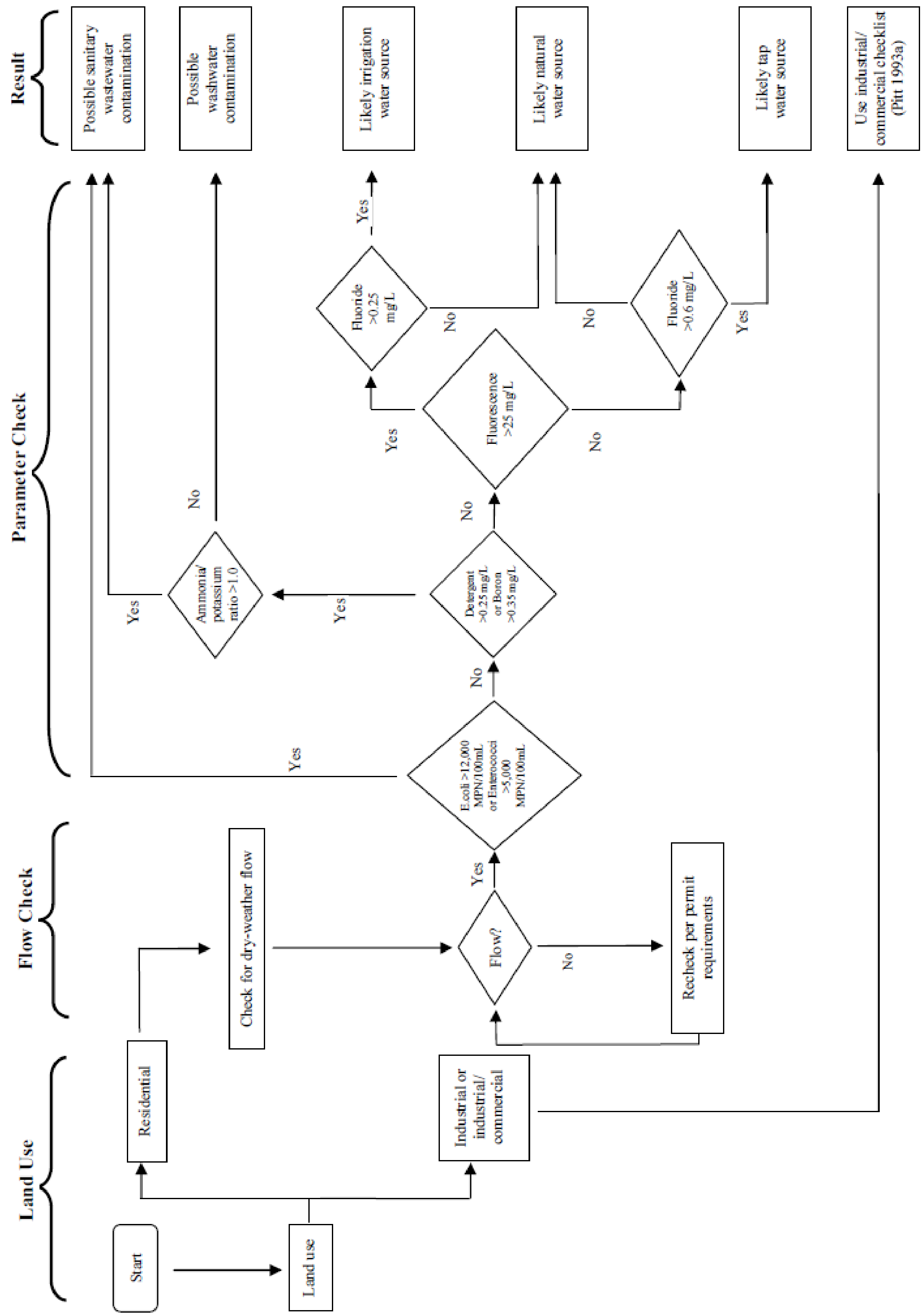
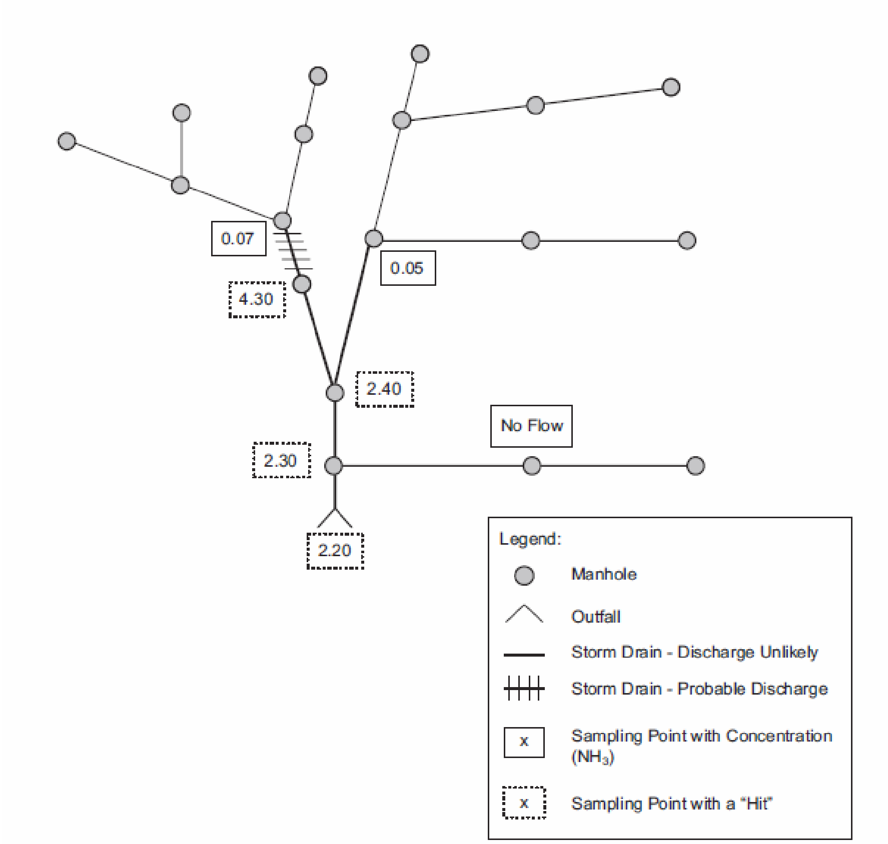


Figure 8. Use of Ammonia as a Tracer to Identify Drainage System Sections Contributing Contaminated Flows

(Source: CWP and Pitt 2004)



2.3.3.2 Advanced Monitoring Using Microbial Source Tracking

Advanced MST tools capable of detecting human fecal contamination are typically employed for one of two purposes: one is implementation-oriented, and the other is oriented to regulatory relief. For implementation-oriented MST efforts, human and non-human fecal markers are used in combination with traditional source tracking tools to evaluate hypothesized sources of fecal contamination (often with samples collected within the MS4 or at an outfall). An example of this is the incorporation of MST markers into enhanced IDDE program activities. The goal of this type of application would be to identify and locate specific fecal inputs into a MS4 and to identify targeted management actions capable of remediating the confirmed sources (i.e., elimination of illicit discharges and/or leaks, or other structural and nonstructural BMPs). Such a project may also incorporate confirmatory sampling within the MS4 or at the outfall to verify successful elimination of human fecal contamination in the discharge after the remedial action is completed. This section describes the use of MST tools for this purpose.

The second, regulatory-focused purpose of MST studies involves use of MST tools to demonstrate the absence (or near absence) of human fecal contamination in a receiving water, often to confirm its eligibility for a site-specific standard (since it is generally understood that the default recreational criteria values are conservatively low for non-sewage impacted receiving waters). In this case, in some states such as California, human markers may be used to support a natural source exclusion request,[9] or they may be used in combination with the direct measurement of pathogens to quantify the illness risk associated with water contact recreation to support the development of risk-based criteria calculated using QMRA. The use of advanced MST tools for QMRA is described in more detail in Section 7.2.

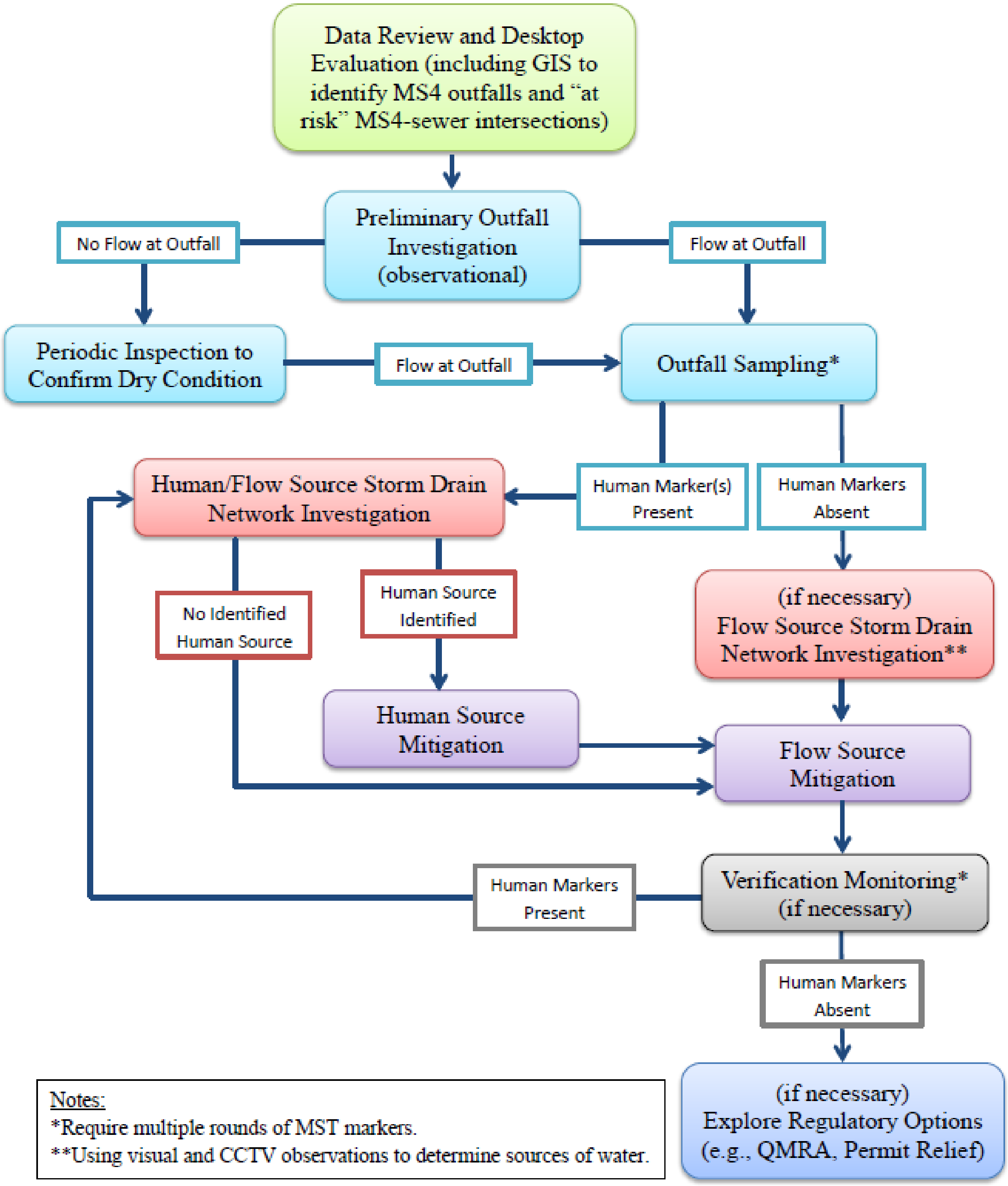
Recent progress in the use of advanced molecular methods as part of a source tracking toolbox has led some communities nationally to move towards routine use of these methods as part of dry weather monitoring at storm drains discharging to impaired waterbodies in urban areas. These methods are able to directly measure source-specific fecal bacteria (i.e., do not require the creation of a library to identify sources). Furthermore, EPA has recognized the increased reliability of these methods for characterizing fecal pollution and is currently developing a standardized method for the measurement of human markers in environmental waters. Two specific methods approved by EPA for human markers include HF183/BacR287 (Method 1696.1) and HumM2 (human mtDNA) (Method 1697.2). For more information on EPA-approved methods, see https://www.epa.gov/cwa-methods/other-clean-water-act-test-methods-microbiological

Many human and nonhuman source-specific markers have been tested and method recommendations for human, dog, gull, cow, and other markers can be found in the California Microbial Source Identification Manual (Griffith et al. 2013) and are accessible through commercial microbiology laboratories as well as at some universities. The use of these advanced molecular markers is a fecal source tracking exercise. Source-specific markers are often not correlated with FIB in the MS4 due to the presence of non-fecal FIB sources (e.g., soil, sediments, decaying plant matter) and non-anthropogenic fecal sources (e.g., wildlife) contributing to the overall FIB concentration measured. Differential decay of markers compared to FIB and FIB regrowth may also result in weakly correlated data.

Figure 9 provides an example flow chart illustrating how such methods can be applied. Initial steps in this process focus on desktop review of available data, including GIS mapping of sanitary sewers and storm drains, to identify potential problem areas. Next, initial field investigations focus on identifying and mapping outfalls with dry weather flows. This approach then moves directly to sampling outfalls with dry weather flows for human markers using molecular methods, with a key objective being to quickly determine the presence or absence of human sources of fecal contamination. Where human markers are identified, then additional investigations regarding sources of the flows are initiated, using a toolbox of methods such as those listed in Table 7. Once sources of human contamination are determined, then mitigation of these sources can begin. Where human sources are absent, it may still be possible to reduce flow sources to reduce *E. coli* loads, in some cases (e.g., excessive irrigation).

[9] Currently, Colorado does not offer a natural source exclusion; however, this may be a topic warranting further exploration. In California, the Natural Source Exclusion Approach recognizes natural sources such as direct inputs from birds, terrestrial and aquatic animals, wrack line and aquatic plants, or other unidentified sources within the receiving waters. The Natural Source Exclusion Approach requires the control of all anthropogenic sources of bacteria and the identification and quantification of natural sources of bacteria. Exceedances are allowed based on residual exceedances due to natural sources.

Figure 9. MS4 Microbial Source Identification Investigation Approach
(Source: Geosyntec Consultants, as presented in UWRRC [2014])



Weber et al. (2013) provide an example application of a microbial source tracking toolbox approach in response to the San Diego River TMDL. A process similar to Figure 9 was followed in this investigation. The regulatory driver for the investigation was the San Diego Regional MS4 Permit, which implements requirements of a FIB TMDL. The requirements focus on dry weather sources associated with TMDL compliance goals, with actions oriented toward prioritizing human fecal sources, as well as "controllable anthropogenic" sources (domesticated animals, etc.). Reconnaissance activities associated with this study included identifying areas with potential for human fecal inputs and categorizing outfalls based on proximity to receiving waters, and sewer mains/septics. As part of the reconnaissance effort, approximately 110 outfalls were visited, with 19 determined to be flowing. Electronic field forms (i.e., a mobile "app" for use on field tablets) were used to document key field conditions and directly associate collected data with GIS mapping of the storm drain system (automatically uploaded to a database), which enabled development of consolidated information. Tabular review of data enabled a "weight of evidence" approach to assess the likelihood of human sources, as shown in Table 8.

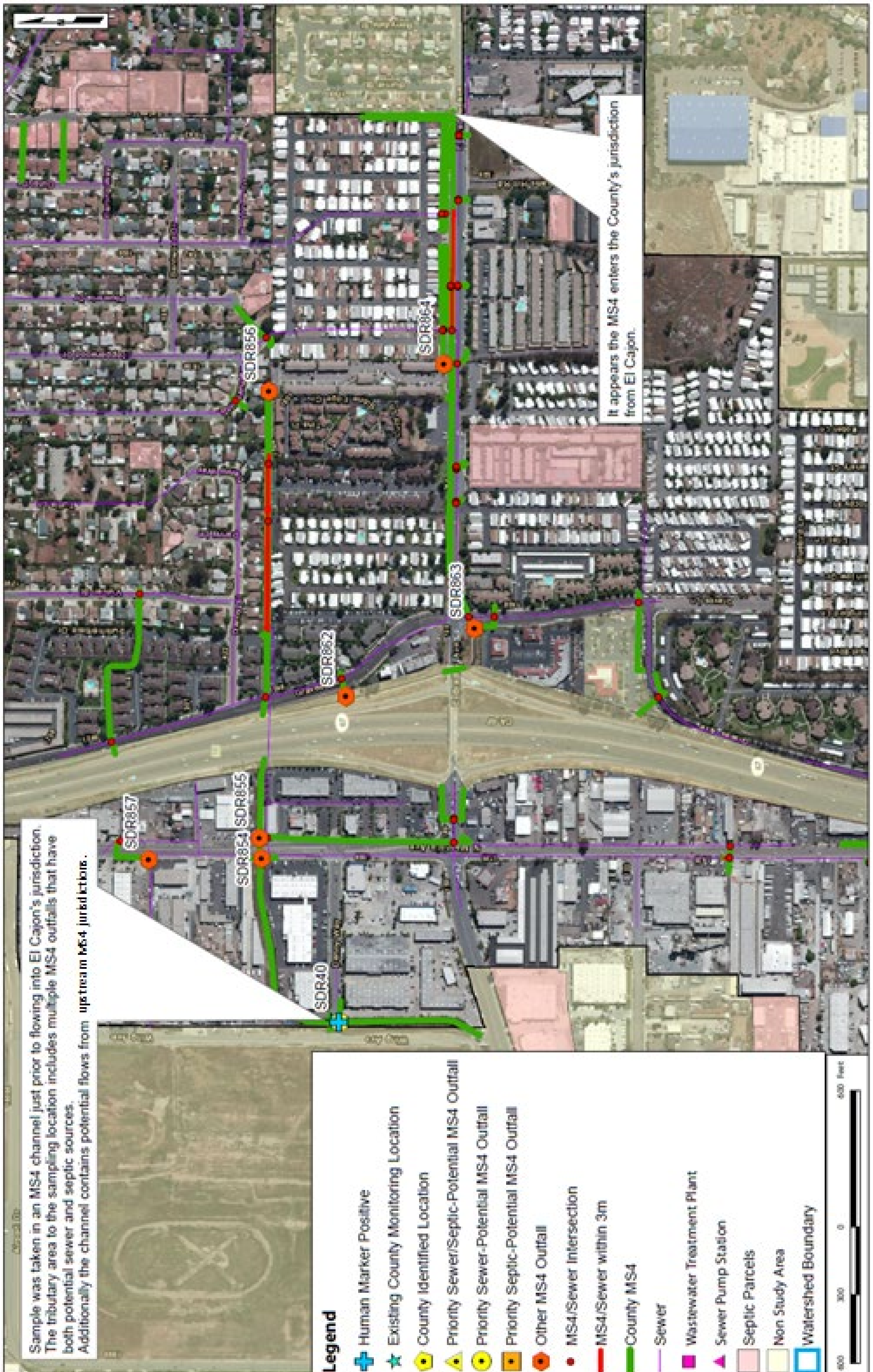
Table 8. Example Tabulation of Results from Microbial Source Tracking Using a Toolbox Approach in San Diego

(Source: Weber et al. 2013)

Outfall ID	Human - HF183	Human - HumM2	Dog - BacCan	Ammonia as N (mg/L)	Total Phosphate as P (mg/L)	MBAS (mg/L)	Caffeine (ng/L)	Cotinine (ng/L)	Sucralose (ng/L)
SDR-13	0	0	0	0.18	0.28	<0.10	310	38	N/A
SDR-15D	0	0	1	0.06J	0.23	<0.10	6.1	4.5	N/A
SDR-35	0	1	0	<0.02	0.03J	<0.10	150	21	1300
SDR-41	0	0	1	0.08J	0.12	<0.10	52	15	N/A
SDR-696	0	0	0	0.15	0.18	1.4	37	13	91
SDR-714	0	0	0	0.18	0.51	0.32	1000	1200	N/A
SDR-739	0	0	0	0.13	0.1	<0.10	46	30	N/A
SDR-751	0	0	0	1.19	1.07	<0.10	32	8.9	N/A
SDR-754	0	1	0	0.2	0.3	<0.10	14	6.1	N/A
SDR-758	0	0	0	1.06	0.18	<0.10	150	6.3	N/A
SDR-760	0	0	0	0.37	0.12	<0.10	2000	96	N/A
SDR-770 & 769	1	0	0	0.13	0.17	<0.10	9.8	<2	73
SDR-774A	0	0	0	0.07J	0.13	<0.10	7.4	<2	34
SDR-780	0	0	0	0.15	0.12	<0.10	1.8	<2	N/A
SDR-791	0	0	0	0.27	0.61	<0.10	67	12	N/A
SDR-825	0	0	1	0.28	0.52	<0.10	60	24	430
SDR-858	0	1	0	0.13	0.04J	0.1	220	130	420
SDR-939	0	0	0						N/A
SDR-999	0	0	0	0.21	0.33	<0.10	88	17	N/A

Note: Rows highlighted in blue detected one or more human molecular markers, also shown as "1" if present and "0" if absent.
Human HF183, Human HumM2, and Dog BacCan are tests for molecular markers.
MBAS is a methylene blue active substances assay, which is a colorimetric analysis test method that uses methylene blue to detect the presence of anionic surfactants (such as a detergent or foaming agent) in a sample of water.
Caffeine, cotinine and sucralose are chemicals commonly associated with human waste.

Figure 10. Example Use of GIS in Microbial Source Tracking Studies
(Source: Weber et al. 2013)



Some of the questions that can be asked using a weight of evidence approach, once data are tabulated, include:

- What is the method sensitivity and specificity (likelihood of false negative and false positive results due to poor detection limits and potential cross-reaction, respectively)?[10] Conducting several sampling events for key markers may help to reduce likelihood of false negatives or positives.

- What are the marker concentrations and frequencies of detection?

- Do the molecular or chemical marker results correlate with FIB concentrations? [11]

- Was the presence of a human marker due to a single fecal contamination event (e.g., a discrete SSO) or representative of persistent pollution (e.g., a leaking sanitary sewer)?

- Do the results match up with visual information (e.g., from surveys, CCTV, dye tests)?

In the example shown in Table 8, the appropriate next steps for the project were determined to be follow-up on the four outfalls where human markers were detected. Activities considered for follow-up included additional investigation of flow sources to and within the storm system networks using techniques such as CCTV and dye testing of the target area, as well as additional sampling within the storm system network for FIB, sucralose, and human markers.

Studies of storm drains in Santa Barbara, San Diego and elsewhere (e.g., Monroe 2009) have consistently found a lack of correlation between FIB and human markers, confirming the understanding that urban sources of FIB are ubiquitous and typically persist even when human sources are controlled. At the same time, these and other recent advanced source tracking studies and ongoing nationwide MS4 IDDE programs have shown that human fecal contamination within urban stormwater infrastructure is not uncommon (Li et al. 2025, Young et al. 2022, Ahmed 2019); therefore, elevated FIB and detectable human waste may be two persistent but separate issues that urban MS4 permittees need to address.

2.3.3.3 MST Study Design Basics

The success of any MST study depends on proper study design. A hypothesis-driven study approach is essential to producing scientifically conclusive results. Numerous examples exist where agencies have conducted poorly planned MST investigations, resulting in inconclusive and unsatisfying results, wasted money, and not met project objectives. These examples reinforce the need for clear study objectives and proper study design to maximize the likelihood of achieving desired project outcomes. To guide proper study design, study hypotheses are generated concerning the potential sources of fecal contamination through the following activities (Griffith et al. 2013):

- Consulting with local experts and other stakeholders with knowledge of the watershed and its potential contamination sources.

[10] The occurrence of false negative and false positive results may be mitigated through the use of validated markers, proper quality assurance and quality control (QA/QC) techniques for sample collection and processing, an experienced source tracking laboratory, and robust technologies such as droplet digital PCR (ddPCR).
[11] Correlations are often not observed due to multiple sources of FIB (human, non-human, and non-fecal) contributing to FIB concentrations.

- Gathering information about MS4 and sanitary sewer infrastructure (e.g., GIS location data, age, material).
- Gathering historical FIB and other relevant monitoring data.
- Conducting field reconnaissance and sanitary surveys.
- Synthesizing all information gathered to generate hypotheses as to the primary sources responsible for elevated FIB concentrations.

Formulated hypotheses as to what sources are suspected and where they are located will then guide the selection of source-specific markers (e.g., human, bird, dog), representative sampling locations (e.g., outfalls, receiving waters, source areas), the number of samples needed, and the timing of sample collection. When infrastructure sources are suspected, it is generally preferable to collect samples as close to the source as possible, thereby reducing the chances of not detecting markers due to sample dilution in the receiving water. Where reclaimed water is used for irrigation, irrigation runoff (e.g., overspray, over-irrigation) may also be a source of human markers (i.e., “dead” or not viable human DNA remaining in the disinfected wastewater). Source samples (e.g., animal feces, reclaimed water) can be collected and analyzed to evaluate the potential for cross-reaction or confounding sources of DNA.

The collection of samples for advanced molecular methods requires that special collection and handling procedures be followed to prevent sample contamination. Similarly to procedures used for FIB sampling, sterile sampling techniques must be used including sterile sample containers and clean gloves being used for each sample collected. Any equipment used to collect samples must be either discarded after use or sterilized between samples (by autoclave or acid washing). While standard sample holding times have not been established for methods using DNA markers, it is recommended that samples for molecular analysis be immediately placed on ice and filtered as soon as possible (e.g., within 6-24 hours of sample collection. Follow instructions provided by the lab analyzing the samples.

Quality assurance and quality control (QA/QC) procedures are also critical during sample processing and analysis. Sample filtration may be performed by those collecting the samples, by the lab performing FIB analysis, or by the lab performing the molecular analysis (water samples can be shipped overnight on ice). To ensure that sterile techniques are being followed during filtration, field or filter blanks (sterile water filtered in parallel with samples) should be prepared and analyzed along with collected samples. Experienced source tracking labs that have participated in multi-lab validation studies (such as those sponsored by EPA and SCCWRP) should be selected for analysis. Molecular analyses performed at these labs should include analysis of control samples including DNA extraction blanks, negative and positive reaction controls, and inhibition analysis. Lab selection will also depend on the availability of desired markers. Several markers including the HumM2 human and CowM2 cow markers require licenses obtained from the EPA for use.

Advanced MST tools are most successfully used as part of a weight-of-evidence approach to identifying fecal sources. The use of two human markers, such as the HF183 and HumM2 markers, can help provide an additional line of evidence that human fecal sources are present or absent. Because these two markers have slightly different molecular targets, a positive detection for both markers gives increased confidence in the results and greatly reduces the chance of false positive results. Additionally, the HF183 marker has been shown to be more sensitive to low concentrations of human fecal contamination, while the HumM2 marker is more specific to human fecal sources (Griffith et al. 2013). If budget allows, it can be useful to use multiple human markers in combination with non-human markers, chemical indicators, and other traditional tools such as dye testing to fully evaluate hypothesized sources. Practically speaking, due to the cost of analyzing multiple human markers, many communities in Colorado that have gained experience with molecular methods utilize the human marker HF183 to identify human waste sources. CDPHE does not currently have formal guidance related to acceptable levels of HF183 for action thresholds identifying the need for further investigation at outfalls.

2.4 Novel Approaches for Differentiating Various Human Sources of Fecal Contamination

In communities that have used MST to confirm human contamination, it is possible that questions still remain regarding the sources of human contamination, which is important for identifying effective control strategies targeting the source(s). Novel research to further partition human sources has been conducted in California, among others. Concept-level introductions to some of this research are provided very briefly below and may be of further interest for mature programs that have identified human sources but have not been able to determine the best abatement strategies due to uncertainties regarding the human source(s).

SCCWRP (Schiff et al. 2025) conducted a five-year study in the San Diego River watershed quantifying the relative contributions of six major human fecal sources during wet weather. The study identified the largest contributors of human fecal contaminations including public sewer overflows (SSOs), exfiltration from public sewer pipes, and onsite wastewater treatment systems (OWTS/septic systems). The minor contributors included private sewer overflows and exfiltration from private laterals. The smallest contributor was from people experiencing homelessness. To support the analysis, researchers collected stormwater samples throughout the watershed and analyzed them for HF183 to confirm the presence and magnitude of human sewage contamination, then paired these data with measurements of sewer system performance—such as documented sewer overflows and assessments of public sewer exfiltration—and information on onsite wastewater treatment systems, private laterals, and encampments. Using this integrated dataset, SCCWRP applied a structured mass-balance approach to "tease apart" the relative contributions of six hypothesized sources.

Additional SCCWRP research has included characterizing the microbial communities present in sanitary sewers and storm pipes using biofilm signatures to differentiate whether a storm pipe is influenced by sanitary flows (Schiff, Steele and Griffith 2023). During wet weather, storm flows were sampled for HF183 and microbial community biofilms. If present, the HF183 confirms there is a human source in stormwater and if a sanitary sewer biofilm community signal is found, then the strength of the signal can be used to assess whether the HF183 is originating from a sanitary sewer.

Another technique is next-generation sequencing (NGS). NGS is a set of "massively parallel" DNA sequencing technologies that generate very large numbers of sequence reads from an environmental sample, allowing characterization of entire microbial communities rather than targeting a single organism or indicator. In stormwater and receiving-water studies, NGS is most commonly applied as 16S rRNA gene amplicon sequencing to describe bacterial community composition ("community fingerprints") and how that composition shifts across space and time. SCCWRP frames these molecular approaches as part of an expanding toolbox for microbial water-quality management—supporting faster, more informative detection and, when paired with other lines of evidence, improved understanding of contamination sources and transport processes. For example, SCCWRP researchers combined culture-based enterococci, digital PCR human markers (e.g., HF183), and 16S community sequencing to evaluate sewage influence along the U.S.–Mexico border shoreline, illustrating how NGS can complement targeted assays by providing a broader microbial-community signature that can be compared to candidate sources (Zimmer-Faust et al., 2021).

NGS results are best interpreted as supporting information for screening, pattern recognition, and hypothesis generation—not as a direct compliance metric—because important limitations affect how data can be used in MS4 decision-making. First, 16S amplicon sequencing typically yields relative abundance (proportions of sequences) rather than absolute concentrations, so NGS alone cannot identify whether bacteria levels exceed standards or quantify pathogen dose without additional measurements. Second, results can be influenced by sample processing and analytical choices (e.g., filtration/extraction methods, primer and PCR bias, sequencing depth, bioinformatics pipelines), which can affect comparability across projects unless standardized approaches and QA/QC are used (Zimmer-Faust et al., 2021). Third, detection of DNA does not necessarily indicate viable organisms or direct human health risk, so SCCWRP implementations typically pair NGS with conventional indicators and targeted human markers to strengthen interpretation and support source investigations (e.g., adaptive sampling with HF183 to pinpoint human inputs in an urban watershed) (Steele et al., 2019).

2.5 MS4 Permit Compliance Monitoring

For stream segments with *E. coli* TMDLs, CDPHE typically requires some type of monitoring to support an understanding of progress towards TMDL goals. The type of monitoring varies based on permit type and renewal date, with individual permits (e.g., Denver, Colorado Springs) and recently renewed permits typically having more stringent requirements. The purpose of this discussion is to provide MS4s with an overall perspective of the costs and benefits of various types of monitoring that may be required or part of a menu of options in MS4 permits. CDPHE (2025) has identified these monitoring goals:

- Characterize baseline conditions so that progress can be measured over time
- Provide information on sources of pollutants
- Measure (evaluate) trends over time
- Assess effectiveness of control measures to address prioritized sources

Table 9 provides an overview of potential permit-required monitoring with additional discussion following based on monitoring type. Some MS4 permits allow for regional coordination of monitoring, which is also discussed. In general, dry weather monitoring is less expensive and has lower staffing and training requirements. Dry weather monitoring is useful for identifying persistent sources of *E. coli*, whereas wet weather monitoring characterizes episodic loading in response to precipitation events. Additionally, dry weather is the dominant condition when recreation is occurring, and some local governments provide targeted public health messaging to discourage recreating with 24-48 hours of a precipitation event.

Table 9. Overview of Permit Compliance Monitoring Approaches

Types	Benefits	Limitations/ Drawbacks	Relative Cost
Instream (Dry weather or ambient)	Hot spots Seasonal trends Temporal trends Attainment evaluation	WLA Reductions may be in the "noise" for *E. coli*	Low to Medium (depends on partners)
Dry Weather Outfall	Source ID/control Prioritize actions Conducive to phased approach	Private property Accessibility Natural sources Number of outfalls	Low-Medium (depends on phasing)
Wet Weather Outfall	Quantify loads relative to TMDL WLAs	"Known" information—unlikely to direct new actions Safety/Equipment/Training	High
Wet Weather BMP/SCM Effectiveness	Identify best performing practices/design improvements	Skill/equipment/training	High
Wet Weather Instream	Assess whether wet weather attains standard Trends over time (if long-term monitoring program)	"Known" information—unlikely to direct new actions Skill/Training Safety/Equipment	High

2.5.1 Instream (Dry Weather or Ambient)

Instream dry weather or ambient monitoring are common among many watershed organizations and collaborative multi-jurisdictional municipal and county programs. Dry weather programs may specify a dry-weather antecedent condition such as 72 hours, whereas ambient programs monitor conditions that happen to occur on the planned monitoring day (e.g., third Thursday of the month). Most of the streams with *E. coli* TMDLs on the Front Range are part of such monitoring programs, which typically include *E. coli*. Monitoring frequencies for these programs vary but typically include a minimum of monthly grab samples during the recreation season. Some programs monitor weekly and others monitor monthly year-round. In some cases, programs have chosen to monitor weekly for a limited time period and then reduce the frequency to monthly if no significant new information was being gleaned from the more intensive monitoring frequency.

Representative Front Range Regional Monitoring Programs

Arkansas Fountain Coalition for Urban River Evaluation (AF CURE)

Barr Milton Watershed Association

Bear Creek Watershed Association

Big Dry Creek Watershed Association

Cherry Creek Basin Water Quality Authority

Joint Task Force – Phase 1 MS4s & MHFD

Keep It Clean Partnership (Boulder County)

Lower Poudre Monitoring Alliance

South Platte Coalition for Urban River Evaluation (SPCURE)

A benefit of collaborative or regional monitoring programs is that they provide opportunity for cost-sharing among multiple local governments, either through in-kind staff labor and in-house laboratories or through cost-sharing for consultant contracts. In some cases, the monitoring and analysis is done in-house by staff and a consultant is hired to statistically analyze collected data. Additionally, as a stream crosses multiple municipal boundaries, the monitoring methods and sampling dates are consistent. For example, Big Dry Creek Segment 1 crosses eight city/county jurisdictions over a 34-mile length of stream subject to an *E. coli* TMDL. City staff and laboratories collect and analyze the data with consultant support for annual analysis and database maintenance. A collaborative monitoring approach has enabled an over 25-year water quality record using consistent monitoring and analysis protocols.

Instream dry or ambient based monitoring program components typically include grab samples at fixed locations so that trends can be evaluated spatially, temporally and seasonally. As a companion to water quality sampling, flow measurements (either with a flow meter or downloaded from a stream gauge), weather (e.g., precipitation, temperature), field parameters and field observations (e.g., dense geese presence) are important. Additionally, these monitoring programs can be used to identify "hot spots" where *E. coli* concentrations change spatially or temporally, helping to identify areas warranting more in-depth evaluation. Example sampling and analysis plans, including sample collection procedures are readily available through multiple websites for existing regional monitoring programs (e.g., Keep It Clean Partnership, Big Dry Creek Watershed Association). A written sampling and analysis plan and quality assurance project plan (SAP/QAPP) should be developed and followed for instream monitoring programs.

Topics covered in regional instream monitoring programs (and other types of monitoring programs) should include information on sample locations, sample collection methods, analytical methods and hold times, chain of custody requirements, and quality assurance samples such as field blanks and replicates. Although several analytical methods can be used for *E. coli*, the most common EPA-approved method currently used on the Front Range for *E. coli* is IDEXX Colilert Quanti-Tray/2000. Hold times for *E. coli* are 8 hours with a 10 °C storage temperature; this includes 6 hours from sample collection to the laboratory, which may require samples to be dropped off by mid-afternoon to meet the 8-hour hold time. In some research contexts, longer hold times may be acceptable (Harmel 2016).

A limitation of instream monitoring programs for FIB is that at some point the baseline is characterized and there is a need to shift to outfall sampling or other special studies to identify potential controllable sources of *E. coli* and to identify the nature of the sources (e.g., human, bird, dog). Once sources are abated, long-term instream monitoring can also be used to assess how the stream responded to abatement activities.

2.5.2 Dry Weather Outfall Monitoring

Dry weather outfall monitoring is a key component of assessing whether persistent sources of fecal contamination are originating from stormwater outfalls. This topic is discussed in detail in Section 2.3 of this Toolbox. Depending on the MS4 permit, CDPHE specifies triggers for dry weather outfall monitoring for *E. coli* that include dry weather flows greater than 5 gpm. The number of samples required is specified in the relevant MS4 permit but typically requires a minimum of five spaced approximately weekly. Dry weather *E. coli* sampling is the first step to determine whether more in-depth source identification (e.g., CCTV, DNA markers) is needed in the basin tributary to the outfall. Dry weather monitoring can often be staffed internally with consultant support as needed, depending on the scale of the dry weather sampling. For example, some MS4s have only a few outfalls whereas other MS4s may have over 100 outfalls discharging to multiple *E. coli*-impaired or TMDL segments.

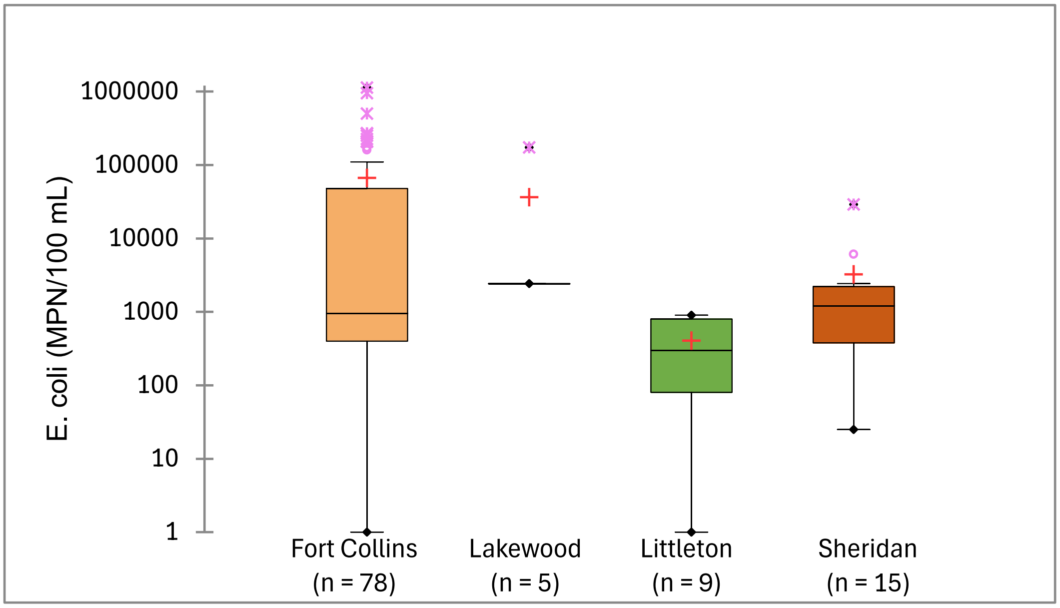
The study cost for dry weather outfall screening varies widely but can range from $10,000-$50,000 for a limited number of outfalls for *E. coli* and flow estimates only to $100,0000-$200,000+ if a large number of outfalls are monitored with supporting GIS documentation, report preparation and follow-up sampling for human DNA markers. A $500,000 dry weather study could be within range for a large system with multiple sampling events and DNA markers. Factors to consider when budgeting for dry weather screening include: availability of reliable outfall mapping in GIS, staffing approach (internal, consultant, combination), accessibility, number of sampling events and in-house vs. commercial laboratory services. Accessibility of outfalls can increase costs if outfalls are not accessible by bike path or car or have complicated private property access issues. Staff training for grab sample collection is straightforward; however, training is often needed for estimating or measuring flows.

2.5.3 Wet Weather Outfall Monitoring

Where permit conditions allow flexibility for designing wet weather monitoring programs, it is important to clearly define monitoring objectives to make the most of the monitoring. Some general "known" characteristics of *E. coli* in urban stormwater runoff include:

- *E. coli* is typically ubiquitously high in urban runoff, typically at least one to two orders of magnitude above the stream standard (Figure 11).
- *E. coli* in urban runoff is highly variable, also often spanning an order of magnitude or more. This can be the case even for a relatively simple land use like a parking lot, using the Fort Collins data set shown in Figure 11 below with *E. coli* results spanning 1 to 1,130,000 MPN/100 mL.
- *E. coli* and other FIB do not necessarily have a first flush effect. Some researchers have found that the highest *E. coli* occurs later in a runoff event. For this reason, individual grab samples may result in both underestimates and overestimates of *E. coli* concentrations and loading.
- Some stormwater SCMs may reduce *E. coli* but effluent concentrations typically cannot consistently meet stream standards at end of pipe.
- Unique considerations for monitoring *E. coli* relative to other pollutants include factors such as more stringent hold times, refrigeration and earlier lab delivery windows. For these reasons, *E. coli* is sometimes omitted from wet weather monitoring programs or discontinued after some point, as was the case with the Joint Task Force (JTF) monitoring program, described in an upcoming section.

Figure 11. *E. coli* in Urban Runoff from Several Urban Areas along Colorado Front Range
(Data Source: International Stormwater BMP Database 2025, inflow data sets)



2.5.4 Wet Weather SCM Effectiveness

Inlet and outlet flow and water quality sampling for SCM effectiveness along the Colorado Front Range could expect to collect potentially 5-8 events per year, depending on weather and timing of events relative to lab hours (weekdays) and staff availability. In some years, three events may be realistic based on monitoring experience of MHFD and others. For SCM sampling using a paired inflow-outflow design, then two autosamplers and water level sensors would need to be installed and calibrated, with a 2025 order of magnitude cost estimate of approximately $30,000 per SCM site. Lab analysis costs vary based on constituents analyzed and whether an internal or commercial laboratory is used. *E. coli* analysis alone is typically <$35/sample but the cost for a full suite of analytes and sample collection can often range higher, depending on constituents analyzed and lab used. A rule of thumb for SCM monitoring is roughly $60,000/year. To conduct performance and trend analysis, seasons of monitoring are likely needed to get 15-20 events; therefore, ballpark costs for an SCM study are on the order of ~$200,000+ for a 3-year study.

2.5.5 Wet Weather Instream

Wet weather instream monitoring has similar logistical and cost challenges to wet weather outfall sampling. Prior monitoring efforts both locally and throughout urban areas in the U.S. show that FIB are elevated in urban runoff. For this reason, it is typically not worth the cost to conduct general wet weather instream monitoring if the monitoring objective is to simply answer whether *E. coli* is elevated in urban runoff. Additionally, the magnitude of exceedance of recreational water quality criteria can be estimated at one to two orders of magnitude higher than the stream standard of 126 cfu/100 mL with large standard deviations. Large intra-storm variability is also well documented, limiting the value of single grab samples (Ahmed et al. 2019). Two examples of wet weather monitoring are described below.

2.5.5.1 *Regional Wet Weather Instream Monitoring Case Study: Joint Task Force*

The most comprehensive wet weather instream sampling program in Colorado that has included *E. coli* has been the work of the Joint Task Force (JTF) that includes Phase 1 MS4 permittees in the Denver Metro area with support from MHFD and the U.S. Geological Survey (USGS). In 1993, the City of Aurora, the City and County of Denver, the City of Lakewood, and the Urban Drainage and Flood Control District (UDFCD) formed the JTF to coordinate efforts regarding the NPDES Phase I permitting requirements and the related goals of the three municipalities. In 1997, one of the principal functions of this group became the annual monitoring of wet-weather water quality in the receiving streams to study the impact on those streams as the result of stormwater runoff from the communities. FIB were included in the program for a number of years, with findings for 2001-2005 provided in USGS Scientific Investigations Report 2008–5134 (Bossong and Fleming 2008), which includes a description of the monitoring methods and detailed statistical analysis results. The report describes the quality of stormwater sampled from October 1, 2001-October 11, 2005. Time-weighted composite stormwater samples were collected by compositing individual aliquots of stormwater that were obtained at fixed time increments typically during 12-hour intervals; bacteriological samples were collected manually from streams during some storms. Monitoring locations included three stations on the South Platte River (Union, Denver, and Henderson), Sand Creek and Tollgate Creek. FIB including *E. coli* and fecal coliform consistently exceeded numeric standards in all samples (Bossing and Fleming 2008).

Key observations for *E. coli* from this data set summarized in Table 10 and Table 11 include:

- Instream samples collected under wet weather instream conditions exceed primary contact standards by one to two orders of magnitude for all locations and water years. Individual samples can be as high as three orders of magnitude above the stream standard.
- For most of the monitoring locations, the falling limb of the hydrograph (later in the storm runoff) was typically an order of magnitude higher than the rising limb of the hydrograph. This finding is important because it confirms that a single grab sample may either over or underpredict the *E. coli* concentrations instream during the course of a storm, depending on when it was collected.
- For any individual water year, *E. coli* concentrations for various storm events can range three orders of magnitude at the same site. Median concentrations are on the order of 10,000 cfu/100 mL, or approximately 100 times the stream standard.

Some additional data are available prior to and following the USGS synthesis report. Because of the additional level of effort associated with the FIB samples as grab samples, additional samples were not collected as part of the JTF program after 2007.

Table 10. ***E. coli*** **(cfu/100 mL) Summary Statistics by Hydrograph Condition for Instream Wet Weather Monitoring Stations (2001-2005)**

(Source: USGS Scientific Investigations Report 2008–5134 by Bossong and Fleming 2008)

Monitoring Station and Flow Condition	n	Mean	Median	StDev	Min	Max
All Stations						
All	22	16,500	**13,000**	20,000	460	92,000
Rising	5	8,670	**1,700**	14,800	460	35,000
Falling	13	14,700	**13,000**	10,800	500	35,000
Rising & Falling Limbs	3	38,700	**13,000**	46,200	11,000	92,000
Unclassified	1	13,000	**13,000**	13,000	--	--
South Platte River below Union Avenue (06710247)						
All	5	26,500	**13,000**	36,900	1,700	92,000
Rising	1	1,700	**1,700**	1,700	--	--
Falling	2	13,000	**13,000**	0	13,000	13,000
Rising & Falling Limbs	1	92,000	**92,000**	92,000	--	--
Unclassified	1	13,000	**13,000**	13,000	--	--
South Platte River at Denver (06714000)						
All	5	13,000	**13,000**	6,870	4,900	22,000
Rising	1	4,900	**4,900**	4,900	--	--
Falling	3	15,600	**17,000**	7,150	7,900	22,000
Rising & Falling Limbs	1	13,000	**13,000**	13,000	--	--
Tollgate Creek above 6th Avenue at Aurora (394329104490101)						
All	3	25,700	**35,000**	16,200	7,000	35,000
Rising	1	35,000	**35,000**	35,000	--	--
Falling	2	21,000	**21,000**	19,800	35,000	--
Sand Creek at mouth near Commerce City (394839104570300)						
All	4	13,500	**9,150**	16,300	500	35,000
Rising	1	1,300	**1,300**	1,300	--	--
Falling	3	17,500	**17,000**	17,300	500	35,000
South Platte River at Henderson (06720500)						
All	5	6,950	**7,000**	5,210	460	13,000
Rising	1	460	**460**	460	--	--
Falling	3	7,770	**7,000**	4,900	3,300	13,000

Table 11. *E. coli* (cfu/100 mL) Summary Statistics by Water Year for Instream Wet Weather Monitoring Stations (2001-2005)

(Source: USGS Scientific Investigations Report 2008–5134 by Bossong and Fleming 2008)

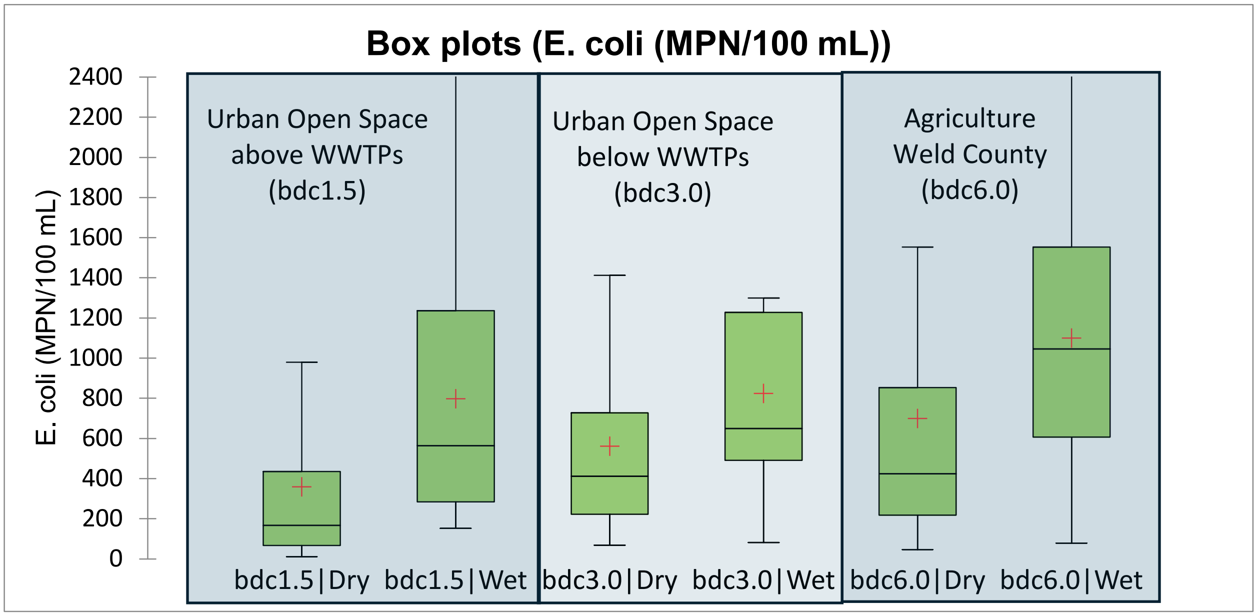
Year	n	Mean	Median	StDev	Min	Max
All Stations						
2002	10	17,100	**13,000**	10,700	3,300	35,000
2004	8	4,600	**3,300**	4,480	460	13,000
2005	4	38,800	**26,000**	36,900	11,000	92,000
South Platte below Union Avenue at Englewood (06710247)						
2002	2	13,000	**13,000**	--	--	--
2004	2	7,350	**7,350**	--	--	--
2005	1	92,000	**92,000**	--	--	--
South Platte River at Denver (06714000)						
2002	2	17,500	**17,500**	--	--	--
2004	2	6,400	**6,400**	--	--	--
2005	1	17,000	**17,000**	--	--	--
Tollgate Creek above 6th Avenue at Aurora (394329104490101)						
2002	2	21,000	**21,000**	--	--	--
2005	1	35,000	**35,000**	--	--	--
Sand Creek at mouth near Commerce City (394839104570300)						
2002	2	26,000	**26,000**	--	--	--
2004	2	900	**900**	--	--	--
South Platte River at Henderson (06720500)						
2002	2	8,150	**8,150**	--	--	--
2004	2	3,730	**3,730**	--	--	--
2005	1	11,000	**11,000**	--	--	--

2.5.5.2 Ambient Instream Monitoring Case Study: Big Dry Creek

The Big Dry Creek Watershed Association (BDCWA) has conducted an ambient instream water quality monitoring program for nearly 30 years, with monthly instream *E. coli* data available at eight upstream to downstream locations. The voluntary program utilizes city and county staff and municipal laboratories to cost-effectively evaluate long-term trends in water quality. As an "ambient" program, samples include a combination of dry weather conditions and some wet weather-influenced events. By pairing sample date with precipitation gauge data, BDCWA was able to "bin" samples influenced by wet weather events of 0.1 inch or more and dry weather samples for a semi-quantitative assessment of the influence of wet weather events. As shown in Figure 12, *E. coli* concentrations under wet weather events were higher at all monitoring locations evaluated, including urban open space (bdc1.5), urban open space below WWTP discharges (bdc3.0) and agricultural use (bdc6.0). Wet weather-influenced events were also more likely to exceed the upper quantification limit (2419.6 MPN/100 mL) associated with IDEXX Colilert methods so the data are not directly comparable to the JTF results discussed in

Section 2.5.5.1 above.[12] For more information about the BDCWA sampling program, see www.bigdrycreek.org.

Figure 12. Big Dry Creek Watershed Association Upstream to Downstream Boxplots of Dry and Wet Weather Influenced Instream Samples (WWE 2025)



Note: Upper quantitation limit = 2,419.6 MPN/100 mL. Wet-weather influenced conditions may be higher than shown because of the limitation. Outliers not displayed on graph.

[12] Monitoring programs targeting quantification of *E. coli* under wet weather conditions should consider 10X dilution of samples for a quantitative result.

2.6 EMERGING MONITORING TECHNOLOGIES

Monitoring technologies continue to evolve, enabling more robust data and real-time data sets. At the time of this toolbox update, a variety of sensor technologies were evolving, with highlights shown in Table 12. The applicability, reliability and maintenance requirements of these technologies are not explored in detail but provided for general awareness. Real-time sensor technologies are an approach that is being used for communication with the public to inform risk for recreators (e.g., H2NOW Chicago, Guillot-Le Goff et al. 2026).

Field installation of a Lume sensor in Boulder.

As one local example of sensor technology being tested, CU Boulder researchers and the City of Boulder are testing instream sensors (Knopp et al. 2026; https://virridy.com/lume/) that measure tryptophan-like substances instream. Sensors currently costing approximately $1,000 each are being correlated (or trained) to instream *E. coli* concentrations. The city has six sensors in Boulder Creek that are being “trained” to measure instream *E. coli* concentrations. If proven accurate and reasonably maintainable, these could provide real-time information for public messaging when *E. coli* concentrations are elevated. Common challenges with sensors include fouling, vandalism, and maintenance requirements; therefore, field-based testing is important to assess practical viability of new technologies.

Table 12. Overview of Emerging Sensor Technologies

Technology Type	What It Actually Measures	Key Strengths	Key Weaknesses / Limitations	Appropriate MS4 Role
Tryptophan-like fluorescence (TLF)	Fluorescent organic compounds associated with fecal matter (aromatic amino acids)	Real-time; robust in situ; low power and relatively low cost; strong indicator of sewage pulses	Not *E. coli*; sensitive to turbidity and dissolved organic carbon (DOC); site-specific calibration; cannot distinguish human vs. animal	Screening, public communication, IDDE prioritization
Optical biosensors (fluorescence / colorimetric)	Enzyme activity or binding reactions associated with bacteria	Rapid; portable platforms possible; moderate cost	Often detect total coliforms rather than *E. coli*; optical interference; sensor drift	Screening / pilot monitoring
Electrochemical biosensors	Electrical signal from binding of *E. coli* cells or biomarkers	High sensitivity; compact hardware; integrates with telemetry	Fouling in urban runoff; cross-reactivity; frequent maintenance	Research / pilot deployment
Phage-based biosensors	Infection of viable *E. coli* cells by bacteriophages	Detects viable bacteria only; high specificity	Phage stability issues; narrow host coverage;	Research / demonstration
Isothermal amplification (LAMP/RPA)	*E. coli* DNA amplified at constant temperature	Faster than qPCR; lower energy; field-portable	Susceptible to contamination; less standardized	Rapid confirmatory screening
Immunosensor (antibody-based)	Binding of antibodies to *E. coli* surface antigens	Species-specific; faster than culture	Cannot distinguish viable cells; antibody degradation; consumable costs	Focused investigations
DNA-based sensors (qPCR-on-chip)	*E. coli* genetic markers	High specificity; quantitative; aligns with lab-based MST workflows	Not real-time; detects DNA from dead cells; power and reagent needs	Confirmatory investigations
ATP /enzymatic activity sensors	Total microbial metabolic activity	Extremely fast; simple instrumentation	Highly non-specific; poor correlation with *E. coli*	Coarse screening only
Machine learning (ML) based surrogate models	Predicts *E. coli* from turbidity, rain, flow, UV, etc.	Truly continuous; no biological reagents; low marginal cost	Indirect estimate; site-specific calibration; regulatory skepticism	Beach management and forecasting
Portable flow cytometry	Cell counts with live/dead differentiation	High data richness; live/dead info	Expensive; complex operation; limited taxonomy	Specialized studies

2.7 MANAGING DATA

2.7.1 Water Quality Data Basics

When embarking on a source identification program or routine monitoring program, the importance of data management cannot be overstated. An easily corrected, but common, shortcoming of monitoring programs is lack of systematic data management in a manner that enables future access of study data. Data management protocols should be part of any sampling and analysis plan; however, effective data management is often lacking in practice. Some simple considerations that help to maximize investment in monitoring programs include:

- Systematic naming and structure of electronic files supporting the study.
- Timely review of sample results to enable identification and correction of errors or follow-up for unusual results (including explanatory comments when unusual results are observed).
- Developing a standard spreadsheet or database format that all data entries will follow, regardless of the individual conducting data entry. Usually, a database format with column headers such as location, date, analytical parameter, result, qualifier, detection limit, and comments is needed, along with other explanatory information. If the collected data will be used as model inputs, then storage of the data in a format easily uploaded to a model can also be helpful. The Colorado Data Sharing Network and CDPHE physical and chemical data format (accessible at https://www.coloradowaterdata.org/awqmscdsn.html) can be used as a template and can be used in Excel or Access, or imported to a geospatial database.
- Clear identification and nomenclature for sample locations that carry through various study types, even if different entities are conducting the studies. Changing sample location names from year-to-year causes confusion in data analysis. Include latitude and longitude coordinates for all sampling locations and a narrative name to accompany short location labels (e.g., site 120A is located at 120th Avenue upstream of bridge).
- Ensure staff entering or managing data have clear direction on how to record values above or below quantitation limits. For example, < and > values should be stored as qualifiers with the data. A common problem with *E. coli* data sets is dropping the > qualifier if results exceed the upper quantitation limit.
- Record and store field conditions along with water quality data. These anecdotal observations can be critical components for identifying sources of FIB. In Colorado, seasonal flow regimes related to spring runoff from snowpack, highly managed flow regimes due to reservoir releases and irrigation diversions, and others should be documented.
- Measurements of flow and precipitation records should be stored along with water quality data.
- Obtain copies of electronic records with clear description of content from consultants conducting special studies. For special research studies, be sure that researchers use the same nomenclature for existing monitoring locations and that the GPS coordinates are provided for special sampling locations.

2.7.2 Geospatial Tools

Given advances in use of municipal asset management systems and improved storm sewer system mapping in GIS, integration of *E. coli* monitoring program data and metadata with other internal geospatial systems can be a useful tool to better understand trends over time.

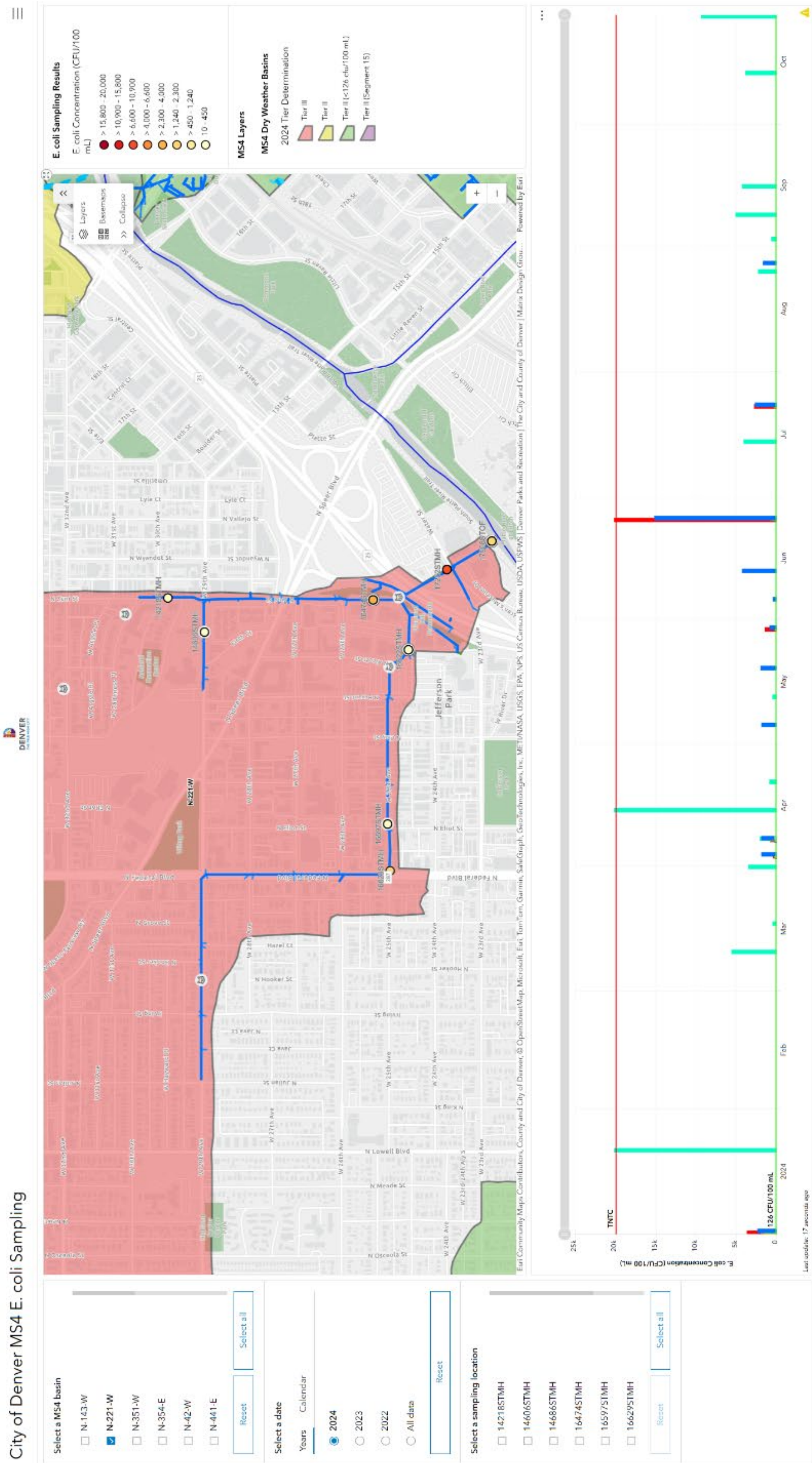
As one example, the City and County of Denver created an internal MS4 *E. coli* sampling dashboard (Figure 13) in ArcGIS to track trends geospatially and communicate across multiple city departments. Prior to development of the dashboard, monitoring data were not mapped geospatially, making it difficult to spot patterns as flows move through the MS4 system or communicate findings across teams. The current dashboard can be used to track dry-weather flow basins and their associated *E. coli* concentrations. As part of this tool, multiple “layers” of information including MST results, animal sightings, land use, inspection and cleaning dates, sanitary crossing points, and general field notes can be accessed through one tool. Denver’s goal is to centralize monitoring data and meta data in one home to more effectively "paint the picture" of fecal contamination within their MS4 and make more informed decisions about source mitigation.

2.8 Interpreting Data: Common Observations for Front Range *E. coli* Data

Although a wide range of trends can occur for *E. coli*, a common trend in warm-water streams along the Front Range is elevated *E. coli* during the summer and/or early fall months and attainment during the winter. Similarly, as mountain snowpack melts in the spring and increases instream flows, *E. coli* concentrations tend to be lower. While these trends may or may not be true for any particular stream, they are commonly observed in multiple streams along the Front Range. Similarly, most urban streams will demonstrate *E. coli* elevated above the stream standard following summer storm events. Flow conditions are an important variable to consider when interpreting *E. coli* data but are often omitted from records associated with monitoring data. (For example, field notes may be collected but not entered into the database or spreadsheet with the water quality data.)

When evaluating trends over time, a common mistake in evaluating whether conditions in the stream are improving, remaining the same or declining, is failure to compare data sets that are collected under comparable hydrologic and seasonal conditions. For example, a Front Range data set that includes six summer sample events and two winter events is likely to show poorer *E. coli* annually than a data set that includes half of samples collected in the summer and half in the winter. Unrepresentative data (or data collected over a limited range of hydrologic conditions) can result in false “success” stories, as well as false conclusions that a SCM/BMP has not provided benefit to the receiving water.

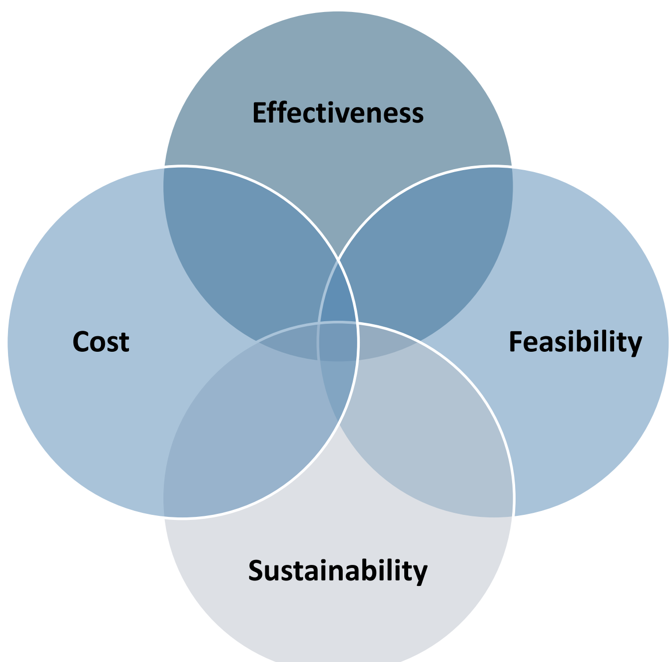
Figure 13. Denver *E. coli* Dashboard in ArcGIS



3 Developing a Control Strategy

Development of a realistic control strategy to reduce *E. coli* involves balancing BMP effectiveness, cost, feasibility and sustainability over the long term. This chapter provides some basic recommendations related to the progression of controls, along with a brief discussion of how models can be used in some circumstances to select the optimal combination of practices. Additionally, Chapters 4 and 5 discuss Source Control Practices and Structural Control Practices that can support a control strategy. A significant challenge for *E. coli* TMDLs is that many unknowns remain regarding both structural and non-structural BMP performance. Additionally, in developed areas, feasibility of implementation will be affected by public vs. private property ownership, space constraints, and physical constraints within watersheds (e.g., high groundwater). Because communities have many responsibilities to their citizens in addition to receiving water quality, cost is a practical constraint when selecting a control strategy, particularly regarding whether practices implemented will be sustainable over the long run. When developing a control strategy to fulfill CDPS permit requirements, it is important to include provisions for adaptive management that account for adjustment of practices implemented, due to the practical uncertainties currently surrounding *E. coli* load reductions.

Figure 14. Balance of Priorities for Selection of Controls in Watersheds



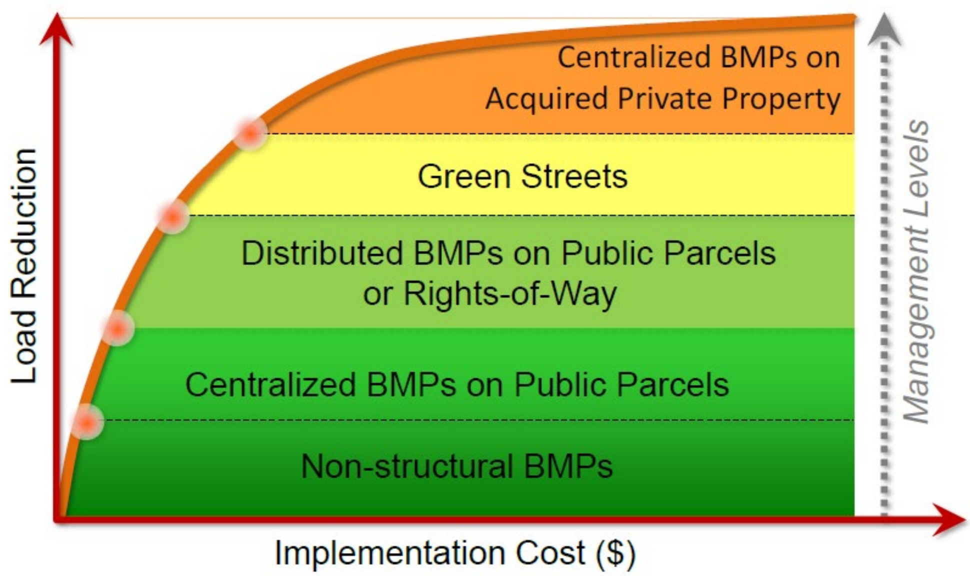
3.1 Progression of Controls

Control strategies for reducing bacteria loading at a watershed scale can be extremely costly. For this reason, it is important to develop a control strategy that builds incrementally, following the progression conceptually illustrated in Figure 15. The progression begins with lower cost non-structural practices, progresses to centralized BMPs on public parcels, then to distributed practices and green streets on public parcels, and culminates with centralized BMPs on acquired private property (or easements). Non-structural practices are the foundation of control strategies, focusing on source controls. Concurrent to this strategy, MS4s are required under their permits to make sure that new development and redevelopment disturbing one acre or more of land implement post-construction stormwater control measures. MS4s also have an oversight role for maintenance of control measures on private development so that private SCMs function as designed. (See discussion in Section 5 for more information on structural control measures.)

Because elevated *E. coli* relative to primary contact recreation standards during wet weather flow conditions is a relatively ubiquitous phenomenon, it is often more cost-effective for communities to focus first on control of dry weather sources of bacteria. Dry weather sources of fecal contamination represent a more persistent human health risk, whereas wet weather sources of bacteria tend to result in more limited duration of exposure.

Figure 15. Conceptual Cost-Benefit Curve and Managements Levels

(Source: San Diego River Watershed Comprehensive Load Reduction Plan Phase II [TetraTech 2013])



During dry weather, these plans rely heavily on source control and nonstructural BMPs first, and then structural BMPs, often as a last resort. Effective dry-weather nonstructural BMPs are those that address sources of human fecal contamination to the MS4, as well as sources of dry-weather urban runoff that mobilize other sources (e.g., catch basin sediments and storm drain biofilms) and contribute to monitorable (i.e., flowing) outfall discharges. Examples of nonstructural BMPs include:

- Identification and control of sewer inputs into the MS4 (particularly where aging leaking sewer lines run near and above storm drains and a hydraulic pathway exists for sewage to enter the MS4 drip by drip over miles of pipe). Although the repair itself is “structural”, the solution is source control based as opposed to SCM-treatment based.

- Enhanced commercial inspection and educational outreach (noting that food outlet dumpster leaks, grease trap leaks, commercial catch basins, and pavement washdown have been identified as potent sources through various source investigations).

- Water conservation programs (targeting residential over-irrigation through smart controller distribution, free home water-use audits, and potentially fines for causing runoff to storm drains). As one Colorado-based example, the City of Boulder and CU Boulder installed a smart ditch headgate on an irrigation ditch to help manage and reduce persistent dry weather flows to the storm drain system. Flow reduction can be a strategy to reduce *E. coli* loads because loading is based on both concentration and flow.

- Waste control programs for unsheltered populations (e.g., enhanced inspection/enforcement, outreach, additional public restrooms, and programs where unsheltered community members are paid to collect trash and waste from encampment areas).

Challenges to including these nonstructural BMP approaches in TMDL implementation plans is that robust data to quantify anticipated effectiveness of these nonstructural practices is generally lacking. Before and after or control-impact studies can be challenging due to multiple variables that may not be able to be controlled in such studies.

During wet weather, implementation plans primarily rely on nonstructural BMPs that address human and anthropogenic non-human sources of bacteria that are located throughout the urban area, because wet weather runoff may mobilize any or all of these. These nonstructural BMPs include waste control programs for unsheltered populations; enhanced pet waste control programs (education/outreach, mutt mitts, and ordinance enforcement); pre-storm-season catch basin cleaning (noting that sediments, trash, and decomposing organic matter all contribute to bacteria levels); and others. However, nonstructural BMPs are not expected to be able to fully reduce wet-weather MS4 bacteria loads; therefore, strategic implementation of structural SCMs are also a key component of wet-weather plans. Few of the passive treatment SCMs alone, such as those in the USDCM Volume 3, are able to consistently achieve effluent concentrations meeting primary contact recreation limits; therefore wet-weather plans must recognize these risks and uncertainties and also must lean more on runoff volume reduction strategies such as infiltration. Potential enhancements to structural SCMs are an evolving area of research and are discussed further in Section 5.1.3.

Even when BMPs are implemented, bacteria TMDL limits, established with the endpoint of meeting primary contact recreations standards instream, are very difficult to meet. See additional discussion in Section 6 related to alternative standards.

3.2 Use of Models to Support BMP Implementation

For pollutants such as sediment, nutrients and metals, models are often viewed as a key planning tool when sufficient data and resources are available. For FIB, modeling is more challenging given the extreme variability in bacteria concentrations, variation in local sources and the fact that bacteria are living organisms that die-off, persist or grow, depending on many factors (e.g., temperature, sunlight, moisture). For this reason, there is increasing debate (e.g., California 2022 Bacteria Summit) about the usefulness of FIB modeling, even in states where modeling has been previously required for reasonable assurance analysis related to permit requirements. For example, the 2022 San Francisco Municipal Regional Stormwater Permit (Order No. R2-2022-0018, p. 298) now clearly states the limitations of modeling for FIB:

> It is not possible to model sources and loading of bacteria in MS4s using watershed pollutant loading models due to the episodic and variable nature of bacteria sources. Some quantitative analysis of loading may be possible through monitoring; however, since bacteria discharge volumes are highly variable both spatially and temporally and

difficult to measure, the analysis would inevitably involve a great deal of uncertainty and be unreliable for purposes of quantifying loads from drainage areas. However, mapping of potential sources areas and targeting control efforts can be tracked and analyzed using geographic information systems.

Nonetheless, there may be situations where modeling is needed to fulfill an objective such as EPA Nine Element Watershed Plans.

Models can be valuable for simulating alternative practices, spatial relationships, various conditions, and future scenarios. For confidence in decision making using models, ideally both monitoring and modeling will be utilized since neither provides all the information needed for decision-making (Harmel 2016a). When considering use of a model to support BMP planning, it is helpful to ask basic questions regarding the model objectives, keeping in mind that the purpose of a model is to help answer: "What is the best way to solve this water quality problem?" As noted by Harmel (2016a), models can help to answer this question, by providing a framework for questions such as:

- What are the important contributors to this problem?
- What are the best practices to implement?
- Where are the best locations to install these practices?
- How can practice effectiveness be evaluated (post-implementation)?

Water quality models are used by MS4 managers and regulators for a variety of purposes, such as for TMDL development and implementation planning. For TMDL development, watershed models and/or load duration curve calculations are used for development of WLAs and LAs for assignment to responsible dischargers. For implementation planning, watershed models are used for systematic siting/placement, selection, and prioritization of management actions to meet TMDL or other MS4 permit requirements, and/or to quantify expected water quality performance (e.g., bacteria load reduction) to demonstrate compliance with a TMDL WLA or other WQS (often referred to as "reasonable assurance analysis"), as well as to quantify costs and other benefits (e.g., water supply capture, urban greening area added, illness rate reduction, etc.).

For implementation planning purposes, which is the focus of this Toolbox, numerous public domain models are available and have been successfully used across the country to support management action selection and prioritization throughout bacteria TMDL-regulated watersheds. Model selection for any given application should be based on functionality needs (selecting a model that is only as complex as necessary), scale of the proposed application, and available data. Table 13 provides a comparison of some of the strengths and limitations of some common models that may be used for FIB. For recent modeling reviews by others focused on FIB, see:

- California Stormwater Quality Association (CASQA) provides an online database of loading tools that has been reviewed for FIB, accessible at: https://www.casqa.org/resources/programmatic-effectiveness-assessment/source-contribution-tools-methodologies
- Minneapolis Stormwater Pathogen Toolbox provides a tabular summary of models with applications for pathogens (City of Minneapolis 2022; see

https://www2.minneapolismn.gov/media/content-assets/www2-documents/departments/Minneapolis-Pathogen-Toolbox_508-compliant.pdf)

In addition to these models, various states and programs also have simpler FIB calculators in Excel workbooks that can be used for estimating load reductions.

Table 13. Brief Comparison of Model Limitations for Several Watershed and Loading Models

Model	Scale & Hydrology Representation	Bacteria Process Representation	Best Application / Strengths	Limitations / Constraints
HSPF (EPA / USGS)	Continuous simulation; mixed land uses; watershed–basin scale	Die-off, limited regrowth; watershed fate/transport	Strong continuous hydrology; widely used in TMDLs	Complex setup; older routines; extensive inputs
SWMM (EPA)	Event + continuous; detailed urban drainage networks	Buildup/washoff + simple die-off; limited in-stream fate	Ideal for MS4 systems; outfall-level loading; IDDE support	Simplified fate; limited watershed scale
SWAT (USDA–ARS)	Large watershed; daily timestep; strong agricultural processes	Manure sources, soil transport, stream fate	Excellent for rural/agricultural watersheds; strong TMDL use	Coarse timestep; limited urban drainage detail
WinSLAMM (PV & Associates)	Urban source loading; simplified hydrology; subcatchment scale	Empirical bacteria sources (pets, birds, wildlife)	Easy; planning level pollutant load reductions; strong BMP/SCM evaluation; MS4 planning	Not watershed-scale; limited fate processes

Consideration should always be given to model calibration needs (water quality monitoring data will be needed to support this—both receiving water and land-use based data), and steps should be taken to perform uncertainty and sensitivity analysis (to understand the limitations of a model's accurate predictive capability). Although most watershed models are capable of modeling structural BMP implementation scenarios, non-structural BMP modeling capabilities are more limited but evolving. Even when robust land-use-based FIB data are available for use in models, FIB concentrations may not be statistically significantly different among land uses. For this reason, many Southern California Reasonable Assurance Analysis (RAA) modeling efforts have moved away from FIB modeling and shifted toward using stormwater volume as a surrogate instead. However, there has also been recognition that volume-reduction strategies at the watershed scale for FIB reduction exceed funding availability.

In another example, WinSLAMM was developed to evaluate stormwater runoff volume and pollutant loadings in urban areas using small storm hydrology. The model determines the runoff based on local rain records and calculates runoff volumes and pollutant loadings from each individual source area within each land use category for each rain. The model then evaluates various stormwater control practices (BMPs) and determines how effectively these practices remove runoff volume and pollutants, also providing cost estimates (http://www.winslamm.com/winslamm_overview.html). An example of a WinSLAMM application in the context of a bacteria TMDL can be found in the Antelope Creek Watershed Basin Management Plan for Lincoln, Nebraska (https://www.lincoln.ne.gov/City/Departments/LTU/Utilities/Watershed-Management/Studies/Comprehensive-Watershed-Master-Plan/Archive/Antelope-Creek).

Understanding the limits of modeling technology and properly accounting for model uncertainty are fundamental to developing a model useful for management decisions (UWRRC 2014, Harmel et al. 2016b, among others). Harmel et al. (2010) provide a concise synopsis of the issues affecting uncertainty for bacteria modeling:

> …there remains a large degree of uncertainty in simulating *E. coli* fate and transport, which is due to several factors. First, relatively few *E. coli* data sets are available for model calibration and validation. Data collected from watersheds of varying scales and land uses with different management practices are especially rare, which severely limits the ability of models to predict *E. coli* fate and transport from various sources in response to management alternatives. In addition, the uncertainty in measured *E. coli* data also contributes to the uncertainty in bacterial modeling (Harmel et al. 2006, McCarthy et al. 2008). Second, large variations in reported values for *E. coli* persistence in the environment result largely from a lack of understanding of the fundamental processes controlling fate and transport mechanisms. For example, it is unclear what proportion of *E. coli* cells are transported via surface flow as single cells as opposed to attached to soil particles (Muirhead et al. 2006a&b; Oliver et al. 2007; Mankin et al. 2007; Soupir et al. 2008a, 2010). Similarly, *E. coli* survival kinetics in different environments (Wang et al. 2004; Soupir et al. 2008b), the resuspension of streambed sediment and associated *E. coli* (Rehmann and Soupir 2009), and the potential for establishment of naturalized populations in soils or sediments (Ishii et al. 2006, Jamieson et al. 2004) are not well understood. Despite numerous laboratory and small-scale studies investigating many of these factors, there is a need for additional studies that compare *E. coli* fate and transport at multiple watershed scales.
>
> …increased attention should be given to the basic science of FIB in the environment. Only with a sound scientific understanding of fundamental processes can the substantial uncertainty associated with bacterial transport assessment and modeling be reduced. Only then can effective and efficient management and regulation of bacterial contamination become a reality.

Ultimately, models are only as useful as the data available to support them ("garbage in equals garbage out") and the knowledge of the user. Models need measured data to give stakeholders confidence in predictions, and a sophisticated, well-calibrated model is typically a substantial and expensive undertaking. Some watershed models can support BMP selection and prioritization, and when combined with cost information, can provide an objective basis for developing a plan of action that maximizes cost-effectiveness of the proposed compliance strategy and minimizes long-term cost to comply with TMDLs. Model outputs should include estimates of uncertainty and should be treated as a planning resource, subject to change as more is learned in a particular watershed as well as practical limitations related to funding, existing infrastructure, and land ownership.

4 Source Control BMPs

Source controls of FIB are the first strategies that should be pursued when impairments are identified. Examples of these strategies are summarized in Table 14 with additional discussion of several of these practices provided in the remainder of this section.

In Colorado, pollutant source control guidance is relatively well developed by entities such as MHFD, the Colorado Stormwater Council, the Colorado Stormwater Center, and various local governments. Many source controls may already be part of minimum control measures being implemented by MS4s (Public Education and Outreach, Public Involvement/Participation, Illicit Discharge Detection and Elimination, Construction Site Stormwater Runoff Control, Post-Construction Management, and Pollution Prevention/Good Housekeeping).

For cases where human sources of FIB are present, controlling and correcting the source of contamination is a basic first step for protecting human health. Once these sources are corrected, diffuse non-human sources typically remain and can be challenging to control. Nonetheless, tools such as pet waste ordinances, bird controls, other urban wildlife controls, and storm drain system maintenance activities should be considered by local governments working to reduce FIB, depending on the sources of elevated FIB in the particular watershed. Limited data are available to evaluate the effectiveness of source controls quantitatively. Effectiveness of source controls on reducing instream FIB is dependent on the dominant sources of FIB in a watershed and the consistency with which source controls are implemented.

Resources/Websites Providing Source Control Fact Sheets

MHFD, Urban Storm Drainage Criteria Manual, Volume 3 for fact sheets related to source controls and structural BMP design and maintenance: https://www.mhfd.org/criteria-manual

Colorado Stormwater Center for training regarding BMP inspection and maintenance and other stormwater infrastructure related training: http://stormwatercenter.colostate.edu/

Splash: https://www.splashco.org/

CLEAR: https://www.douglas.co.us/clear/

Colorado Stormwater Council for Standard Operating Procedures (SOPs) for municipal operations and other BMPs: https://www.colorado-stormwater-council.org (*access to some materials restricted to council members*)

Center for Watershed Protection for illicit discharge detection and elimination guidance and other fact sheets: http://www.cwp.org/

California Stormwater Quality Association: https://www.casqa.org/resources/water-quality-priorities/bacteria

U.S. EPA: https://www.epa.gov/npdes/national-menu-best-management-practices-bmps-stormwater

Green Industries of Colorado (GreenCO) for landscape and water conservation BMPs: http://www.greenco.org/current-bmps.html

Table 14. Sources and Strategies for Bacteria Reduction

Bacteria Source	Stormwater Control/Management Strategy
Illicit Connections to MS4s	Implement an illicit discharge detection and elimination (IDDE) program to identify and remove illicit connections.
Leaking Sanitary Sewer Lines/Aging Sanitary Infrastructure	Conduct investigations to identify leaking sanitary sewer line sources and implement repair. Coordinate with utilities related to repairs in Capital Improvement Planning (CIP) programs.
Onsite Septic Systems and Package Plants	Implement a program to identify potentially failing septic systems. Request CDPHE support for compliance assistance for small package plants.
Illegal Dumping	Implement a reporting hotline for illegal dumping and educate the public/industries that dumping to the storm drain system is illegal.
Dry Weather Urban Flows (irrigation, car washing, power washing, etc.)	Implement public education programs to reduce dry weather flows from storm drains related to lawn/park irrigation practices, car washing, power washing and other non-stormwater flows. Provide irrigation controller rebates. Implement and enforce ordinances related to outdoor water waste and/or collaborate with water utilities to promote turf transformations, water-wise landscapes and irrigation practices. Inspect commercial trash areas, grease traps, washdown practices, along with enforcement of ordinances.
Domestic Pets (dogs and cats)	Provide signage to pick up dog waste, providing pet waste bags and disposal containers. Adopt and enforce pet waste ordinances. Place dog parks away from environmentally sensitive areas. Protect riparian buffers and provide unmanicured vegetative buffers along streams to dissuade stream access.
Wildlife in Urban Areas (e.g., rats, bats, raccoons, beavers, deer, coyotes, foxes)	Reduce food sources accessible to urban wildlife (e.g., manage restaurant dumpsters/grease traps, residential garbage, feed pets indoors). Implement and enforce urban trash management practices. Consult with state wildlife offices (CPW) on strategies to reduce food, shelter and habitat for overpopulated urban wildlife.
Storm Drain Infrastructure & SCMs	Proper maintenance of the storm drain system and water quality BMPs is needed for proper functioning of the system. For example, sediment, organic deposits and biofilms in stormwater facilities can harbor FIB.
Storm Runoff from Urban Areas	Encourage site designs that minimize directly connected impervious areas (e.g., Green Infrastructure, Low Impact Development).
Birds (e.g., Canada geese, pigeons, ducks)	Identify areas with high bird populations and evaluate deterrents, population controls, habitat modifications and other measures that may reduce bird-associated FIB loading.
Unsheltered Populations	Periodic cleanup of encampments near streams. Partnering with non-governmental organizations to provide shelter and support of city shelters and services. Providing public restrooms. Enforcement of camping bans, particularly in riparian areas. Fencing to prevent access to frequently used encampments.

4.1 Education and Outreach

Education and outreach to citizens and businesses is a general overarching source control practice that is needed for other types of source controls to be effective. Education and outreach activities may include signs, brochures, posters, websites, event attendance, utility bill inserts, television advertisements, articles in homeowner association newsletters and other approaches that effectively reach citizens and promote behavioral changes. There may be opportunities for stormwater managers to work in a cross-disciplinary manner with other city utilities to maximize public education dollars. For example, campaigns to reduce water waste by reducing over-irrigation help communities meet both conservation and water quality objectives. Similarly, drinking water departments often focus on source water protection strategies, but due to departmental "silos", opportunities for integrating stormwater and drinking water program objectives may not be fully maximized. As more communities pursue "One Water" and Integrated Planning approaches, *E. coli* load reduction may benefit from more coordinated efforts.

"Live Like You Love It" logo for branded water campaign. (http://lovecoloradowater.org/)

An example statewide campaign that integrates water conservation and water quality practices (both of which benefit *E. coli* load reductions) is the "Live Like You Love It" campaign. An important aspect of effectively communicating with the public involves the use of engaging materials, as well as proper facts. This campaign includes graphically designed materials and a toolkit to support outreach efforts.

4.2 Repair of Aging Infrastructure and Correcting Illicit Connections

Nationally, local governments and regulatory agencies are increasingly recognizing that aging infrastructure is contributing to contamination of MS4 discharges, as evidenced by findings from microbial source tracking studies, IDDE programs and consent decrees with EPA. (For an example consent decree, see http://www.epa.gov/sites/production/files/documents/bwsc-cd.pdf.) In 2025, the American Society of Civil Engineers (ASCE) gave the nation a "D+" for wastewater infrastructure on its "Report Card for America's Infrastructure" (ASCE 2025: 2025 Infrastructure Report Card). Stormwater infrastructure earned a "D." Both scores emphasize major challenges for maintaining aging infrastructure (ASCE 2025). The report stated that, over the last decade, the sector's renewal and replacement rate for large capital projects decreased from 3% to 2% while the average number of collection system failures for combined water utilities increased from 2 to 3.3 per 100 miles of pipe. According to ASCE, in 2024 the wastewater and stormwater annual capital needs were $99 billion, whereas the funding gap was $69 billion, meaning only about 30% of the sector's infrastructure capital needs are being met (Cossin 2025). Funding for these projects affects utility ratepayers and often results in utilities needing to pursue bonds or state revolving loan funding to catch up on infrastructure maintenance backlogs.

Consistent with ASCE's findings, aging sanitary pipes can be a significant source of FIB loading in urban areas (Sercu et al. 2011, Corsi 2014, Sauer et al. 2011). Many communities have implemented Asset Management Programs that provide a systematic strategy to manage, maintain and operate infrastructure. The EPA's Capacity, Management, Operation, and Maintenance (CMOM) (EPA 2005) is probably the most well-known asset management program. Asset management programs provide a framework for self-evaluation and planning for the function, condition, and performance of a sanitary sewer system (TCEQ 2013). Municipalities often follow standardized underground infrastructure evaluation and assessment methods developed by NASSCO including the Pipeline Assessment Certification Program (PACP), Lateral Assessment Certification Program (LACP), and Manhole Assessment Certification Program (MACP) (NASSCO 2025). Examples of sanitary infrastructure defects that can affect *E. coli* in MS4 discharges are summarized in Table 15.

Table 15. Types of Sanitary Infrastructure Defects Potentially Affecting *E. coli* in MS4s

Category	Example Defects	Why It Matters for E. coli
Infiltration / Exfiltration	Active leaks, joint separation	Enables sewage release to soil or storm system
Cross Connections	Sanitary-to-storm connections	Direct conveyance of sewage to outfalls
Structural Failure	Cracks, fractured pipe	Chronic leakage, especially under surcharge
Manhole Defects	Open chimneys, pick holes	Surface inflow or overflow during wet weather
Lateral Defects	Broken laterals	Common, often undocumented sewage sources

Aging and leaking sanitary sewer and stormwater conveyance pipes can introduce pollutants to the MS4 through SSOs caused by blockages, line breaks, or other sewer defects; exfiltration of sewage from sanitary sewers; and infiltration of groundwater when the MS4 lies below the water table (Sercu et al. 2011). Upgrading, repairing, or slip-lining faulty sanitary sewer pipes will reduce pollutant loads by eliminating the leaks in those pipes. Additionally, upgrading or repairing storm pipes can minimize the infiltration of contaminated groundwater into the MS4 (Geosyntec 2012). The cost of a proactive pipe-lining program is much more manageable than replacing failed pipes. For example, the City and County of Broomfield estimates that their Cure in Place Pipe (CIPP) lining program costs ~$140/linear foot, whereas full dig-and-replacement pipe costs >$800/linear foot, with some variation by pipe size (Broomfield 2025).

Measures to reduce SSOs include field inspections and using CCTV to inspect sewer lines, which can reveal blockages from debris to roots to grease and show pipeline cracks, breaks, or deterioration. Once such issues are identified, they can be integrated into planning efforts to maintain, rehabilitate or replace aging sanitary infrastructure.

Accelerated repair or upgrade of sanitary sewer and storm drain systems can be a key measure to reduce human sources of FIB. The location and design of upgrades can be optimized to decrease pollutant loads using information gathered in IDDE programs, GIS analysis of high-risk sewers, and/or special source tracking studies. Strategically planning upgrades to older, clay sanitary sewer laterals that cross or run next to and above storm drains is cost-effective and offers multiple benefits, including benefits to water quality and reduced operations and maintenance costs from newer infrastructure (Geosyntec 2012). For example, a key component of the City and County of Denver's *E. coli* load reduction plan has included investigating and lining sanitary sewers in need of repair, prioritizing locations where sanitary sewers cross above storm drains or where sanitary sewers are parallel in close proximity.

Sanitary sewer overflow. (Photo Courtesy Brandon Steets.)

Where available, storm and sanitary sewer inspections using NASSCO inspection ratings can be integrated into *E. coli* source investigations by using standardized defect information to confirm whether physical pathways exist for fecal contamination identified through sampling. Elevated *E. coli* or human MST results are first used to target specific drainage areas, after which inspections identify structural failures, cross connections, or infiltration/exfiltration that plausibly explain observed bacteria. This multiple lines of evidence approach improves prioritization of corrective actions, supports defensible regulatory decisions, and links infrastructure condition directly to public health outcomes.

If sanitary infrastructure sources are identified, they must be corrected because they represent a direct source of raw sewage discharged to receiving waters. Enhancements to basic IDDE programs may include a tiered dry weather source investigation including: (1) visual surveys of MS4s to identify dry weather flow locations, (2) GIS-based prioritization where aging sewer laterals are above and near storm drains that are observed to occasionally flow during dry weather, (3) video survey of the storm drains to identify leaks from the top of the pipe and/or sewer dye tracing studies, (4) field test kits for ammonia, surfactants and residual chlorine in dry weather MS4 flows as an initial low-cost screening tool, and (4) fecal source tracking studies that use microbial source tracking or other methods (Geosyntec 2012, CWP and Pitt 2004).

City of Fort Collins Infrastructure Repair Case Study

The Cache la Poudre River through Fort Collins and urban creeks such as Spring Creek, Fossil Creek and Boxelder Creek are identified as impaired for *E. coli* and a TMDL is in progress for these stream segments as of 2026. Although the city's voluntary long-term instream monitoring program was useful to identify areas with elevated *E. coli* concentrations, additional study was needed to identify potential sources.

In 2019, the city embarked on an extensive voluntary dry weather sampling program of its previously mapped storm sewer outfalls. The city's well developed GIS that enabled integrated access to the stormwater system, wastewater system, and outfall system mapping was foundational for the source investigation. The sampling program included both traditional fecal indicator bacteria (*E. coli*) and advanced microbial source tracking techniques for human DNA markers (HF183) and other animal markers in some locations. Based on dry weather sampling results, the city's wastewater utilities department provided access to CCTV for review as part of the study to assess whether illicit sanitary connection or leaks into the storm sewer were present. Through a series of sampling over a two-year period, the study team was able to identify a few "hot spots" where aging infrastructure was suspected as a potential source of *E. coli* based on an action threshold of HF183 exceeding 1,000 copies/100 mL. Additionally, pipes with low (or no) HF183 that also had documented animal sources such as raccoons (based on game cameras and fecal latrines) were deprioritized to enable focus on sources expected to pose more significant human health risk.

Through strong internal communication between the stormwater and wastewater utilities groups in the city, the city's Small Capital Improvements group was able to prioritize repair and/or replacement of sanitary sewer mains in areas where sanitary sewer leaks were suspected. The city plans to conduct follow-up monitoring to assess how the sanitary improvements may have affected *E. coli* concentrations in outfalls. A key lesson learned from the City of Fort Collins study was the importance of multiple city departments funded through different budgets being willing to work together proactively to adjust CIP priorities to address potential aging infrastructure sources. The City of Fort Collins has since reorganized its water, wastewater, and stormwater utilities into a One Water utility, which will further facilitate a collaborative approach on complex water quality issues in the future.

4.3 Municipal Maintenance Activities: Supporting Practices

Although municipal maintenance activities do not address the original source of FIB loading, a variety of maintenance activities may support FIB load reduction.[13] Unfortunately, quantitative data and evaluation of the benefits of these practices is generally lacking. Practices that may be considered include:

- **Storm Drain Cleaning:** Storm drains can accumulate trash, sediment, organic matter and animal waste over time. As a result, they can become secondary reservoirs of FIB and other pollutants. Cyclical storm drain cleaning using water jetting and vacuuming jetted water is one tool that some communities have implemented as a source control BMP. Storm drain cleaning is typically done on

[13] Recommendations are based on discussion in the San Diego Comprehensive Load Reduction Plan, Attachment E Non-structural BMPs (Geosyntec Consultants 2012).

a several year cycle to maintain the conveyance function of pipes and can be done more frequently in "priority basins" where elevated FIB at storm drains is identified. Sampling results may be used to help target areas in need of more frequent cleaning such as siphon conditions. WWE and City of Boulder (2025) completed a literature review of storm drain cleaning effectiveness in combination with a pipe cleaning effectiveness study at sites in the City of Boulder. The city's sampling program did not demonstrate *E. coli* reduction benefits at the three outfalls sampled before and after pipe cleaning. Similarly, a national literature review did not provide a quantitative basis demonstrating *E. coli* reduction benefits of pipe cleaning. It is possible that pipe cleaning may provide benefits in specific pipe networks for limited time periods; however, decisions related to increased cleaning frequency should be data driven on an outfall-specific basis. Based on this updated information, storm drain cleaning is a "tool" in the toolbox that may help to reduce *E. coli* in some locations; however, it is expected to provide temporary benefits. For example, game camera studies in Boulder, University of Colorado at Boulder, and City of Fort Collins have documented significant raccoon use of storm drain systems including "latrine behavior" (WWE 2025). Although storm drain cleaning may flush raccoon feces from the system, raccoon sources are likely to return to the systems as an ongoing source of *E. coli*. Storm drain cleaning programs that target *E. coli* should be developed based on local monitoring and knowledge of the system.

- **Catchbasin Cleaning:** Catchbasins and drain inlets play an important role in the prevention of trash and other sediments from entering the storm drain system. Catchbasin cleaning is an important institutional BMP, but the FIB load reduction benefits of increased frequency of catchbasin cleaning have not been rigorously studied. A survey conducted as part of the San Diego River source study found that nearly 50% of commercial catchbasins had moderate buildup and over 30% had ponded water. Signs of washdown and food scraps were frequently associated with catchbasins near restaurants (Weston 2009a). Studies to evaluate the potential benefits of catchbasin cleaning did not show significant reductions in FIB (Weston 2009b). However, in a study conducted in the Telecote Creek watershed in San Diego, commercial catchbasins had significantly higher FIB than residential catchbasins (Weston 2010b); thus, if catchbasin cleaning is being considered as a BMP for *E. coli*, it may be more beneficial to focus on commercial areas first. A recent literature review conducted by WWE and the City of Boulder (2025) found that national literature with quantitative performance data for FIB related to catchbasin cleaning was generally lacking, although some studies quantified total solids removal from cleaning practices.

Biofilms and FIB

In 2025, WWE conducted a literature review regarding biofilms on storm pipe surfaces. Biofilms are diverse communities of microorganisms that attach to surfaces, and there is evidence that stormwater flows can cause shedding of bacteria comprising these biofilms (MPCA 2023; NAS 2014; Roberts 2012; Skinner et al. 2010). Among other microorganisms and bacteria, *E. coli* are able to multiply and survive in biofilms (Skinner et al. 2010). While storm pipe cleaning may temporarily reduce biofilms, biofilms regrow rapidly and according to Roberts (2012) achieved complete regrowth within approximately two months of shedding. Additional findings included that biofilms are predominantly composed of environmental (i.e., non-fecal) strains of bacteria within a month of shedding during wet weather flows (Roberts 2012). The rapid regrowth of biofilms and the transition from fecal to environmental strains of bacteria suggest that pipe cleaning has low potential to reduce *E. coli* concentrations in stormwater runoff because of the rapid rate of regrowth of these biofilms, regardless of whether they have been temporarily reduced from pipe cleaning (WWE and City of Boulder 2025).

- **Street Sweeping:** Streets are part of the stormwater conveyance system in urban areas; therefore, street sweeping is also considered an MS4 maintenance practice. Street sweeping removes sediment, debris, and other pollutants from road and parking lot surfaces. The major factors that impact the effectiveness of a street sweeping program in reducing pollutant loads are frequency and timing of cleaning and the type of street cleaning equipment used. Effectiveness is also dependent on the speed the sweeper travels, the amount of sediment on the street, and how much of the street is swept (e.g., whether parked cars prevent sweepers from accessing the curb). High-efficiency street sweeping equipment, such as regenerative air sweepers or vacuum assisted sweepers can significantly increase the amount of sediment removed from roadways. Additionally, regenerative air and vacuum sweepers were designed specifically to better capture fine particles. Bacteria, as well as metals and other pollutants, adsorbed to sediments are typically associated with smaller sized particles due to a larger surface-to-volume ratio and greater adsorption properties of clay particles (Xanthopoulos and Hahn 1990, Krumgalz et al. 1992). Although measured reductions in discharges of pollutants and FIB to receiving waters due to street cleaning have rarely been observed, street cleaning is an important public works activity to minimize sediment accumulation in drainage systems. MHFD is in the process of completing a street sweeping study for the Front Range area; however, this study is focusing more on nutrients and sediment, including particle size distribution of collected materials (WWE and MHFD 2025).
- **Structural Stormwater BMP Maintenance**: Maintenance of structural stormwater quality BMPs can also help to remove secondary reservoirs of FIB in urban areas. Routine sediment removal from dry extended detention basins and manufactured devices can reduce the likelihood of sediment resuspension and FIB release during storm events. Additionally, routine maintenance ensures that filtration and infiltration practices function as designed (MHFD 2025).

4.4 Downspout Disconnections and Site Designs Minimizing Directly Connected Impervious Area (Green Infrastructure Site Designs)

Roof runoff collected in downspouts that are directed to the storm drain system can be disconnected to reduce runoff volumes and potentially *E. coli* loading from rooftops. Shergill and Pitt (2004) found that roofs with birds and squirrels in overhead tree canopy had higher FIB than those without animal activity. Simply disconnecting roof downspouts can help to redirect runoff to pervious areas, thereby potentially reducing both runoff volumes and FIB loads. Implementation options include redirecting downspouts to lawns, gardens or swales. Downspout retrofits can be an effective stormwater control for commercial, industrial, and public buildings as well.

In addition to downspout retrofits, new developments or redevelopments can be designed to integrate multiple measures that reduce effective impervious area by disconnecting impervious surfaces and that utilize receiving pervious areas for runoff reduction. These Low Impact Development (Green Infrastructure) site designs can integrate non-structural practices, as well as structural stormwater controls such as bioretention, permeable pavement and other practices (see MHFD's USDCM Volume 3 and Denver's Ultra-Urban Green Infrastructure Guidelines). Reducing runoff peaks and volumes during frequently occurring storm events may help to reduce FIB loading, as well as reduce other pollutant loading.

4.5 Pet Waste Disposal and Pet Control Ordinances

The density of pets in urban areas can be quite high; therefore, proper disposal of pet waste is a basic component of FIB control plans in urban areas. Elements of pet control programs may include:

- Providing park and trail signs regarding pet waste disposal requirements and leash laws.
- Providing disposal cans at conveniently spaced intervals on trails and in open space areas. Some communities allow advertising on signs placed at pet waste bag dispensers and disposal cans to partially offset the cost (e.g., Poo Free Parks®).
- Providing and properly maintaining off-leash dog parks, preferably at locations that do not directly drain to receiving waters. Improperly maintained dog parks can become a source of FIB.
- Allowing natural riparian buffers to grow alongside streams to dissuade pet access.
- Providing educational materials regarding the impact of improper pet waste disposal. These materials can be made available in locations such as pet stores, animal shelters, veterinary offices, and other sites frequented by pet owners.
- Enforcing pet waste ordinances and leash laws (or developing them, if they do not exist). While most communities have pet waste ordinances "on the books", enforcement of these ordinances may not routinely occur in many communities. In areas with significantly elevated FIB, allocation of resources to park and open space rangers to enforce pet waste disposal controls and leash laws may be needed.

Doggy Daycare Outreach Case Study

City and County of Denver solicited doggy daycares for the opportunity to display infographics and receive pet waste bags to distribute. Near half of the facilities contacted agreed to participate. Additional efforts are planned to showcase that branded dog waste bags can be a way for facilities to market business and provide "distribution" baskets with infographic information.

Pet waste infographic signage explaining the link between picking up pet waste and water quality in an area frequented by pet owners in Denver. Infographics are targeted to parks and areas around dog friendly hotels. (Photo: Brad Cox.)

Pet waste messaging in Boulder County by the Keep It Clean Partnership.

Pet waste cans and signage at a Denver-area park. (Photo Courtesy Jane Clary.)

Effectiveness of pet waste control programs is limited in terms of instream responses to implementation of such programs, in part because pet waste programs may be implemented in combination with other practices. Several surveys and reports exist that attempt to quantify behavioral change associated with such programs. For example, the Phase I Report for the San Diego River Kelp and Dog Waste Management Plan for Dog Beach and Ocean Beach found that public compliance with the "scoop the poop" policy was highly dependent on awareness of the policy and availability of waste disposal bags and trash cans (Weston 2004). Public surveys in the City of Austin indicated their educational campaign resulted in a nearly 10% improvement in the number of pet owners who claim to regularly pick up waste (City of Austin 2008). Studies in San Diego have shown that installation of pet waste stations has resulted in a nearly 40% reduction in the total amount of pet waste in city parks (City of San Diego 2011). Hillsborough County / University of South Florida conducted a Pet Waste Research & Social Marketing Study during 2008-2011. The targeted education and social-marketing, pickup compliance tracking, and monitoring in pilot areas suggested a ~30–50% fecal coliform reduction reported for pilot areas (dry-weather focus) (Hillsborough County & USF 2011).

4.6 Dog Parks BMPs

In Colorado, a common question from MS4s relates to dog park control measures. In general, dog park control measures are similar to those described above; however, pet waste pickup may be more challenging to enforce in large off-leash areas. A recent USGS study (McKee and Couch 2024) conducted in the Atlanta metro area showed a positive correlation between *E. coli* levels and the number of dog parks in drainage basins. The study also showed a negative correlation with distance to the nearest dog park in a drainage basin, with sites with at least one dog park in close proximity having higher summer *E. coli* concentrations than those further away.

General recommendations for dog parks include:

- Avoiding direct drainage from dog parks into receiving waters and detention basins.
- Preventing routine inundation of dog use areas.
- Requiring enhanced pet waste controls where dog parks drain to receiving waters.

Dog Parks and Detention Basins

Local governments are often asked about multipurpose use of extended detention or flood detention facilities for dog parks. Local ordinance may have specific requirements, but general guidance is provided below for protection of water quality:

Strongly discouraged practice:

- Dog parks located **within** extended detention basin bottoms
- Areas subject to routine ponding or wetting
- Direct drainage from dog areas to outfalls

Conditionally acceptable practice:

Dog parks **adjacent to** basins with:

- Full runoff separation
- Infiltration or filtration treatment
- Intensive pet waste management

Preferred practice:

- Dog parks located **outside stormwater facilities**
- Drainage routed to infiltration BMPs or landscaped buffers/receiving pervious areas

4.7 Animal Facilities Management

A variety of animal-related facilities may be located in urban areas. Examples include "Doggy Daycares," veterinary clinics that board pets, small horse properties, and zoos (including petting zoos). The primary BMPs for these facilities include dry shoveling and disposal of solid waste and washdown practices that direct washwater to the sanitary sewer system. Particularly for older facilities, it may be worthwhile to confirm that floor drains and washdown areas are not being directed to the storm drain.

For hobby farms or ranchettes along streams, fencing, stream setbacks and drainage management from pens and barns are also important. CDPHE (https://cdphe.colorado.gov/dehs/eag/bmps) recommends these practices:

Divert clean runoff away from animal confinement areas, manure stockpiles and wastewater control facilities.

- Construct ditches, terraces or berms to channel clean water away from pens, manure storage, and wastewater control facilities.
- Install gutters and downspouts to divert clean roof drainage.
- Build roofs over animal confinement areas where practical.

Reduce wastewater discharges to surface water.

- Collect and allow wastewater to evaporate.
- Collect and evenly apply wastewater to land application sites at agronomic rates.
- Locate wastewater storage away from stormwater runoff, streams, ditches or other channels that can carry waste to surface water.

Minimize manure transport to surface water.

- Locate stockpiles away from surface water and floodplains.
- Maintain adequate manure storage.
- Collect manure from pens frequently.
- Apply manure to land application sites at an agronomic rate.

Protect groundwater.

- Maintain a buffer area around water wells when applying manure or wastewater to fields.
- Locate manure and wastewater facilities downhill and at least 150 feet away from all water supply wells.
- Install liners in wastewater impoundments to reduce seepage if a significant risk of groundwater contamination exists.

4.8 Bird Control

High densities of resident Canada geese are common in Front Range parks and ponds. (Photo Courtesy Jane Clary.)

Birds are a common source of FIB in urban areas in Colorado. In particular, geese are considered a public nuisance due to large populations, creating large amounts of feces, especially in open-space areas (e.g., parks, playing fields, ponds) (Manny et al. 1975, French and Parkhurst 2009, Bowen and Valiela 2004, Kear 1963). Clark (2003) reported that non-migratory Canada geese increased eight-fold in a 20-year period (1980s to early 2000s) in North America. Pigeons, blackbirds, starlings, ducks, and other birds also can pose similar problems when they roost on public buildings and bridges. Birds are documented sources of elevated FIB in many studies. Examples include research by Alderisio and Deluca (1999), Stoeckel (2010), Kolb and Roberts (2009), Kirschner et al. (2004), Shergill and Pitt (2004), Hussong et al. (1979), Fleming and Fraser (2001) and many others. For this reason, a fairly detailed discussion of potential control strategies for birds follows, since most urban areas are expected to have at least some contribution of FIB from birds. As a local example, the City of Fort Collins conducted a microbial source tracking study on Fossil Creek in 2019, which has significant natural areas and associated bird populations. Avian DNA was present at concentrations ranging from over 1,000 copies/100 mL to nearly 15,000 copies/100 mL (WWE and Geosyntec 2021).

The University of Nebraska at Lincoln (2010), USDA APHIS (1994a&b, 2003), the Internet Center for Wildlife Damage Management (www.icwdm.org) and others provide guidance on control strategies for geese. Canada geese are protected by federal and state laws. While it is illegal to intentionally kill a wild goose (other than during licensed hunting seasons) or to harm nesting geese and eggs without a permit, there are several methods used to discourage geese from congregating in specific areas. Non-lethal control activities do not require federal or state permits, and most non-lethal activities can be conducted throughout the year, except using trained dogs for hazing. Any activities that result in handling, damage, or destruction of geese, their eggs or nests require permits (CPW 2014).

Effective geese control often requires early detection of the problem, persistence, and use of multiple methods (CPW 2014). Both the City and County of Denver and CU-Boulder have reported some success with use of a mechanical "Goosinator" deterrent. In the case of campus settings where manicured lawns and sidewalks are present, CU-Boulder has observed a decrease in goose droppings on sidewalks, which has the added benefit of decreasing fecal matter tracked inside of buildings on shoes and wheelchairs (Personal Communication with Mark Lapham, CU-Boulder). Additional monitoring would be needed to determine whether the use of the Goosinator on campus has translated into reductions in *E. coli* at stormwater outfalls. Table 16 summarizes measures that have been used for geese control, followed by additional discussion of several of these measures. Overall, USDA APHIS (2009) recommends that the most efficient and effective way to manage resident geese is to harass them before nests are built. If this is not possible, nest destruction and egg oiling are the best options. Successful geese control can be elusive though, as noted by a USDA study for Denver Parks (USDA, 2019) which found that hazing and egg oiling/addling programs are costly, have temporary impacts, and the dispersed geese remain within two miles of the original locations (Holevinski et al., 2006; Preusser et al., 2008; Seamens et al., 2009).

Table 16. Summary of Selected Waterfowl Management Techniques

(Adapted from Smith et al. 1999, Smith 2006, NYCDEP 2004, as summarized in UWRRC 2014)

Technique
Public Education
Discontinuance of feeding
Habitat Modification
Porcupine wires (for roosting waterfowl and pigeons)
Eliminate shorelines, islands, peninsulas (in constructed waterbodies)
String wire lines or place Mylar tape grids above roosting and pond areas
Fence barriers
Vegetative barriers (taller grasses)
Rock barriers
Floating plastic balls (may wash away during storms)
Reduce or eliminate mowing (adjacent to waterbodies)
Place walking path near water
Place playing fields away from water
Deterrence Measures (may have short-term effectiveness)
Sprinklers and motion-detected activated sprayers
Pyrotechnics
Sonic Devices: ultrasonics, distress calls, sirens, horns whistles, propane cannons
Active Visual Deterrents: strobe lights, lasers, light beams
Passive Visual Deterrents: "eye-spot" balloons or kites, flags, scarecrows, floating predator decoys (benefits may be temporary, as waterfowl may habituate over time)
Dispersion Measures
Dogs
Swans (can also be a source of FIB)
Falcons (often impractical to maintain)
Radio-controlled aircraft or boats
Chemical Repellents (methyl anthranilate)
Reproductive Controls
Removing nesting materials (before egg laying)
Oil/addle/puncture eggs (during incubation)
Replace eggs with dummy eggs
Sterilization (oral contraception or surgical neutering)
Removal
Relocate (may not be effective)
Various lethal measures (e.g., hunts, kill permits)

Remote controlled goose hazing device, “Goosinator,” used to deter resident waterfowl in Denver Parks.

Questions remain as to the long-term benefits of various control measures; however, several case studies suggest that combinations of these control measures can be successful in reducing FIB concentrations (e.g., NYCDEP 2014, Swallow 2010).

The USDA has developed control strategies for other bird species, including pigeons (Williams and Corrigan 1994), blackbirds (Dolbeer 1994), and swallows (Salmon and Gorenzel 2005), as a few examples. Of these birds, pigeons are often a dominant concern in urban areas. Measures listed as alternatives by the USDA-APHIS for pigeons are summarized in Table 17. Some of these measures would not be expected to be appropriate in urban areas (e.g., shooting, certain toxicants).

In summary, birds can contribute substantially to FIB loading to receiving waters, posing challenges to attainment of numeric water quality limits for FIB. The extent of the impact of birds and the success of control measures varies based on site-specific conditions. A variety of source control measures have been developed by state and federal agencies to help manage the impacts of birds. These measures typically require ongoing attention, and the effectiveness of these measures may vary over time and require adjustments to reduce the likelihood of habituation to the technique.

Table 17. Summary of Pigeon Control Measures

(Adapted from Williams and Corrigan 1994)

Measure Type	Description
Exclusion	• Screen eaves, vents, windows, doors, and other openings with 1/4-inch (0.6-cm) mesh hardware cloth. • Change angle of roosting ledge to 45 degrees or more. • Attach commercially available porcupine wires to roosting sites. Install electrical shocking device/repelling systems on roost sites. • Construct parallel or grid-wire (line) systems.
Habitat Modification	• Eliminate food supply. Discourage people from feeding pigeons in public areas. • Eliminate standing water.
Frightening	• Visual and auditory frightening devices are usually not effective over time.
Repellents	• Tactile: various commercially available nontoxic, sticky substances manufactured for this purpose. • Odor: naphthalene flakes.
Toxicants	• Consult with local and state agencies on allowed toxicants.
Fumigants	• Generally not practical.
Trapping	• Several live trap designs are effective.
Shooting	• Where legal. Not a viable option in most urbanized areas.
Other Control Methods	• Alpha-chloralose (immobilizing agent used under the supervision of certified personnel only). • Nest removal.

4.9 Urban Wildlife (Mammals) Management

Urban wildlife can be a key source of FIB loading to urban streams. Fecal matter from wildlife can enter streams through direct overland flow into streams as well as become concentrated by animals living in storm drains and stormwater facilities. Raccoons can be particularly problematic in the storm drain system itself. Beavers can be a direct source of instream pathogens, including *Giardia* and *Cryptosporidium*, as well as a source of elevated FIB instream (Wade and Ramsey 1986, AWWA 2006).

While it is likely impossible to completely control urban wildlife, there are strategies that can be considered to reduce FIB loading from urban wildlife, including:

- Develop a wildlife management plan, working with city wildlife conservation staff and/or Colorado Parks and Wildlife.

- Modify habitat and reduce urban food sources. Raccoon problems may be alleviated by making the habitat less favorable. Because raccoons have fairly large territories, a neighborhood or community-wide effort may be more successful than isolated control measures in urban areas. Removing potential sources of food, water, and shelter is the first step in eliminating the problem. In areas with raccoon activity, garbage cans should be tied down to a solid structure so they cannot be overturned, and lids should be tight fitting, tied or weighted down to deny access to garbage (Pierce 2001). Reduce food sources for urban wildlife through better management of dumpsters, garbage cans and restaurant waste. Additionally, pet food should be stored indoors and pets fed inside (or at least not left out overnight).

- Relocate wildlife by trapping. If no other control methods are effective, the problem animals may need to be removed from the area by trapping (Pierce 2001). Although beavers may provide ecosystem benefits, they can be a significant management issue in urban areas where maintaining channel capacity is important for infrastructure protection. The Big Dry Creek Watershed Association and the City of Westminster have documented elevated *E. coli* in areas

Colorado Raccoon Study

Working with the USDA National Wildlife Research Center in Fort Collins, the City of Fort Collins, City of Boulder and CU Boulder installed game cameras in manholes in selected storm drainage systems to begin developing data to assess the potential contributions of racoons to discharges from MS4s. Initial findings included:

- High usage of the MS4 by raccoons
- High prevalence of raccoon latrines/feces (estimate at 40% of manholes in a Fort Collins network segment
- High traffic of raccoons through the system
- Potentially significant fecal loading from the system originating from raccoons.

CU Boulder and City of Boulder have found *E. coli* concentrations in raccoon feces exceeding > 241,960 MPN/100 mL.

As part of the same study, concerns about potential cross-reactivity of raccoon and human DNA markers were also explored with technical assistance from EPA Office of Research and Development and the USDA. Cross-reactivity was found to be unlikely in fecal samples for raccoons with controlled diets and environments; however, some research questions remain because HF183 was present in some wild raccoon samples (WWE 2025).

downstream of beaver dams. Even when beaver dams are proactively broken up, it is common for them to continue to return to the same location or stay in the area.

- In limited circumstances, it may be possible to install storm drain inlet/outlet controls through grates and trash racks, but only if inlet capacity can be maintained without flooding and safety concerns. Where raccoons are an issue in storm drains, some communities initially reduced end-of-pipe FIB concentrations through installation of grates on storm drain inlets and outlets. However, the City of Boulder found that even when an entire outfall network had pipe inlet and outlet grates installed that concentrations increased to pre-control levels after time (Personal Communication with Michael Lawlor, City of Boulder). CU Boulder initiated an evaluation of raccoon densities in portions of the campus with grates and areas without grates utilizing game cameras; however, results regarding impact on raccoon densities in grated versus ungrated systems are not yet available.

  If the grate approach is considered, it should only be implemented when public safety is not jeopardized by increased flooding or danger of entrapment in a storm drain. By placing grates on storm drain inlets, the inlet capacity is reduced, which may require fairly costly retrofitting to maintain design capacities (HDR 2013). The effectiveness of this practice on receiving waters is not well-documented. For example, if grates are only placed on certain drains, then raccoons may simply relocate to other areas, which may also drain to the stream. For example, the home range for male raccoons is 3 to 20 square miles for males, and 1 to 6 square miles for females (Clark 1994), so eliminating a home in one storm drain will likely result in displacement to another nearby location within the home range.

- Clean out storm drains to remove animal waste. When storm drains are power washed ("jetted"), it is important the discharge be collected by a vacuum truck, otherwise, pollutants are simply flushed into the receiving water. Because animals return to storm drains and continue to defecate, the benefits of storm drain cleaning are expected to be of a limited duration. When storm drain cleaning is used as a control strategy, it may be beneficial to prioritize pipes cleaned to those with known animal usage in areas where outfalls discharge to actual recreational use areas (e.g., kayaking, tubing).

Other considerations include:

- For raccoons, there are no chemical repellents registered for controlling or repelling raccoons, although a variety of materials have been tested. Similarly, the use of scare tactics or devices is not effective or practical in controlling raccoons, particularly in urban areas.

- When managing urban wildlife, it is important to recognize that states retain primary authority over resident wildlife. When considering possible manipulation of an urban wildlife species, it is important to be aware of the legality of such actions. When in doubt, always contact a wildlife resource agency for consultation (University of Illinois Extension 2014).

Due to uncertainty associated with the effectiveness of these practices on receiving waters, it is important to conduct baseline and follow-up monitoring to assess their effectiveness.

Raccoons inhabiting storm drain system (a) and retrofitted storm drain inlet (b).
(Photos courtesy of City of Boulder, Colorado)

4.10 Irrigation, Car Washing and Power Washing[14]

Over-irrigation, car washing and power washing discharges can mobilize FIB deposited on impervious surfaces, as well as contribute to continually moist conditions in storm drain systems conducive to biofilms. Public education regarding the water quality impacts of these practices is important for changing public behavior.

Irrigation runoff from lawns, gardens, parks, and other vegetated areas can result in dry-weather nuisance flows with high concentrations of nutrients and also mobilize and transport pollutants accumulated on ground surfaces. The contribution of dry weather inflows from irrigation runoff to a stagnant pool has also been known to foster in-situ bacterial growth (Geosyntec 2010). Effective methods to reduce irrigation runoff may include development of educational outreach, increased inspections, fines for overwatering, tiered water rates, or distribution of smart irrigation controllers and/or other financial incentive programs that decrease watering volume. By promoting better irrigation runoff management, communities may find that they are able to reduce water waste (increase conservation), as well as improve water quality.

Two studies in Orange County measured the effectiveness of advanced irrigation systems for reducing irrigation runoff. A residential runoff study conducted in five neighborhoods found dry-weather runoff decreased by 50% in areas where weather-based irrigation controllers were installed (IRWD and OCMWD 2004). Berg et al. (2009) found dry-weather runoff reductions of 25% to 50% for a similar study of 4,100 Smart Timers installed in residential and commercial areas. In addition to potentially elevated *E. coli* concentrations in irrigation runoff from parks and yards, the increased flows also allow for regrowth in the MS4 and mobilization of pollutants in the MS4 to the receiving waters. Based on these studies, it is anticipated that increased irrigation runoff controls, such as inspection, enforcement, and incentives in commercial and residential land uses will generate pollutant load reductions. Irrigation controller rebates are periodically offered by water providers such as Denver Water.

[14] Adapted from San Diego Comprehensive Load Reduction Plan, Attachment E Non-structural BMPs, prepared by Geosyntec Consultants (2012).

Additionally, in Colorado, turf limits for new development and turf landscape transformations are a significant initiative under the Colorado Water Plan that may help to reduce irrigation-related contributions to MS4s. Specifically, the Colorado Water Plan, Agency Action 1.7, directs the Colorado Water Conservation Board (CWCB) to explore Colorado's transformative landscape change practices, including turf replacement. These practices aim to decrease outdoor municipal water demand and increase efficiency while preserving resilient, livable, and aesthetically pleasing outdoor environments (CWCB, 2025a).

In 2010, the Division provided Low Risk Discharge Guidance: Discharges from Surface Cosmetic Power Washing Operations to Land in accordance with Water Quality Policy 27, Low Risk Discharges with revisions in 2023 (Division 2023). The Division has not developed a general permit for this type of discharge and is instead managing the discharge through the development of guidance. The guidance sets forth a variety of BMPs and also states that if washwater reaches the street, curb flow line, impermeable channels, or other open impermeable areas, it must remain in the operator's control and be immediately collected (including all deposited pollutants) for discharge in accordance with all conditions of the Division's guidance. The Division (2010) outlines the following alternatives for disposing of power washing wastewater:

- Contact the local wastewater treatment facility to determine whether discharge of the wash water to the sanitary sewer system is allowed. If discharge to the sanitary sewer is approved by the wastewater treatment facility, collect the wash water and send it to the sanitary sewer system in accordance with the requirements of the wastewater treatment facility.
- Collect the wash water and dispose of it appropriately at a disposal facility.
- Remove solids and any pooled liquids prior to washing, fully contain the wash water on an impervious area, and allow it to completely evaporate. This activity must be conducted under the control of the operator, and in a manner that prevents any potential discharge to a storm drain or other conveyance to surface water.
- Apply for coverage under a CDPS Individual Permit.

Similarly, individual car washing can increase dry weather urban runoff and mobilizes FIB present on impervious surfaces. To reduce FIB loads, educational outreach could be increased to encourage car owners to minimize washing activities that increase runoff to storm drains.

4.11 Good Housekeeping/Trash Management (Dumpsters, Restaurants, Garbage Cans)

Good housekeeping practices involve establishing and enforcing ordinances for commercial, industrial and multi-family residential facilities. An ordinance requiring covered trash enclosures and frequent cleaning can help reduce the FIB load associated with dumpsters. Some local governments such as City and County of Denver are actively providing sturdy plastic trash cans with hinged lids, which may help to reduce exposure of garbage to rain and leakage from the bottom of the can.

For restaurants, it may be beneficial to increase inspection and enforcement of grease removal equipment, monitoring trash enclosures for proper waste disposal, and cleaning of private catch basins and drain inlets. The wet weather sources targeted by these BMPs include dumpsters and grease traps. A source tracking study performed in the San Diego River Watershed found that approximately 20% of all dumpsters or grease traps had evidence of liquid leaks. These leaking containers are of especially high importance as a result of significant concentrations of bacteria in the leaking liquid (Weston 2009a).

Municipalities can also implement restaurant inspection and trash management programs. Uncontained restaurant and grocery store wastes can be a significant FIB source in urban runoff, especially during wet weather. An expanded education and outreach program would increase restaurant and store operator awareness of this potential FIB source and provide solutions to trash management concerns. Local governments may also be able to leverage inspections conducted under Industrial Pretreatment Programs (for the sanitary collection system) as an opportunity to promote BMPs for storage of fats, oil and grease (FOG).

a) Exposed commercial waste bins in commercial areas allow rainwater to infiltrate and leak from dumpsters.
B) Improved waste management through providing good-quality residential garbage containers with hinged lids may help to reduce bacteria loading in residential areas. (Photos courtesy of Jane Clary.)

Figure 16. Example Excerpts from a Denver Multi-lingual Brochure Targeting Restaurant Staff to Increase Awareness of Trash Management Practices and Targeting Raccoon Sources

4.12 Mobile Sources of Human Waste: Portable Toilets and RV Dumping

Temporary sources of FIB can include portable toilets and illicit RV dumping. The relevance of these sources to FIB impairments is dependent on the particular watershed.

BMPs for portable toilets should address site location, cleanout frequency and transportation/hauling requirements. The placement of the portable toilet is particularly important. Guidelines for portable toilet placement may include requirements such as:

Improperly placed portable toilet with biocide running down gutter toward storm drain. (Photo courtesy of Wright Water Engineers.)

- Locate portable toilets away from high-traffic vehicular areas.
- Locate portable toilets at least 20 feet away from all storm drains: never locate a portable toilet on top of a storm drain inlet. Place portable toilets on a level ground surface that provides unobstructed access to users and servicing pump trucks.
- Wherever possible, locate portable toilets on natural ground and not on or within 5 feet of a paved surface such as asphalt, concrete or similar.
- If portable toilets must be placed on a paved surface exposed to rainwater or stormwater runoff, extra care must be taken during servicing to ensure any wastewater spilled onto the paved surface is rinsed and adequately collected so as not to leave any residue. A wet shop vacuum or similar device would provide for adequate collection.
- As a minimum, portable toilets should not be located within the 75-foot buffer of any stream or lake, or within any other larger stream/lake buffer that may have been established.

For an example of a portable toilet BMP fact sheet, see https://www.gwinnettcounty.com/static/departments/publicutilities/pdf/WQ-04%20Portable%20Toilet%20Management-%20Final.pdf).

Illicit RV dumping to storm drains can be managed in recreational areas by providing public education on appropriate practices, publicizing RV dump locations, by providing a citizen’s reporting hotline, and by publicizing fines (e.g., $1,000 fine for illegal dumping in San Diego). Educational materials can include tips such as:

- Use only designated dump stations.
- Never dump into the curb, gutter or sand.
- Connect to sanitary sewer with the correct size hose, and an airtight connection.

For an example of an RV dumping brochure, see the brochure developed by “Think Blue San Diego”: http://www.sandiego.gov/thinkblue/pdf/rvdumpcard.pdf. Locations for RV dumping in Colorado can be searched by city here: https://rvshare.com/dumpstations/colorado.

4.13 Septic Systems and Other Onsite Wastewater Treatment Systems

Onsite wastewater treatment systems (OWTSs) include a variety of on-site systems for the collection, storage, treatment, neutralization, or stabilization of sewage that occurs on a property. In some cases, OWTSs are present in urbanized areas, particularly within urban growth boundaries in areas near city limits. OWTSs include traditional septic systems, as well as other small on-site treatment systems.

In addition to approving and tracking OWTS permits, local governments can provide guidance on OWTS maintenance and on signs of failing OWTSs. As an example, Boulder County, Colorado operates a "Septic Smart" program that provides guidance to septic system owners about signs of failing septic systems, including:

- Test results of nearby well water show the presence of bacteria.
- The ground in the area is wet or soggy.
- Grass grows greener or faster in the area.
- Sewage odors in the house or yard.
- Plumbing backups into the house.
- Slowly draining sinks and toilets.
- Gurgling sounds in the plumbing.

If one or more of these warning signs exist, Boulder County recommends that the homeowner should contact a licensed septic system cleaner to have the system inspected and pumped. Additionally, the County recommends that homeowners have septic tanks proactively pumped out by a licensed OWTS cleaner every three years. Additionally, in order to optimize outreach and public education related to potentially problematic OWTSs, the county has inventoried OWTS locations using GIS and ranked and prioritized permitted sites, high risk sites, etc. For more information on this Septic Smart program, see: https://bouldercounty.gov/environment/water/septicsmart/. EPA also provides a variety of septic resources here: https://www.epa.gov/septic.

4.14 Encampment Outreach and Enforcement

Urban encampments and gathering areas for unsheltered populations can be a source of human waste posing potential human health risks in recreational waters. Housing unsheltered individuals is a serious social issue in many communities and is often a sensitive public policy issue. Based on experience gained in Southern California addressing this issue (Geosyntec 2014), recommendations for an effective encampment enforcement/outreach program may include:

- Collaboration with other agencies.
- Targeted MS4 channel cleanups.
- Enhancing programs to reduce the number of people in encampments.
- Establishing ordinances that reduce encampments.
- Enforcing new and existing laws to decrease the negative impact on water quality.

Encampment beneath bridge with human excrement on concrete. (Photo courtesy of Darren Mollendor.)

The Contra Costa County Flood Control and Water Conservation District undertook an extensive research project to understand the best approaches for addressing water quality pollution from encampments (DeVuono-Powell 2013). They found collaboration with other agencies to be the most effective approach for addressing the long-term concerns of encampments.

Options to reduce water quality impacts of encampments should ideally be combined with broader efforts to provide shelter for the unhoused community. One example is a grant-funded pilot program on Coyote Creek in San José, California that employs individuals living in creek encampments to remove trash and litter and to engage in peer-to-peer outreach with others living in the encampment. Participants are housed temporarily and given food vouchers, case management services, employment skills, and assistance at transitioning to permanent housing (EPA 2011).

Ultimately, the long-term solution to the water quality related aspects of encampments lies in the social arena. For example, see goals and actions for reducing the unsheltered community in Denver (Homelessness Resolution - City and County of Denver).

4.15 Narrowing the "Laundry List" of Potential Source Controls

The list of source controls provided in this section is broad and intended to provide ideas for approaches that local governments may want to consider to reduce *E. coli* loading; however, actual effectiveness will depend on how well the source(s) are understood and whether the suggested practice is feasible considering various financial and practical constraints. In other words, the list of practices above can be characterized as a "menu of controls" that should be considered in an adaptive management context.

5 STRUCTURAL CONTROL PRACTICES

Structural control practices to reduce *E. coli* loading include options for treating urban runoff through "passive" stormwater BMPs such as those included in the USDCM Volume 3 (MHFD 2024). Active treatment options, which are typically considered a last resort for managing dry weather flows, include low-flow diversions to the sanitary sewer if allowed by the sanitary utility and active treatment using disinfection at the outfall.

5.1 PASSIVE STORMWATER STRUCTURAL BMPS

Urban stormwater BMPs can be implemented to improve water quality for a variety of pollutants transported in wet weather flows. This section provides an overview of BMPs typically used in Colorado, expected performance of BMPs, considerations for enhancing BMP performance, and considerations for evaluating proprietary devices.

5.1.1 Urban Stormwater BMPs and Expected Effectiveness for Bacteria

In the USDCM Volume 3 (www.MHFD.org), MHFD provides BMP selection, design, construction and maintenance guidance for structural BMPs suitable for use in urban areas in most of Colorado. (Some adaptations are needed in mountain areas.) This guidance is oriented to settings found in urban areas in Colorado and considers state-specific constraints, such as Colorado water rights. The menu of structural BMPs in Volume 3 is summarized in Table 18 along with general characterization of expected effectiveness for bacteria and a summary of unit treatment process, or removal mechanisms, provided by the BMP.

Removal mechanisms for FIB in stormwater control practices include both passive and active processes. Based on a literature review conducted for the Water Environment Research Foundation (WERF) Stormwater Challenge (Strecker et al. 2009), the dominant passive removal mechanisms for FIB include natural inactivation, predation, inert filtration and sedimentation, sorption and chemical inactivation (via contacting products). Key passive pollutant removal processes that may be present in various stormwater control types are described below (Strecker et al. 2009, Leisenring et al. 2013, WERF 2007, UWRRC 2014, Clary et al. 2020).

- **Natural inactivation** is a general removal mechanism that refers to FIB die-off or inactivation due to a wide range of environmental factors. Unless provided with suitable conditions for reproduction, the number of live cells will tend to decrease with time. Growth and decay rates are highly dependent on environmental factors, which are continually changing. The most important environmental factors affecting rate of inactivation are exposure to sunlight, water temperature, and exposure to air (drying or desiccation). Additionally, FIB bound to particulates have been found to be inactivated at slower rates because particulates are hypothesized to provide both nutrients and shelter (WERF 2007).

- **Predation** of FIB by other microorganisms is interrelated with natural inactivation and has been found to be a major removal mechanism. The most important predators of FIB are believed to be protozoa and other eukaryotic organisms. Studies have found that predation may account for approximately 90% of overall mortality rates of FIB (WERF 2007). Additional studies such as Zhang et al. (2011) have begun to explore changes in microbial ecology in bioretention cells, but more research is needed in this area.

Table 18. Structural BMPs in MHFD USDCM Volume 3

BMP Type	Expected Effectiveness for FIB	Dominant Removal Processes for FIB for BMP Type	Additional Considerations
Grass Buffer	Poor	Infiltration	Buffers may increase bacteria concentrations if frequented by urban wildlife and pets.
Grass Swale	Poor	Infiltration	Swales may increase bacteria concentrations if frequented by urban wildlife and pets.
Bioretention	Moderate to High	Infiltration Filtration Biological Processes	Proper design and maintenance are important to avoid media clogging.
Green Roof	Not Well Characterized	Evaporation Filtration Biological Processes	Green roofs in Colorado typically require irrigation.
Extended Detention Basin	Poor to Moderate (*highly variable*)	Sedimentation Infiltration (limited)	The performance of EDBs for FIB reduction varies widely.
Sand Filter	Moderate	Filtration	See Section 5.1.3 for media adaptations to enhance bacteria reduction.
Retention Pond (Wet Pond)	Moderate	Sedimentation Biological Processes (predation)	Many wet ponds demonstrate significant bacteria reductions. In Colorado, water rights constraints and land requirements may limit application.
Constructed Wetland Pond	Moderate	Sedimentation Biological Processes (predation)	Wetland ponds can potentially provide bacteria reductions; however, some wetlands can export bacteria when birds and other wildlife utilize these areas for habitat. Water rights constraints.
Constructed Wetland Channel	Poor to High, depending on design	Sedimentation Biological Processes (predation)	See additional discussion in Appendix A for adaptation to a subsurface constructed wetland channel. Water rights constraints.
Permeable Pavement (various types)	Not Well Characterized	Infiltration Filtration	The primary benefit of permeable pavement is volume reduction.
MTDs (Proprietary Practices)	Variable	Device-dependent HDSs are not typically designed to remove FIB	Proprietary practices continue to evolve. Effectiveness depends on the MTD. See additional discussion in Section 5.1.4.

- **Inert filtration**[15] **and sedimentation** of solids are mechanisms that would be expected to remove FIB bound to particulates from the water column. The effectiveness of particle removal at reducing FIB concentrations is a function of the partitioning of FIB between particulate-bound and free-floating forms, and the association of FIB across the particle size distribution. Once again, the removal of FIB from the water column through sedimentation or filtration does not necessarily constitute an ultimate removal mechanism because the survival of FIB is expected to be greater when FIB are bound to sediment, and resuspension of communities of FIB sheltered by sediment could represent a significant later source of FIB via resuspension in some systems. Typical trapping efficiencies for sand filters and bioretention cells are estimated to be in the range of 60 to 80% for well-designed devices, with trapping efficiency decreasing as untreated runoff bypasses the devices and is discharged through the overflow structures during periods of high flows or when the filter is clogged (Barfield et al. 2010, Hayes et al. 2008).

  Additionally, Clark and Pitt (2012) note that most bacteria are in the lower limits of the size range for effective physical filtration using a sand medium (Figure 17). However, as the filter ages, removals will tend to increase, partly due to reduction in the effective pore size and due to the exopolymers that many bacteria excrete. These exopolymers provide surface reactive sites, even on a relatively inert sand media. Because of their negative surface charge, bacteria can be removed by attaching to these surface reactive sites. Organic media provide a location for captured bacteria to reside and grow (with potential for predation, as well). The challenge in filtration media selection is to encourage capture and potential growth to create reactive sites, but without excessive growth that sloughs off the media and is flushed out of the media with successive storms.

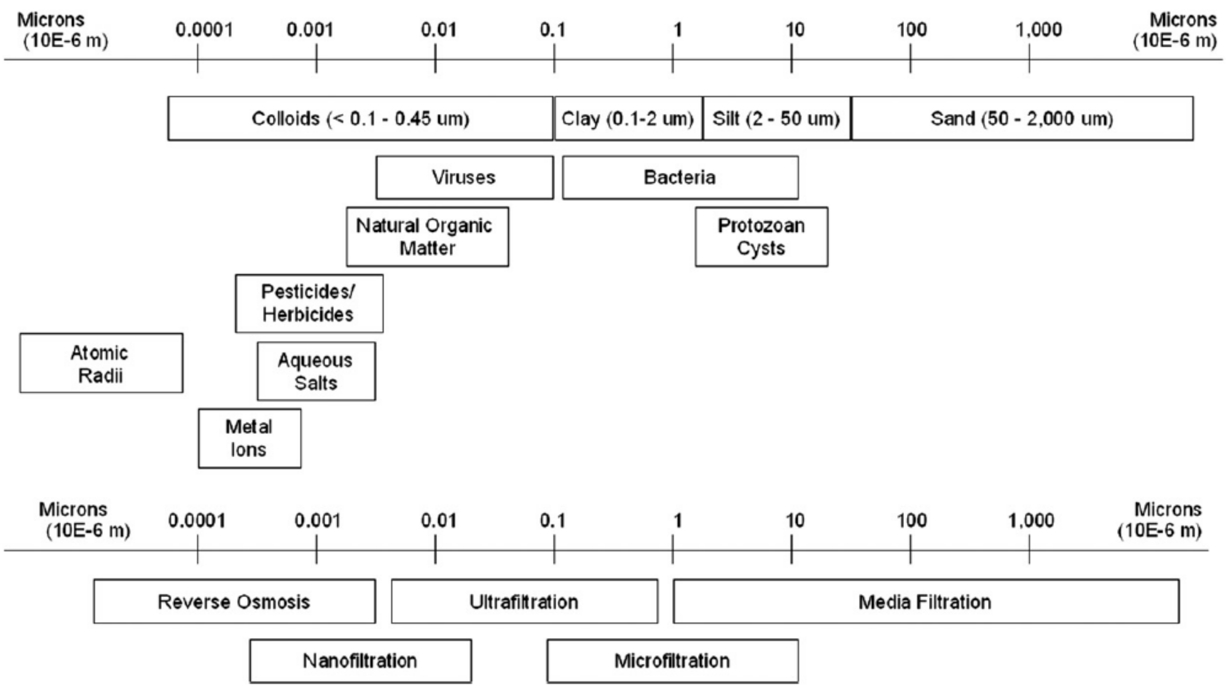
- **Sorption** involves the bonding of microorganisms to the surface of particles. This bonding is affected by parameters related to electrostatic charge, polarity and other factors. Sorption may be reversible as conditions change (WERF 2007). Partitioning of FIB to particles is expected to depend on a variety of environmental factors, stormwater characteristics and hydrodynamics and is expected to change drastically with time and likely from site to site.

- **Chemical inactivation** of FIB through contact with antimicrobial products is an approach used in a variety of proprietary BMPs. A common agent in these types of treatment devices is an organosilane derivative (C-18 organosilane quaternary), which is reported to inactivate most FIB without being consumed or dissipated and without producing toxic byproducts (Nolan et al. 2004). It is presumed that effectiveness of stormwater controls relying on a fixed microbial agent would depend on the degree of contact and contact time between stormwater and the microbial agent, dilution, and the amount of FIB bound to particulates. It is not clear whether C-18 organosilane degrades over time and needs to be recharged/replaced. If so, the time since installation or last maintenance would be expected to influence the effectiveness of such proprietary devices. Silt films on the microbial agent would also be expected to decrease their performance.

[15] Inert filtration includes physical filtration processes but does not encompass sorption and other chemical-physical processes that may occur in filter media.

In addition to these treatment mechanisms, volume-related management practices, such as infiltration, reduce FIB loads reaching waterbodies by controlling the volume component associated with pollutant loading in runoff. For considerations related to groundwater contamination associated with stormwater infiltration, see Pitt et al. (1994).

Figure 17. Particle Sizes of Viruses, Bacteria and Protozoan Cysts
(Source: Clark and Pitt 2012)



5.1.2 BMP Performance Findings from the International Stormwater BMP Database

The International Stormwater BMP Database (www.bmpdatabase.org) provides a growing repository of BMP performance data, including performance results for various FIB such as *E. coli*, enterococcus and fecal coliform. Performance analysis summaries are generated periodically to summarize expected performance of various categories of BMPs. This section provides a summary of the 2020 analysis of the BMP Database (Clary et al. 2020).

Side-by-side box plots for the various BMP measurements were generated using the influent and effluent concentrations from the studies, as provided in Figure 19 and Figure 20, for *E. coli* and fecal coliform, respectively. For each BMP category, the influent box plots are provided on the left and the effluent box plots are provided on the right. A key to the box plots is provided in Figure 18. In addition to the box plots, Table 19 and Table 20 summarize influent/effluent medians, 25th and 75th percentiles, and number of studies and data points are provided, along with 95% confidence intervals for the medians. The median and interquartile ranges were selected as descriptive statistics for BMP performance because they are non-parametric (do not require distributional assumptions for the underlying data set) and are less affected by extreme values than means and standard deviations. Additionally, the median is less affected by assumptions regarding values above upper quantification limits. See Clary et al. (2020) for more detailed information on the analysis.

Figure 18. Boxplot Key

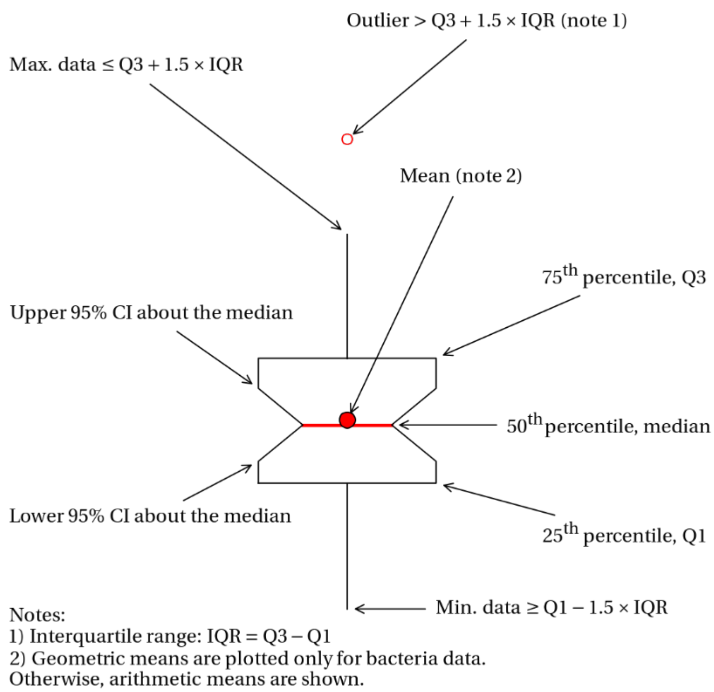


Figure 19. International Stormwater BMP Database Performance Data for *E. coli*

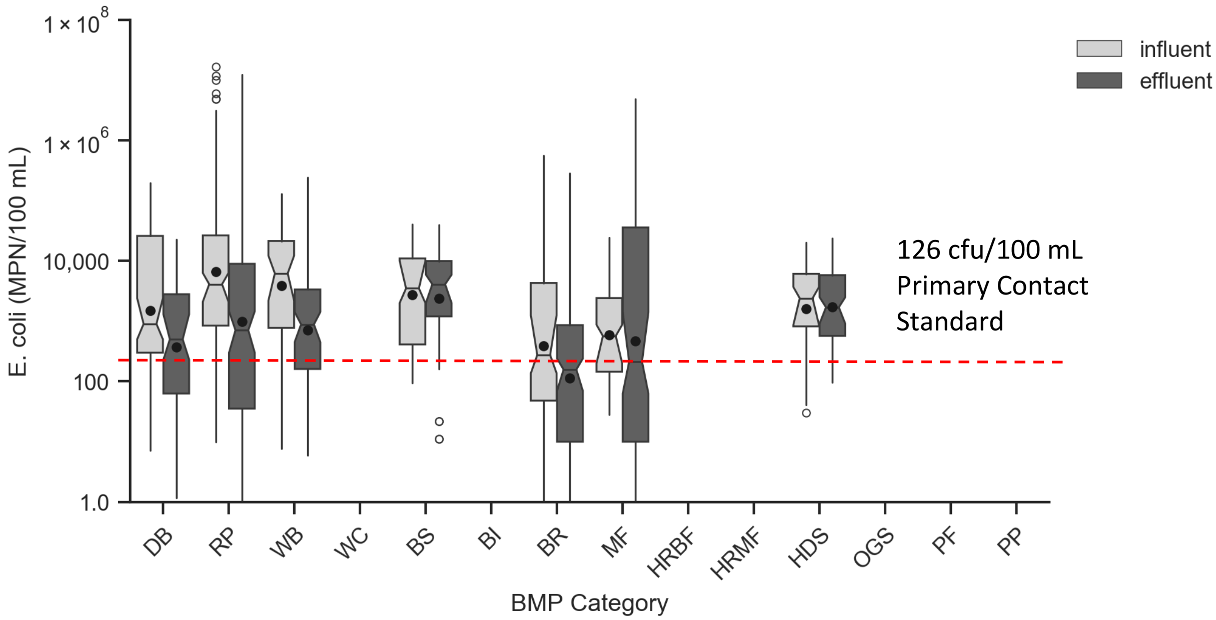


Table 19. International Stormwater BMP Database Performance Data for *E. coli*

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	3; 37 (5.4%)	3; 37 (8.1%)	300 - 26,000	63.0 - 2,800	900 (430; 1,990)	500 (133; 980)	◇▼▼
Retention Pond	7; 103 (0.0%)	7; 100 (1.0%)	854 - 26,500	35.5 - 8,980	4,110 (1,980; 6,100)	708 (156; 1,370)	▼▼▼
Wetland Basin	9; 106 (0.9%)	11; 97 (1.0%)	774 - 21,400	161 - 3,360	6,210 (2,150; 11,700)	884 (311; 1,320)	▼▼▼
Grass Swale	5; 39 (20.5%)	5; 39 (0.0%)	411 - 11,000	1,200 - 10,000	3,500 (411; 5,600)	4,100 (1,200; 5,900)	◇◇◇
Bioretention	12; 121 (8.3%)	12; 120 (16.7%)	48.0 - 4,300	10.0 - 863	275 (120; 766)	158 (46.5; 212)	◇▼▼
Media Filter	5; 54 (0.0%)	6; 74 (17.6%)	145 - 2,420	10.0 - 36,700	570 (180; 851)	214 (41.5; 664)	◇◇▼
HDS	3; 33 (0.0%)	3; 33 (0.0%)	820 - 6,100	570 - 5,800	2,400 (860; 3,400)	1,700 (780; 2,500)	◇◇◇

*Confidence interval about the median; computed using the BCa bootstrap method described by Efron and Tibishirani (1993).
**Each symbol represents an influent/effluent comparison test. Left position compares overlap of 95% confidence intervals around influent/effluent medians. Middle position compares Mann-Whitney rank-sum hypothesis test P-value to a significance value of 0.05. Right position compares Wilcoxon signed-rank hypothesis test P-value to a significance value of 0.05.

NA not available or less than three studies for BMP/constituent
% ND percentage of non-detects
◇ influent/effluent comparison test indicates no significant difference in concentrations
▼ influent/effluent comparison test indicates significant reduction in concentrations
△ influent/effluent comparison test indicates significant increase in concentrations

Credit: Tables 19 & 20 and Figures 19 & 20: © The Water Research Foundation. Clary et al. 2020. BMP Database 2020 Summary Statistics. Accessible at https://bmpdatabase.org/

Figure 20. International Stormwater BMP Database Performance Data for Fecal Coliform

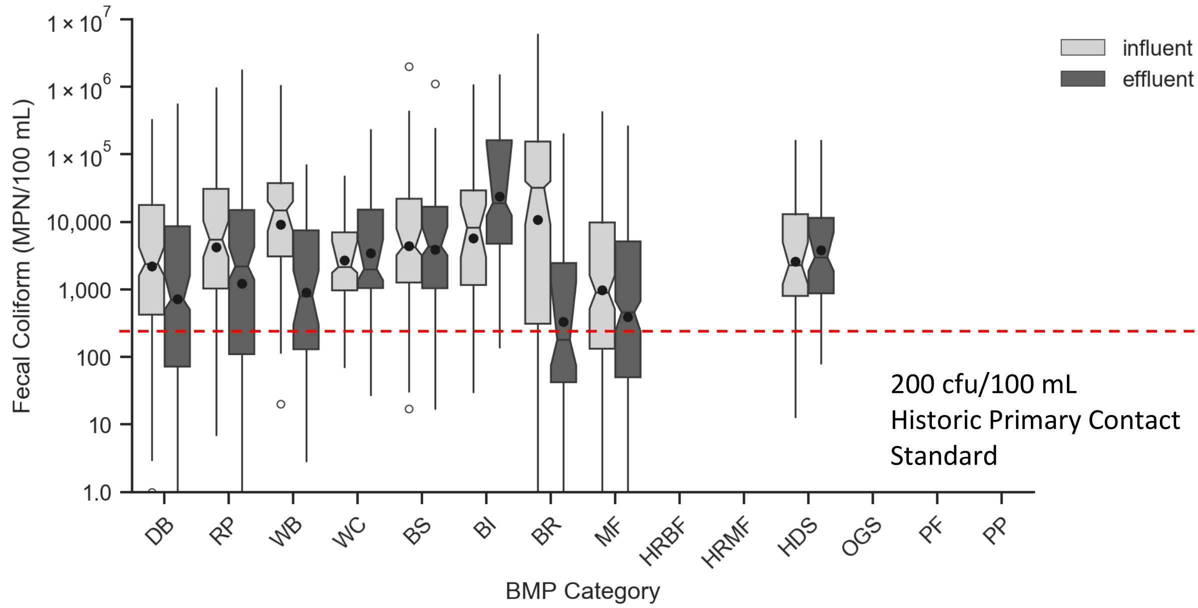


Table 20. International Stormwater BMP Database Performance Data for Fecal Coliform

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	20; 240 (2.1%)	20; 253 (2.0%)	423 - 17,800	72.0 - 8,620	2,420 (1,500; 4,010)	700 (300; 1,000)	▼▼▼
Retention Pond	15; 163 (0.0%)	18; 211 (8.1%)	1,030 - 30,800	110 - 15,000	5,500 (2,730; 10,200)	2,200 (800; 3,700)	◇▼▼
Wetland Basin	7; 65 (1.5%)	8; 53 (7.5%)	3,080 - 37,500	130 - 7,490	15,000 (5,250; 16,200)	800 (230; 1,900)	▼▼▼
Wetland Channel	7; 45 (0.0%)	7; 52 (0.0%)	967 - 7,000	1,050 - 15,400	2,150 (1,230; 4,600)	2,000 (1,230; 4,000)	◇◇◇
Grass Swale	12; 91 (14.3%)	11; 82 (4.9%)	1,260 - 22,000	1,040 - 16,800	4,200 (2,000; 5,500)	4,350 (2,500; 6,100)	◇◇◇
Grass Strip	5; 37 (18.9%)	3; 23 (0.0%)	1,160 - 29,300	5,430 - 163,000	8,200 (1,160; 16,000)	19,100 (2,800; 116,000)	◇△◇
Bioretention	11; 86 (4.7%)	8; 52 (21.2%)	312 - 155,000	42.2 - 2,480	32,500 (6,250; 40,000)	180 (58.2; 396)	▼▼▼
Media Filter	19; 212 (3.8%)	22; 238 (7.6%)	132 - 9,790	50.0 - 5,140	905 (500; 1,540)	457 (216; 593)	◇▼▼
HDS	3; 40 (0.0%)	3; 40 (0.0%)	800 - 13,000	875 - 11,500	2,300 (800; 3,000)	3,000 (881; 4,000)	◇◇△

*Confidence interval about the median; computed using the BCa bootstrap method described by Efron and Tibishirani (1993).
**Each symbol represents an influent/effluent comparison test. Left position compares overlap of 95% confidence intervals around influent/effluent medians. Middle position compares Mann-Whitney rank-sum hypothesis test P-value to a significance value of 0.05. Right position compares Wilcoxon signed-rank hypothesis test P-value to a significance value of 0.05.

NA not available or less than three studies for BMP/constituent
% ND percentage of non-detects
◇ influent/effluent comparison test indicates no significant difference in concentrations
▼ influent/effluent comparison test indicates significant reduction in concentrations
△ influent/effluent comparison test indicates significant increase in concentrations

Key findings and observations based on the 2020 analysis of the International Stormwater BMP Database include:

- Regardless of FIB type, the available data set shows that concentrations in urban stormwater runoff typically exceed primary contact recreation standards, often by one or more orders of magnitude.

- Regardless of stormwater control type or FIB type, both inflow and outflow concentrations are highly variable, typically spanning an order of magnitude or more for the interquartile range.

- Currently available data suggest that it is unlikely that conventional structural stormwater controls using passive treatment can consistently reduce FIB concentrations in runoff to primary contact recreation standards. Sand filters are the only stormwater control category evaluated with effluent concentrations approaching primary contact stream standards for *E. coli*, and retention (wet) ponds approached the primary contact standard for enterococcus (analysis not shown in this Toolbox). Although the bioretention data set's median concentration for *E. coli* was below stream standards, this data set had low *E. coli* in the influent relative to other BMP categories; therefore, these findings are inconclusive for bioretention performance.

- Bioretention (potentially), sand filters, retention (wet) ponds, extended detention basins (dry) and composite (treatment train) stormwater controls appear to be able to reduce FIB concentrations to some extent, based on hypothesis testing conducted in the BMP Database analyses. Unit processes such as sorption and filtration are present in bioretention and media filters, whereas wet ponds may provide long holding times that enable sedimentation, solar irradiation and habitat conducive to natural predation. Detention basins rely primarily on sedimentation; however, scouring and resuspension of sediment deposited in detention basins may be a potential ongoing source of FIB loading in the effluent. Review of individual detention basin studies shows that some detention basins export FIB, whereas others reduce FIB concentrations.

- Grass strips and swales do not appear to reduce FIB concentrations in their effluent. Instead, increases in effluent concentrations for fecal coliform are shown for grass strips and some grass swales studies. These stormwater control types may be exporting FIB, either from entrainment of previously deposited FIB or from new sources (e.g., animal excrement). (Note: reductions in FIB loading due to infiltration and evapotranspiration are not evaluated in this analysis.)

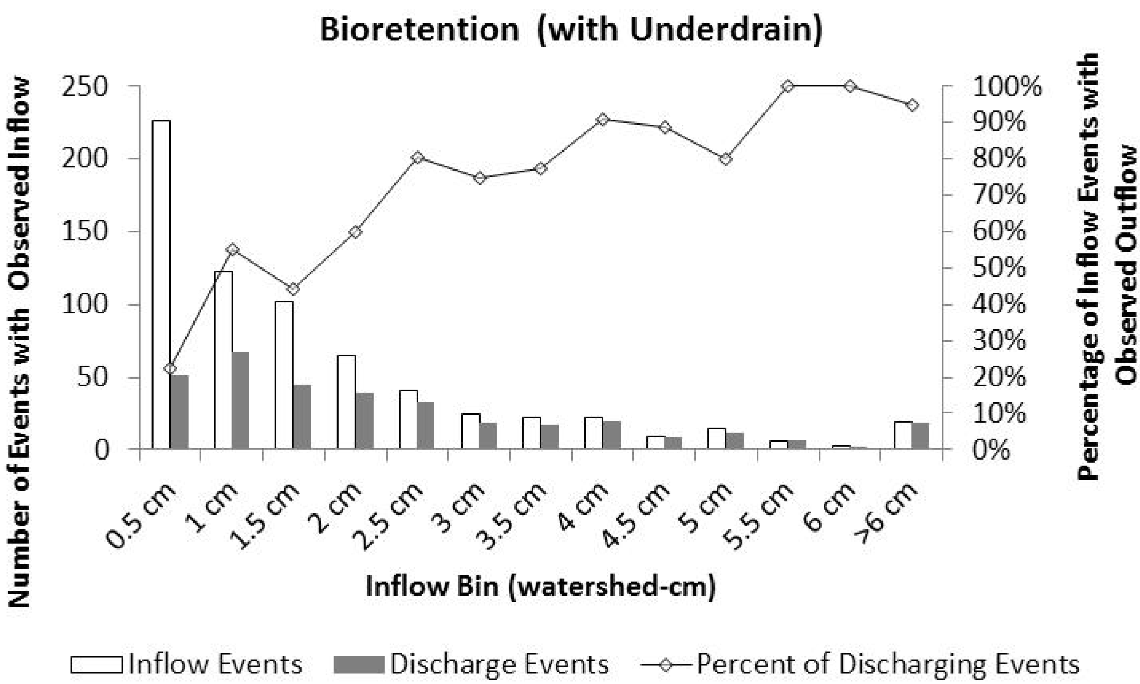
- Inadequate data sets are available to evaluate the performance of permeable pavements and green roofs. Previous review of the green roof data in the BMP Database has shown that even though roofs have relatively few sources of FIB (e.g., birds), sample results an order of magnitude above primary contact stream standards are not uncommon (WWE and Geosyntec 2010).

- The manufactured treatment device (MTD) category in the BMP Database includes a range of proprietary devices that rely on various unit treatment processes; therefore, performance should be evaluated on a unit treatment process basis for purposes of MTD selection. The only category of MTDs included in this analysis is hydrodynamic separators (HDSs), which do not demonstrate reduction of FIB. There is insufficient data to evaluate other subcategories of MTDs for FIB for the studies currently included in the database.

The concentration-based analysis presented above does not account for load reductions that may result from reduced surface volumes discharged from the various SCMs. For more information on volume reduction benefits of SCM/BMPs, see *International Stormwater Best Management Practices (BMP) Database Technical Summary: Volume Reduction* (Geosyntec and Wright Water Engineers 2011) and *Addendum 1 Expanded Analysis of Volume Reduction in Bioretention BMPs* (Geosyntec and Wright Water Engineers 2012b) for a discussion of volume reduction analyses conducted for the BMP Database. Practices that infiltrate runoff can help to reduce the number of runoff events discharged from a stormwater control device and reduce runoff volumes, which may help to reduce the number of exceedance days associated with wet weather conditions, and will reduce in-stream final concentrations. Figure 21 provides an example of analysis of discharge events for bioretention with underdrains, with inflow concentrations grouped into inflow bins of runoff normalized to watershed-centimeters.

Currently, insufficient permeable pavement studies for FIB have been submitted to the BMP Database for analysis for FIB. To the extent that permeable pavement sites reduce runoff volumes from a site, they would be expected to help reduce discharged pollutant loads under wet weather conditions and to reduce the frequency of exceedance days, similar to bioretention.

Figure 21. Presence/Absence of Discharge Plots for Bioretention Sites with Underdrains
(Source: Geosyntec and WWE 2011)



5.1.3 Optimizing Stormwater BMP Designs to Enhance Bacteria Removal

Typically, the most cost-effective BMPs for bacteria removal from urban runoff rely on infiltration; however, infiltration is not always a viable approach when site soils prohibit infiltration, sufficient space is not available for adequate detention of flows prior to infiltration, or high groundwater is present. As noted in the previous section, some BMP types can provide statistically significant reduction of FIB; however, few, if any, can consistently meet primary contact standards, except for disinfection, which is typically unrealistic for most wet weather applications.

An area of current research relates to optimizing filtration media and design components in bioretention (biofilters) and media filters. Effluent concentrations for fecal coliform and *E. coli* in these BMPs vary depending on climate and design parameters, with removal rates generally greater than 50%.[16] Overall, a somewhat limited number of field studies have been performed. Many of the available studies are laboratory-based utilizing column tests with lab-created ("synthetic") stormwater, which may not reflect all the complexities of a full-scale system with actual stormwater runoff (e.g., low natural organic material (NOM) results in inflated FIB removal rates, and low TSS or unrealistic particle size distributions result in overestimated times to clogging). Table 21 provides a summary of some of the research over the past 10 years related to media amendments to improve FIB and pathogen removal since publication of this Toolbox.

The 2016 version of this Toolbox provided additional discussion of research available at that time that has been moved to Appendix A. As described in more detail in Appendix A, representative considerations from available literature suggest that incorporating the following design components may improve FIB reduction in biofilters:

- Media amendments such as biochar and zeolite; however, continued field testing is needed related to real-world installations in terms of clogging and maintenance requirements.
- Vegetation with specific root structures to promote pollutant removal and infiltration.
- Outlet control with sufficient contact time. (MHFD criteria provide sufficient contact time.)
- The presence of a saturated zone.

Also included in Appendix A is a discussion of subsurface flow wetlands, which are a potential adaptation of a wetland channel with the potential to reduce FIB. Because this practice is not typically used in Colorado, it has also been moved to the appendix.

Beyond specific media mixes, research by the University of Minnesota has also focused on more basic design questions such as whether more infiltration can be achieved to reduce pollutant loads by capping underdrains in conservatively designed bioretention facilities that have characteristics suitable for infiltration (Erickson 2018).

[16] In addition to recent references in Table 21, earlier representative references include: Barrett 2003, Hunt et al. 2008, Rusciano and Obropta 2007, Zhang et al. 2010, Kim et al. 2012, Chandrasena et al. 2014, Chandrasena et al. 2012a, Chandrasena et al. 2012b, Passeport et al. 2009, Mwabi et al. 2012, Prabhukumar 2013, Zhang et al. 2010, Mohanty et al. 2014, Mohanty et al. 2013, Hathaway et al. 2012, Hathaway et al. 2001, Li and Davis 2009,Li et al. 2014a, Li et al. 2014b, Li et al. 2012, Miller 2009.

Table 21. Representative Media Amendment Studies for FIB and Pathogen Removal

Year	Source	Amendment / Agent	BMP / Setup	Indicator(s)	Study Type	Lab Results	Field Results
2014	Li et. al. (2014)	Antimicrobial-modified media: Cu-immobilized zeolite; Cu(OH)2-coated GAC (plus other agents screened)	Gravity-fed columns with natural stormwater; 24-week operation; contact-time tests	E. coli	Lab/mesocosm (column; natural stormwater)	Estimated ~2-log E. coli reduction within 40 min; ~0.8-log removal at ~4.5 min contact time.	Not reported (column study).
2014	Mohanty et. al. (2014)	Biochar (5% w/w) in sand biofilter media	Lab columns; steady & intermittent flow; with/without natural organic matter (NOM)	E. coli	Lab (column)	Biochar retained up to ~3 orders of magnitude more E. coli than sand and reduced mobilization; NOM reduced removal but biochar still outperformed sand.	Not reported.
2015	Torkelson et. al. (2015)	QAS-coated sand; ZVI; biochar (media amendments)	Long-term intermittent stormwater column experiments (weekly dosing) + drinking water chapters	E. coli; MS2 (and others in dissertation)	Lab (long-term columns) / dissertation	Improved pathogen/indicator removal with amended media; performance sensitive to ionic strength, flow, and humic acid fouling (by chapter).	Not field; simulated storm cycles in columns.
2016	Chandrasena et. al. (2016)	Field biofilters; indicator vs pathogen comparison under normal vs challenging conditions	Two established field-scale biofilters treating urban stormwater	E. coli; Campylobacter spp.	Field (biofilter monitoring)	Not applicable.	E. coli log reduction higher than Campylobacter; no correlation between their log removals; only one biofilter met guideline log reduction targets on average.
2017	Shingle Creek WMC (2017)	Biochar + iron-enhanced sand (IES) in filters	Field trials (pond bench retrofits and catch basin inserts); multi-year monitoring described	E. coli (and others)	Field (pilots)	Notes lab experiments show biochar + IES can remove bacteria in synthetic stormwater.	Monitoring described; project page does not provide a single consolidated removal statistic.
2018	Afrooz et. al. (2018)	Biochar-amended stormwater biofilters (geomedia)	Lab-scale biofilters; pathogen and viral indicator challenge tests	Salmonella Typhimurium; Staphylococcus aureus; E. coli; MS2	Lab (biofilter)	Up to ~3.9 log10 removal for pathogenic bacteria; ~1.9 log10 for E. coli; ~1.8 log10 for MS2.	Not reported.
2019	Kranner et. al. (2019)	Biochar amendment; saturated zone (media saturation)	61-week conditioning with natural stormwater; then wastewater-spiked challenge tests	E. coli; enterococci; F+ coliphage	Mesocosm/simulated field + challenge tests	Challenge tests: biochar enhanced removal of all fecal indicators; saturated zone improved removal.	Conditioning: biochar improved E. coli removal early (~31 wks) but not late (~30 wks); mobilization minimal (<2.5%).
2020	Boehm et. al. (2020)	Biochar in biofilters (systematic review)	Systematic review of lab/mesocosm studies (subset meeting inclusion criteria)	Microbial pollutants (multiple indicators) + trace organics	Review / synthesis	Across included studies, biochar media generally showed higher microbial log10 removal than controls (sand/soil/compost).	Not a field monitoring study; discusses implications and longevity.
2020	Rahman et. al. (2020)	Biochar-amended sand columns (property comparison: CEC vs surface area)	Column study with acclimation and multiple urban storm events	E. coli	Lab/mesocosm (columns)	Reports improved E. coli removal for higher-surface-area biochar in early storm events (reported as 100% in the document).	Not field installation.
2021	Ghavanloughajar et. al. (2021)	Iron filings (3% and 10% by weight) in compost+sand biofilter media	Lab columns; intermittent E. coli-contaminated stormwater; focus on	E. coli	Lab (column)	10% iron reduced first-flush E. coli leaching by ~32% vs compost columns; DOC reduced adsorption capacity.	Not reported.
2021	Valenca et. al. (2021)	Biochar selection (high-temp wood-based) for E. coli removal	Lab columns for screening; pilots summarized in program materials	E. coli	Lab (column) + pilot field trials (reported)	Program summary reports ~99.95% E. coli removal in lab trial for selected biochar media (example).	Program summary reports small-scale field trials ~49–93% E. coli reduction (site-specific pilots).
2023	Mitchell et. al. (2023)	Biochar and fungi (Stropharia rugosoannulata) in bioretention media	Bioretention columns; roadway runoff dosing across 8 events over 14 months	E. coli; fecal coliform	Mesocosm/ column (long-term; real runoff)	First dosing event exported FIB; subsequent events showed treatment; findings suggest biochar improved E. coli treatment (qualitative).	Not field installation.
2023	Ulrich (2023)	Biochar selection and translation to field performance	Presentation summarizing lab evidence and field testbed outcomes	E. coli	Presentation (lab-to-field translation)	Summarizes lab-scale support for E. coli removal with selected commercial biochars (references Valenca et al.).	Reports no improvement of custom-produced biochar relative to sand-only in referenced field context (as presented).
2024	Ulrich et. al. (2024)	Biochar-amended sand vs sand vs iron-enhanced sand (IES) filters	Field testbed treating parking lot runoff; 21 precipitation events over 2 field seasons	E. coli	Field (event monitoring)	Not reported.	Biochar amendment did not improve E. coli retention relative to sand; IES showed >90% net TP retention.
2025	Wilkins et. al. (2025)	Biochar (literature review / synthesis)	Review of biochar properties, dosing, particle size, longevity, leaching	Microbial pollutants (general)	Review / synthesis	Summarizes that biochar can improve microbial removal in some controlled studies; emphasizes variability.	Summarizes mixed field outcomes depending on biochar and operating conditions.

5.1.4 Considerations for Evaluating Proprietary Devices

The proprietary market for stormwater controls is continually evolving, and significant changes are occurring related to verification and certification programs. A systematic evaluation of manufactured devices designed to reduce FIB and pathogens was not completed for purposes of this report. Based on observations from studies in the International Stormwater BMP Database, HDSs typically do not reduce *E. coli* due to short residence times and lack of biological or chemical treatment mechanisms. Filtration devices such as high rate media filters and high rate biofilters may be able to reduce *E. coli*. Research continues on various amendments to filtration-based products related to bacteria removal. The following guidance should be considered when reviewing performance data and literature associated with the antimicrobial or bacteria removal claims of a proprietary device:

- **Use “real” stormwater**: It is preferred that “real” stormwater (including NOM and suspended sediment) be used in such evaluations rather than synthetic stormwater; otherwise, performance results may not be representative of installed conditions. If synthetic stormwater is used, NOM and suspended solids should be added to mimic “real” stormwater and influent FIB concentrations should be representative of typical stormwater runoff concentrations.
- **Effluent concentrations reported:** It is preferable to review independently measured quantitative results for each monitored event (including effluent concentrations), rather than simplified percent removal tabulations, since effluent concentration tends to be a more robust predictor of performance.
- **Independently conducted or verified field-based studies:** If only laboratory studies are available, they should include careful control, measurement, and reporting of practical contact times in order to scale results for field implementation. However, it is highly preferred that field demonstration test results are provided because lab and field studies do not always result in the same findings.
- **Availability of study design details:** Studies should provide design details (influent and effluent concentrations for the monitored storm events, precipitation and flow data associated with monitored events, and information on the sampling plan) for careful review and applicability to site-specific applications.

Some proprietary devices with antimicrobial claims may be subject to registration with regulatory agencies (e.g., the EPA or possibly the Colorado Department of Agriculture). Investigation into these regulatory review processes and registrations is important before making any agreements with suppliers since proper registration and review may be legally required and will aid in protecting the environment from potential uncontrolled exports of toxic material.

Examples of detailed proprietary device evaluations based on field installations can be obtained from:

- New Jersey Department of Environmental Protection (https://dep.nj.gov/stormwater/stormwater-manufactured-treatment-devices/)
- New Jersey Cooperative for Advance Technology (NJCAT) program (http://www.njcat.org/verification-process/technology-verification-database.html);
- Washington State Department of Ecology TAPE Program (TAPE) (https://ecology.wa.gov/regulations-permits/guidance-technical-assistance/stormwater-permittee-guidance-resources/emerging-stormwater-treatment-technologies)
- International Stormwater BMP Database (www.bmpdatabase.org)

- The National Center for Stormwater Testing and Evaluation for Products and Practices (STEPP) (likely to be a future source of information) (https://ms4nmsa.org/stepp/)
- Other sources such as in-depth academic dissertations and publications (e.g., Cai et al 2014), as a few examples.

If a proprietary device is selected, care should be taken to ensure proper maintenance following manufacturers' guidance, since they are often underground (out-of-sight). When proper maintenance is not conducted, sediment and organic materials captured in the device can become a source of FIB. Similarly, if devices allow resuspension and scouring of sediment, then export of FIB may be an issue.

5.2 Low-Flow Diversions for Dry Weather Flows

Diversion of storm sewer flows to sanitary systems is not typically allowed in Colorado; however, in some states, diverting dry weather flows to the sanitary sewer system for treatment has been used as an option for reducing dry-weather *E. coli* loading if such flows cannot be practically or cost-effectively controlled. Typically, feasible source control reduction measures should be implemented before considering a low-flow diversion. This approach has been used frequently in California for outfalls that discharge to swim beaches. As of 2015, there were over 125 of these projects in response to bacteria TMDLs for California beaches. The range of costs for dry-weather diversions reported by the Surfrider Foundation for 35 diversion projects in California funded under the Clean Beaches Initiative (CBI) was $200,000 to $5 million, with a median cost of approximately $750,000. (Note: 2026 costs would be much higher because the year of cost basis is likely 15-25 years old and has not been updated for inflation.) For examples, see http://www.beachapedia.org/Dry_Weather_Diversions_in_California_-_Diverted_by_Diversions%3F.

In Colorado, local governments should anticipate significant obstacles to implementing this approach for the following reasons:

- Legal prohibition of storm discharges to the sanitary sewer system.
- Possible water rights complications related to changing the point of discharge and ambiguity of flow sources.
- Concerns from WWTP operators regarding other difficult-to-treat pollutants such as selenium and arsenic that may be present in groundwater.

These challenges may be more manageable if the MS4 and WWTP are operated by the same municipality. In cases where a municipality's wastewater is treated by a special district, this option may not be viable. When discussing potential options with WWTPs, it is important to clarify that the flows being treated are dry weather discharges rather than stormwater dischargers.

Low-flow diversion systems are designed to operate only during periods of dry weather. During significant wet weather, the systems are typically shut off or bypassed. Diversion structures vary in complexity from temporary inflatable dams and portable pumps to complex engineered systems with automatic controls, flow meters, and alarm systems. The systems may be by gravity flow or rely on pumps. In many cases there is some type of screening, filtering, or centrifugal separation device installed as part of the diversion that keeps trash and large solid particles out of the sewer lines. The low-flow diversion can be constructed underground in roadways.

Advantages of low-flow diversions include:

- Effectively and reliably remove low-flow loading from diverted outfalls during dry weather conditions.
- May be more cost-effective than alternatives, depending on site conditions.
- Effective with varying flows up to allowed diversion capacity.

Potential disadvantages in Colorado include:

- Requires pre-treatment to remove trash and to prevent entry of hazardous materials.
- High sanitary tap fees, particularly if the WWTP ownership and the MS4 permittee are different entities.
- Not effective during wet weather.
- In some cases, the capacity of the sewer lines or the unwillingness of the sewer agency to accept the diverted dry weather urban runoff may preclude use of this option.
- Capital cost to install diversions varies widely, depending on such factors as the flow, the nearness and relative elevation of sewer lines and the degree

Representative Requirements Established by WWTPs Allowing Dry-Weather Stormwater Diversions to Sanitary Sewer

- The diversion must be designed to exclude wet weather flow and must have a lockable shut-off device accessible to WWTP agency.
- The applicant must apply for and obtain a permit from the WWTP agency prior to discharging.
- The permit applicant must demonstrate that other disposal alternatives have been considered, evaluated and deemed not feasible.
- Debris and pollutants of concern must be prevented from entering the sewer system.
- The daily total flow must be measured.
- The applicant must employ BMPs designed to minimize or eliminate dry weather urban runoff.
- The quality of the discharge must meet the WWTP agency's standards, the discharger must conduct quarterly self-monitoring and submit reports to WWTP agency.
- Discharges must be shut off no later than the commencement of any measurable rainfall and cannot be resumed without written approval from WWTP agency.

Source: OCSD, 2015

of automated control desired. The cost may range from a few thousand dollars to hundreds of thousands of dollars. Depending on the sewer agency, there will likely be a continuing cost based on the flow rate and/or the concentration of contaminants.

- Possible disruption of wastewater treatment process due to high pesticides/herbicides, TDS, spilled gasoline or dumped oil. (These are also reasons that a wastewater utility may choose not to accept MS4 flows.)
- Possible ecological effects from decreased baseflows to the stream which could disrupt movement of fish, and/or reduce water supporting downstream riparian habitat.
- Water rights constraints (depending on the stream segment).

5.3 Active Disinfection Practices

Active disinfection methods include techniques such as UV light irradiation, chlorination, ozonation, peracetic acid, and others (UWRRC 2014). These methods are well documented as effective treatment techniques for sanitary wastewater (sewage); however, they are typically a last resort for treatment of dry and wet weather discharges. The reasons that active disinfection methods are typically a last resort include:

- Disinfection does not provide benefits for reducing nutrients and other pollutants that may be associated with bacterial discharges to streams. Additionally, FIB are readily inactivated at low UV doses ($\approx$10–20 mJ/cm^2), whereas viral pathogens typically require several-fold higher doses, meaning FIB reductions alone may not mean that there is corresponding comprehensive pathogen risk reduction, depending on how the system is operated (EPA 1999, Masjoudi 2021).
- Most urban streams in Colorado include multiple outfalls rather than a single combined major outfall enabling consolidation of treatment facilities in a central facility. (In contrast, most of the active disinfection examples for California beaches enable use of a single facility for a swim beach.)
- Existing outfalls are inherently located in already developed areas, which present space constraints for end-of-pipe treatment. Although disinfection of low flows may be feasible with a relatively compact treatment facility footprint, wet weather treatment facilities require a substantially greater footprint and capital cost due to the need for flow equalization basins.
- Active disinfection requires active operation and management over the long-term with significantly greater costs than passive BMPs. These costs can include electricity, UV bulb replacement, other parts replacement, mechanical repairs, vandalism repairs and labor. Additionally, for UV disinfection to be effective, sediment needs to be removed from flows, which results in additional maintenance of pretreatment facilities such as vaults and hydrodynamic separators.
- Although disinfection can effectively treat flows for pathogens, the downstream receiving water may not necessarily attain recreational water quality criteria since new sources of FIB (e.g., wildlife, birds) may be introduced following treatment (Murray and Steets 2009).

For these reasons, when considering use of active treatment, it is generally recommended that source controls should be implemented as a primary stormwater treatment strategy first, followed by carefully selected passive-treatment structural stormwater controls (BMPs). In cases where these practices are not effective and high levels of recreational use are present, disinfection may be a viable alternative of last resort, particularly if human sources of FIB have been confirmed and not controlled by other measures.

City and County of Denver UV Disinfection Case Study for Dry Weather Flows

The City and County of Denver's MS4 permit requirements are based on achievement of an end-of-pipe concentration-based *E. coli* limit of 126 MPN/100 mL. In order to achieve these numeric limits, Denver installed end-of-pipe UV treatment at three high priority outfalls in the 2017-2020 timeframe. Design and construction cost per treatment system ranged from $200,000 to $500,000, with ongoing equipment, power and maintenance costs for perpetuity of operation. Representative maintenance costs include replacement of UV bulbs and sediment removal from upstream pretreatment (e.g., hydrodynamic separators). For one outfall (N-411-E), Denver estimates that 350 staff hours per year are needed for maintenance, including vault cleanout up to twice per month. Operational challenges have included issues such as flows short-circuiting the treatment system. Although the UV treatment systems have reduced *E. coli* at end-of-pipe, instream monitoring in the South Platte River has not shown a corresponding reduction in *E. coli* attributable to these treatment systems. (Personal Communication with Brad Cox, Denver Department of Transportation and Infrastructure)

UWRRC (2014) provides an overview of the strengths and weaknesses of several disinfection practices that may be considered for active disinfection such as UV disinfection, ozonation, peracetic acid and chlorine, discussed primarily in the context of treating dry weather flows. UV disinfection is described below since it has been implemented in the metro Denver area.

UV light irradiation, known as UV disinfection, involves UV bulbs used for wastewater disinfection emit energy at a wavelength of about 254 nm, which penetrates the cell wall of a microorganism and is absorbed by cellular materials such as nucleic acids. This absorption will either keep the cell from reproducing or destroy the cell entirely. UV disinfection requires a relatively high level of pretreatment to reduce suspended solids (Field 1996), typically using sand filtration or another method, a pump, and backwashing for filter maintenance. UV disinfection effectiveness requires careful design with regard to flow rate, which is a principal determinant of the dosage of UV light necessary for effective disinfection (Wojtenko et al. 2001). UV disinfection is a safer option than chemical disinfectants and has no known downstream ecological effects. The system may be placed in a pump house and does not require additional land. The capital cost is low compared to other active treatment alternatives. Operation and maintenance (O&M) includes regular inspection, cleaning, bulb replacement, and an energy supply (Geosyntec 2009). Because fouling materials deposited on quartz sleeves of UV bulbs decrease transmittance of UV light and associated disinfection capability (Oliver and Cosgrove 1975), an in-place cleaning system should be considered to remove fouling materials from the quartz sleeves.

Effectiveness of disinfection is influenced by the water quality (e.g., turbidity and organic matter content), type of disinfectant used, disinfectant dosage and disinfectant contact time. Challenges arise in disinfecting urban runoff due to the extreme variability between dry and wet weather flow volumes (Stinson and Perdek 2003). Disinfection of urban runoff requires some form of filtration, sedimentation prior to introduction of disinfecting chemicals or irradiation (EPA 1973a&b). High levels of particulate matter in urban runoff (particularly during wet weather conditions) can provide a "shielding effect" in which particles protect the microbes from the disinfecting agent (Sakamoto and Cairns 1997). To enhance treatment of wet weather flows, it is essential that mechanical or chemical pretreatment processes are applied prior to disinfection and are subjected further to high-rate filtration processes prior to discharge to waterbodies. Thus, the costs of active treatment for disinfecting stormwater include additional costs for pretreatment and flow equalization prior to the disinfection process itself.

5.4 Considerations for Channel Designs

Currently available research related to channel enhancements for bacteria reduction is relatively limited, although research related to wetland channels and stormwater BMPs provides insight into principles and unit treatment processes that may help to reduce bacteria loading (e.g., UWRRC 2014, Kadlec and Wallace 2009, WWE and Geosyntec 2010). Removal mechanisms include solar irradiation, predation/antagonism/competition from other microorganisms, sedimentation and filtration (Kadlec and Wallace 2009). Sorption to filter media, physical straining, and other chemical/biological ecological processes may also be important removal mechanisms that are leveraged by channel designs that incorporate subsurface flow wetlands elements. Additionally, lower nutrient conditions may also be beneficial for controlling bacteria regrowth within the stormwater conveyance system (McCarthy 2008, Surbeck et al. 2010). The survival of *E. coli* in the environment depends on interaction of multiple factors and many questions exist in the scientific community regarding the fate and transport of bacteria, so uncertainty exists regarding how successful any particular design feature will be in a particular location for reducing *E. coli* loading (UWRRC 2014). Nonetheless, the following design and maintenance considerations may be worthwhile to consider as part of channel design features:

- Increase sunlight (UV exposure), which is a benefit of an open channel versus a piped channel. However, there are tradeoffs related to other water quality concerns like temperature when tree canopy is present, which can provide shade that reduces temperatures.

- Increase hydraulic residence time and minimize channel velocities. For example, a sinuous low-flow channel can help to lengthen the flow path and increase hydraulic residence time. These features enhance natural die-off, sedimentation, and generally improve effectiveness of other treatment processes.

- When water rights and site constraints allow, consider using a constructed wetland channel design rather than a grass-lined channel. Grass-lined swale designs generally do not show reductions in bacteria concentrations for urban runoff (although volume reduction may contribute to load reductions) (WWE and Geosyntec 2010, 2014). Wetland channel designs incorporate additional unit treatment processes that may help to reduce bacteria loading.

- Consider integration of a subsurface flow treatment wetland for baseflow (dry weather) conditions (see Appendix A). Subsurface flow wetlands consist of a gravel or media bed planted with wetland vegetation where the water is kept below the surface of the bed and flows horizontally from the inlet to the outlet. An advantage that subsurface flow wetlands have over other constructed wetland systems (e.g., free water surface wetland) is that the water is not exposed above the surface during the treatment process, thus reducing the risk associated with human or wildlife exposure to pathogenic organisms. In addition, properly designed and maintained systems do not provide suitable ponded water habitat for waterfowl or mosquitos. Subsurface flow wetland systems typically include inlet piping, a lining system, filter media, emergent vegetation, berms or dividers, and outlet piping with water level controls. For stormwater flows, a constraint for this approach is that a flow equalization basin upstream of the system is usually required, which requires land availability and increases cost.

- If subsurface flow wetlands are infeasible, integrate wetland vegetation in the channel or along channel edges. This has the dual benefit of discouraging geese loafing up to the edge of the channel and provides substrate for predatory microbes. A potential downside of wetland channels in some locations, however, is that they can attract natural wildlife, which may be a potential source of bacteria loading in some conditions. Other wetland features such as a mixture of shallow and deeper water zones may also be beneficial, if site conditions allow.

- Consider features that promote sedimentation and reduce scour (resuspension). This could be accomplished by sediment traps and/or baffling features. Although dry weather flows typically have relatively low sediment loads, storm runoff would be expected to have higher sediment loads, which can be deposited in the channel, becoming a persistent source of bacteria, particularly if disturbed and resuspended.

- Design the channel with velocity control features so that low-flow channel segments are protected from scour/resuspension during the higher flows expected during storm runoff.

- If wetland features are incorporated into the channel design, water rights must be taken into consideration as part of the feasibility evaluation and design.

- Manage nutrient loading from overland flow areas to the channel by utilizing native or low-maintenance vegetation in landscaped areas draining to the channel. If manicured turf is utilized, fertilizer and irrigation practices should be carefully managed.
- Where parks and trails are components of the drainage feature design and are expected to be frequented by pets, provide and maintain appropriate pet waste disposal cans and signage.

6 PUBLIC HEALTH ADVISORIES

Figure 22. Public Health Signage

The ultimate purpose of recreational water quality criteria and standards is to protect public health; therefore, when standards are exceeded, local governments are encouraged to provide signage or other educational information to educate recreators regarding potential health risks and practices that reduce the inherent health risks from recreating in natural waters.[17] Figure 22 provides examples of signage that can be posted in areas where recreation commonly occurs, and Figure 23 and Figure 24 provides an example of public health information that can be posted on a website and/or provided to park rangers or open space staff for communication with the public.

Although some locations may have consistently elevated *E. coli*, it is more common in Colorado for *E. coli* concentrations to vary seasonally (higher in the summer) and following storm events. Research is underway in various parts of the country related to "now casting" conditions that are correlated with elevated FIB for purposes of Clean Water Act beach closure notification programs. Variables such as precipitation, temperature, sunlight (UV irradiation), turbidity, humidity and other factors may be part of such predictive tools, but the correlations are site specific and not transferable between beaches (Brady and Plona 2012, Huey and Myer 2010). Also see discussion of emerging technologies such as real-time sensors that may be used for early warning in Section 2.6.

In addition to "reactive" public education and outreach, local governments should also consider proactively reaching out directly to recreational user communities to provide education on "best practices" when recreating in natural waters. Even when a stream is not labeled as impaired, there are always inherent risks when recreating in natural waters, which are not chlorinated like swimming pools.

[17] Designated "natural swimming areas" in Colorado, which are typically located at lakes and reservoirs with fee-based access, have additional specific requirements as described in 5 CCR 1003-5.

Figure 23. Example Denver Recreational Advisory Messaging

Figure 24. City of Boulder Public Messaging
(Source: https://bouldercolorado.gov/e-coli-boulder-creek)

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E. Coli in Boulder Creek

Recreate Safely

When wading or swimming in any natural water body, including Boulder Creek, you may be exposed to *E. coli* and other microorganisms. Most types of *E. coli* do not cause illness, but there are certain strains that can cause gastrointestinal illness and symptoms can include nausea, vomiting, stomachache, diarrhea, headache and fever. Boulder Creek does periodically exceed the level of *E. coli* deemed safe for recreational use by the U.S. Environmental Protection Agency.

Use these tips to help reduce the chance of getting sick while swimming:

- Don't get water in your mouth, eyes or open wounds.
- Stay out of the water if you are sick or have a weakened immune system.
- Wash your hands and shower after being in the creek.
- Don't swim within 48 hours of a rainstorm or if the water looks cloudy or discolored.
- Be aware that small children and older adults may have more risk of contracting serious illness from waterborne pathogens.

What can you do to help reduce bacteria pollution?

Everyone can help reduce pollution in Boulder Creek and other creeks in Boulder. Stormwater run-off goes directly into our creeks without being treated. Trash, debris and pollution you see on streets, sidewalks and parks is therefore likely to end up in the creeks.

- Pick up after your pets at home, in your neighborhood and on the trails.
- Keep trash bins closed and inaccessible to wildlife.
- Replace cracked waste bins, keep street gutters clean from trash and pick up after yourself and your neighbors to avoid attracting wildlife. Contact your property manager if your waste area does not look well maintained.
- Use waterwise landscaping and talk with your neighbors about water conservation.
- Reduce or eliminate lawn and garden irrigation, fix leaking or broken irrigation equipment and keep sprinklers aimed at landscaping, not the sidewalk or road. Report over-irrigation on city properties or broken irrigation equipment on Inquire Boulder.
- Follow Leave No Trace principles when recreating outdoors. Always use restrooms, and always properly dispose of soiled diapers.
- Report illegal dumping or improper waste disposal, and anything but clean water (e.g., paint, chemicals) entering the street, storm drains or any body of water. Report these issues on Inquire Boulder or follow steps to report a spill to the stormwater quality program.
- Visit the Keep It Clean Partnership to learn more about how you can protect water quality by preventing stormwater pollution.

7 REGULATORY CONSIDERATIONS/SITE-SPECIFIC STANDARDS

Once local governments have identified and corrected controllable sources of *E. coli* to the "maximum extent practicable," it is possible that streams and stormwater outfalls may continue to exceed recreational water quality standards. In such cases, regulatory adjustments to stream standards or discharge permit conditions may be appropriate at some point. Because only a limited number of *E. coli* TMDLs have been completed in Colorado to date with MS4 permit requirements, the Division is still gaining experience in such situations. This chapter provides basic information on regulatory alternatives in Colorado, followed by guidance from EPA that provides additional detail on site-specific standards under EPA's 2012 Recreational Water Quality Criteria and 2024 Technical Support Materials. Although not applicable in Colorado, a summary of experiences in California with natural source exclusions and human-source prioritization strategies is also included.

7.1 COLORADO'S APPROACH TO REGULATORY ALTERNATIVES FOR *E. COLI* STANDARDS

Regulation 31, The Basic Standards and Methodologies for Surface Water, outlines regulatory options for assigning stream standards in Colorado. The primary options for modifying a stream standard include changing the designated use based on a Use Attainability Analysis (UAA), changing the standard based on a site-specific analysis, adopting a discharger specific variance (DSV), or a temporary modification to the standard. Additional information for two of these options includes:

- **Ambient Quality-Based Site Specific Standards:** Regulation 31 allows adoption of "ambient quality-based standards" where evidence has been presented that the "natural or irreversible man-induced ambient water quality levels" are higher than the stream standard but are determined adequate to protect classified uses. In this case, the Commission may adopt site-specific chronic standards equal to the existing quality of the available representative data. Site specific standards must be supported by a use attainability analysis (UAA) or other site-specific analysis completed in accordance with EPA-approved methods or in accordance with comparable procedures deemed acceptable by the Commission (paraphrased from Regulation 31, Section 31.7). Longevity plans must also be developed to support these standards.

  In Colorado, UAAs resulting in changes of recreational use have occurred when the Division has determined that no existing recreational uses are in place and that access and flow conditions preclude future use.[18] In urban areas in Colorado, the potential for waterplay by children is a factor that significantly limits relaxation of standards and use classifications for recreational use, even if the standard is not attainable. EPA's most current guidance for UAAs along with examples from various states is provided at https://www.epa.gov/wqs-tech/use-attainability-analysis-and-use-revision-process. Section 7.2 of this Toolbox provides information on EPA's current guidance related to site-specific standards for *E. coli*.

- **Discharger-Specific Variance (DSV):** A variance to a water quality standard may be granted by the Commission when certain criteria are met. A DSV is adopted as a water quality standard (as opposed to a permit limit). DSVs are considered temporary and must be re-examined not less than once every three years. A DSV is authorized only where a comprehensive alternatives

[18] For examples, see CDPHE Use Attainability Library accessible at https://cdphe.colorado.gov/environment/water-quality/clean-water/water-quality-standards.

analysis demonstrates that there are no feasible alternatives that would allow for the regulated activity to proceed without a discharge that exceeds water quality-based effluent limits. In addition, an applicant for a variance must satisfy both of the following criteria:

i. Tests to Determine the Need for a Variance

- Limits of Technology: Demonstration that attaining the water quality standard is not feasible because, as applied to the point source discharge, pollutant removal techniques are not available or it is technologically infeasible to meet the standard;

- Economics: Demonstration that attaining the water quality standard is not feasible because meeting the standard, as applied to the point source discharge, will cause substantial and widespread adverse social and economic impacts in the area where the discharge is located. Considerations include such factors as the cost and affordability of pollutant removal techniques; or

- Other Consequences: Human caused conditions or sources of pollution prevent the attainment of the use and cannot be remedied or would cause more environmental damage to correct than to leave in place.

ii. Demonstration that the conditions for granting a temporary modification to the stream standard are not met; or, if those conditions are met, determination by the Commission, after considering the site-specific circumstances, that granting a DSV is preferable as a matter of policy.

A limitation of a DSV is that it only applies to dischargers with numeric effluent limits assigned in their CDPS permits. Most MS4 permits in Colorado rely on BMP-based approaches implemented to the maximum extent practicable (MEP), as opposed to numeric effluent limits enforced at the end-of-pipe; therefore, DSVs may not provide regulatory relief for MS4s. Additionally, although DSVs can be renewed, they are considered temporary and require ongoing attention to maintain.

7.2 Other State Approaches to Site-Specific Standards

In other states, examples of site-specific standards using UAAs include temporary suspension of recreational uses during high flows (e.g., Los Angeles, Kansas, New York) and in some cases for ephemeral streams (e.g., Missouri, New Mexico). Additionally, EPA approved a wet-weather-limited recreational sub-use category and corresponding numeric criteria that provides increased regulatory flexibility in CSO-impacted areas in New York based on a UAA (EPA 2024).

For over a decade, California's regulatory framework for FIB TMDLs has recognized that natural sources of FIB can contribute to exceedances of water quality standards. A reference condition approach has been integrated into water quality standards and FIB TMDLs. More specifically, streams and beaches representing reference conditions (i.e., natural conditions) serve as the basis for allowable exceedance days for WLAs assigned in TMDLs. Although a detailed discussion of this procedure is not repeated here, the basic concepts for this approach include characterizing dry and wet weather exceedances of numeric FIB standards in a natural reference area and allowing comparable exceedances in a TMDL waterbody. An example outcome from the TMDL for Bacteria in San Pedro Creek and at Pacifica State Beach (California Regional Water Quality Control Board San Francisco Bay Region 2012) is shown in

Table 22. In this table, the second row of data shows the wet and dry weather exceedance days for the Water Quality Objective (WQO) for freshwater and beach reference sites with the final row providing the reduction target in days for the TMDL waterbodies. For more detailed information on this procedure, see: https://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/pacificabacteria/Final%20Staff%20Report.pdf

Table 22. San Pedro Creek and Pacifica State Beach TMDLs and Allocations Using the Reference System (Table 8.3 from TMDL)

(Source: San Francisco Bay Regional Water Quality Control Board 2012)

Table 8.3. TMDLs and Allocations for San Pedro Creek and Pacifica State Beach Expressed As Allowable Exceedances of Single-Sample Objectives

	San Pedro Creek		Pacifica State Beach		
	Dry Weather	Wet Weather	Summer Dry Weather (Apr. 1 to Oct. 31)	Winter Dry Weather (Nov. 1 to Mar. 31)	Wet Weather
Number of Days (in critical reference year 1994)	229	136	176	53	136
WQO Exceedance rate (observed at the reference systems)	1.6%	19%	0%	3%	22%
Allowable Exceedances of Single-Sample Objectives (assuming daily sampling is conducted) [1,2,3]	4	26	0	2	30
Allowable Exceedances of Single-Sample Objectives (assuming weekly sampling is conducted) [4]	1	4	0	1	5
Current Exceedances of Single-Sample Objectives (assuming weekly sampling is conducted)[5]	14	14	1	1	5
Required Reduction in Number of Exceedances of Single-Sample Objectives (assuming weekly sampling is conducted)	13	10	1	0	0

1. Allowable exceedances are calculated by the following equation: Allowable Exceedances = WQO Exceedance rate in Reference System(s) x Number of Days during each respective period in 1994.
2. Consistent with the Santa Monica Bay Beaches Bacteria TMDL, and to end up with whole numbers, where the fractional remainder for the calculated allowable exceedance days exceeds 0.1, then the number of days are rounded up.
3. The calculated number of exceedance days assumes that daily sampling is conducted.
4. To estimate the number of exceedance days during the reference year given a weekly sampling regime, as practiced for monitoring San Pedro Creek and Pacifica State Beach, the number of exceedance days were adjusted by solving for "X" in the following equation: X = (exceedance days x 52 weeks) / 365 days.
5. For Pacifica State Beach, the current exceedance rate is based on the "Linda Mar Beach #5" monitoring station, where an exceedance of any single-sample objective on any day counts as an exceedance. For San Pedro Creek, the exceedance rate is based on the "Creek Mouth" station located near the mouth of the creek, where an exceedance of any single-sample objective on any day counts as an exceedance (see Table 8.1).

In practice, reference waterbodies often do not meet the TMDL WLAs. Other cases where WLAs have not been met include 1) streams and beaches in subwatersheds with >95% undeveloped open space, 2) streams and beaches during dry weather where 100% of flows are diverted to the sanitary sewer or to UV disinfection treatment, and 3) streams and beaches where several million dollars have been invested in aggressive wet-weather controls. In cases where BMPs are not achieving the desired TMDL endpoint and human sources of bacteria have been mostly controlled, communities may need to consider developing the groundwork for a site-specific standard, as discussed in Section 7.3.

7.3 EPA's Approach to Site-Specific Alternative Recreational Criteria

In the 2012 Recreational Water Quality Criteria (2012 RWQC), EPA provided three alternatives for developing site-specific standards, which are further described in EPA's Overview of Technical Support Materials: A Guide to the Site-Specific Alternative Recreational Criteria TSM Documents (EPA 2014). Detailed Technical Support Materials (TSMs) to further explain and provide guidance on each of these alternatives are being developed by the EPA, with some TSMs now available. EPA generally describes these approaches as:

1. alternative health relationships ("Epidemiological Studies")
2. non-human fecal sources ("Quantitative Microbial Risk Assessment")
3. alternative indicators and methods

Each of these alternatives is briefly summarized below, as described by EPA.[19] From a practical perspective, epidemiological studies are extremely costly and likely beyond the financial means of most MS4s. To achieve regulatory modification to account for non-human sources of bacteria, QMRA is expected to hold the most promise; therefore, additional practical steps for conducting a study to support QMRA are provided in addition to EPA's overview. A TSM document for the development of alternative indicators and methods has already been published by EPA (2024), while detailed guidance for the development of alternative health relationships through epidemiological studies and performing QMRAs for non-human fecal sources have yet to be released.

7.3.1 Epidemiological Studies

Epidemiological studies have traditionally been used to describe the probability of illnesses associated with exposure to recreational waters containing fecal contamination as measured by FIB. It is important to note that the FIB do not necessarily cause illness. Instead, they are used to gauge the magnitude and extent of fecal pollution in a waterbody. Epidemiological studies, with or without QMRA, could be used to develop an alternative health relationship for a water quality metric. This alternative health relationship could inform the basis of site-specific alternative criteria. EPA's National Epidemiological and Environmental Assessment of Recreational Water (NEEAR) epidemiological study was conducted in water primarily impacted by human fecal contamination, with the exception of one site that was impacted by urban runoff (EPA 2010b; Wade et al. 2006, 2008, 2010). Statistically significant associations between water quality, as determined using EPA's Enterococcus spp. quantitative polymerase chain reaction (qPCR) Method 1611 (EPA 2012b), and reported GI illness were observed in the temperate marine and freshwater beaches impacted by WWTPs. In the U.S., other agencies have

[19] Text adapted from EPA (2014) Overview of Technical Support Materials: A Guide to Site-Specific Alternative Recreational Criteria TSM Documents.

also conducted recreational water epidemiological studies. For example, epidemiological studies of recreational water exposures have been conducted in Southern California (Colford et al. 2012), Southern Florida (Fleming et al. 2006, 2008; Sinigalliano et al. 2010), and Ohio (Marion et al. 2010). As one example focused on wet weather sources, the Southern California Coastal Water Research Project (SCCWRP 2016) Surfer Health Study (Technical Report 943) included a three-year investigation into illness risks associated with surfing during wet-weather conditions in San Diego. The study integrated epidemiology, water-quality monitoring, and QMRA to quantify the relationship between pathogen exposure and gastrointestinal illness to identify the illness rates of surfers at beaches in the San Diego area during wet weather. This study provided one of the first empirically grounded demonstrations that wet-weather surfing in Southern California carries a substantially increased risk of gastrointestinal illness, directly linked to stormwater-borne pathogens (Schiff et al. 2016; Layton et al. 2015).

Several factors can influence the potential epidemiological relationship between indicator density and the potential for human illness. Some of the potentially important factors include the source of fecal contamination, age of the fecal contamination, solar radiation, water salinity, turbidity, dissolved organic matter, water temperature, and nutrient content. Additionally, numerous factors also affect the occurrence and distribution of FIB and pathogens, including but not limited to: predation of bacteria by other organisms; differential interactions between microbes and sediment, including the release and resuspension of bacteria from sediments in the water column; and differential environmental effects on indicator organisms versus pathogens (EPA 2010b; WERF 2009).

States or local agencies may choose to conduct epidemiological studies in their waterbodies and use the results from those studies to derive site-specific alternative criteria. To derive scientifically defensible alternative water quality criteria for adoption into state standards, ideally the epidemiological studies should be rigorous, comparable to those used to support the 2012 RWQC, and peer reviewed. However, smaller scale epidemiological studies may also provide a scientifically defensible foundation for alternative criteria. Additionally, QMRA (see Section 7.3.2.1) can enhance the interpretation and application of new or existing epidemiological data (Boehm et al. 2009; Dorevitch et al. 2011; Soller et al. 2016). QMRA can supplement new or existing epidemiological results by characterizing various exposure scenarios, interpreting potential etiological (disease causing) drivers for the observed epidemiological results, and accounting for differences in risks posed by various types of FIB sources. The additional insights QMRA can provide in these situations may help inform site-specific alternative water quality criteria development.

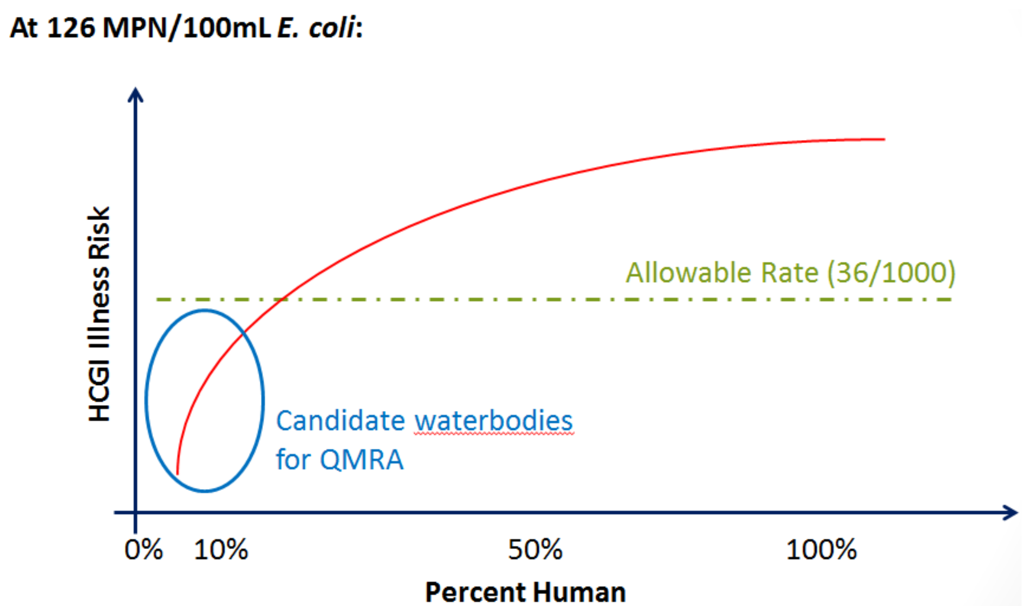
7.3.2 Quantitative Microbial Risk Assessment (QMRA) for Waters Impacted by Non-human Fecal Sources

In addition to being used for source identification (described in Section 2.3.2), advanced MST tools (i.e., human markers) can be used to demonstrate the absence (or near absence) of human fecal contamination in a receiving water, which is a prerequisite for QMRA eligibility (Figure 25). To perform QMRA, human markers (e.g., HF183) may be used in combination with the direct measurement of pathogens (either by culture or advance molecular methods) to quantify the risk associated with water contact recreation. Estimated illness rates are calculated using concentrations of markers and pathogens along with dose-response relationships and exposures estimates. The outcome of this process could lead to alternative water quality criteria that are equally protective of human health.

This section provides an overview of EPA's guidance regarding the use of QMRA for developing site-specific standards, along with additional practical guidance (at an overview level) for communities that eventually may be considering a QMRA study or want to develop a conceptual-level understanding of the process.

Figure 25. QMRA Candidate Waterbodies

(Source: Steets et al. 2013, based on Soller et al. 2014)



7.3.2.1 EPA's Framework for Use of QMRA for Developing Site-Specific Standards

EPA's 2012 RWQC were developed to be protective of the primary contact recreational designated use for waterbodies affected by any source of fecal contamination. The 2012 RWQC were informed by studies conducted in WWTP effluent-impacted waters. Because the pathogens in human feces are highly infectious to other humans, EPA believes that developing criteria recommendations based on these studies represents a prudent and health protective benchmark. However, there are scenarios of contamination from non-human sources and non-fecal sources of FIB that potentially present markedly different probability of illness relative to human sources. QMRA can be used as a basis to develop site-specific alternative criteria, where sources are characterized predominantly as non-human or non-fecal (EPA 2009).

EPA's research indicates that understanding the predominant source of fecal contamination could help characterize the human health risks associated with recreational water exposure. QMRA studies have demonstrated that the potential human health risks from human and non-human fecal sources could be different due to the nature of the source, the type and number of human pathogens from any given source, as well as variations in the co-occurrence of pathogens and fecal indicators associated with different sources (Till and McBride 2004; Roser and Ashbolt 2006; Ashbolt et al. 2010; Schoen and Ashbolt 2010; Soller et al. 2010b; Wuertz et al. 2011; Soller et al. 2016). Further, research demonstrates that swimming-associated illnesses can be caused by different pathogens, which depend on the source of fecal contamination. For example, in human impacted recreational waters, human enteric viruses appear to cause a large proportion of illnesses (Soller et al. 2010a). In recreational waters impacted by gulls and agricultural animals such as cattle, pigs, and chickens, pathogenic bacteria and protozoa are the likely etiologic agents of concern (Roser and Ashbolt 2006; Schoen and Ashbolt 2010; Soller et al. 2010b). The relative level of predicted human illness in recreational waters contaminated by non-human fecal sources can also vary depending on whether the contamination is direct or via runoff due to a storm event (Soller et al. 2010b; EPA 2010a; De Man et al. 2014; Soller et al. 2014; Sunger and Haas 2015).

As of 2025, no QMRA-derived site-specific recreational criteria are known to have been approved by EPA, despite initiated case studies in some areas. For example, two QMRA test cases were conducted in Southern California: Inner Cabrillo Beach in Los Angeles and Tecolote Creek in San Diego. SCWWRP led the Cabrillo Beach study, with the objective to conduct a QMRA at a California marine beach to establish a case study precedent for technical QMRA implementation. A goal of this case study was to ensure a sufficient technical foundation was built to support policy discussions and decision making for creating FIB site-specific water quality objectives or TMDL numeric targets based on quantified swimmer health risk (Schiff et al. 2019). In 2016, the study began with a rigorous source identification study that found that human fecal contamination sources were present too frequently to apply a QMRA approach. Repairs to sanitary sewer infrastructure were completed in the Port of Los Angeles in an effort to reduce human sources, but it was subsequently determined that low level, diffuse human sources persisted, even with those repairs.

For the Tecolote Creek case study that the City of San Diego began in 2013, human sources were also too prevalent to proceed with QMRA. Monitoring data collected between 2013-2016 indicate FIB in the creek are likely from human sources. Information in the California Water Boards Report Card for the creek indicate that source investigation and abatement such as sewer main replacement are underway (California Water Boards 2020). Completion of corrective actions and abatement of human sources of bacteria are needed for QMRA to proceed.

In addition to these two California studies, various studies are also occurring in other parts of the country such as in Florida where QMRA is being used to refine understanding of recreational risk based on sources of FIB; however, standards have not been revised based solely on QMRA (Gitter et al. 2023).

To derive site-specific alternative criteria that are considered scientifically defensible and protective of the designated use, QMRA studies should be well documented, transparently presented, follow accepted practices, and rely on scientifically defensible data. A sanitary characterization can provide detailed information on the potential source(s) of fecal contamination in a waterbody to determine whether the predominant source is human or non-human. EPA developed a QMRA-specific sanitary survey application, which could be included in a sanitary characterization, to capture information directly applicable to a QMRA. At sites where non-human sources predominate, QMRA can be used to determine an alternate enterococci or *E. coli* criteria value that is equally protective of human health compared to the recommended 2012 RWQC. Fundamental to this approach is a thorough understanding of the potential sources of fecal contamination impacting a waterbody.

7.3.2.2 EPA's 2024 Technical Support Materials: Developing Alternative Recreational Criteria for Waters Contaminated by Predominantly Non-Human Fecal Sources

In 2024, EPA published "Technical Support Materials: Developing Alternative Recreational Criteria for Waters Contaminated by Predominantly Non-Human Fecal Sources." The TSM supports the implementation of the EPA's 2012 Recreational Water Quality Criteria using QMRA to derive site-specific alternative water quality criteria for ambient recreational waters where the predominant contamination is from non-human fecal sources. The TSM is highly technical and targeted to risk assessors and those who prepare or review water quality standards packages. Concepts considered in the guidance include exposure scenarios, reference pathogens, QMRA parameters such as dose-response functions, information on risk characterization and other information. The TSM describes the scientific basis and process for developing alternative water quality criteria that are considered scientifically defensible and protective of the primary contact recreational designated use at the same level of health protection as the 2012 Recreational Wate Quality recommendations (EPA 2024). The TSM also includes example case study calculations and computer code (in Python and R) to perform the QMRA calculations. The TSM provides guidance on three key questions, corresponding to the process shown in Figure 26:

- Are the predominant fecal contributions to the site from non-human sources?
- What is the potential risk from recreational exposure to feces-associated waterborne pathogens at the site?
- How do I calculate alternative criteria to ensure that the proposed site-specific criteria are protective of the primary contact recreational designated use?

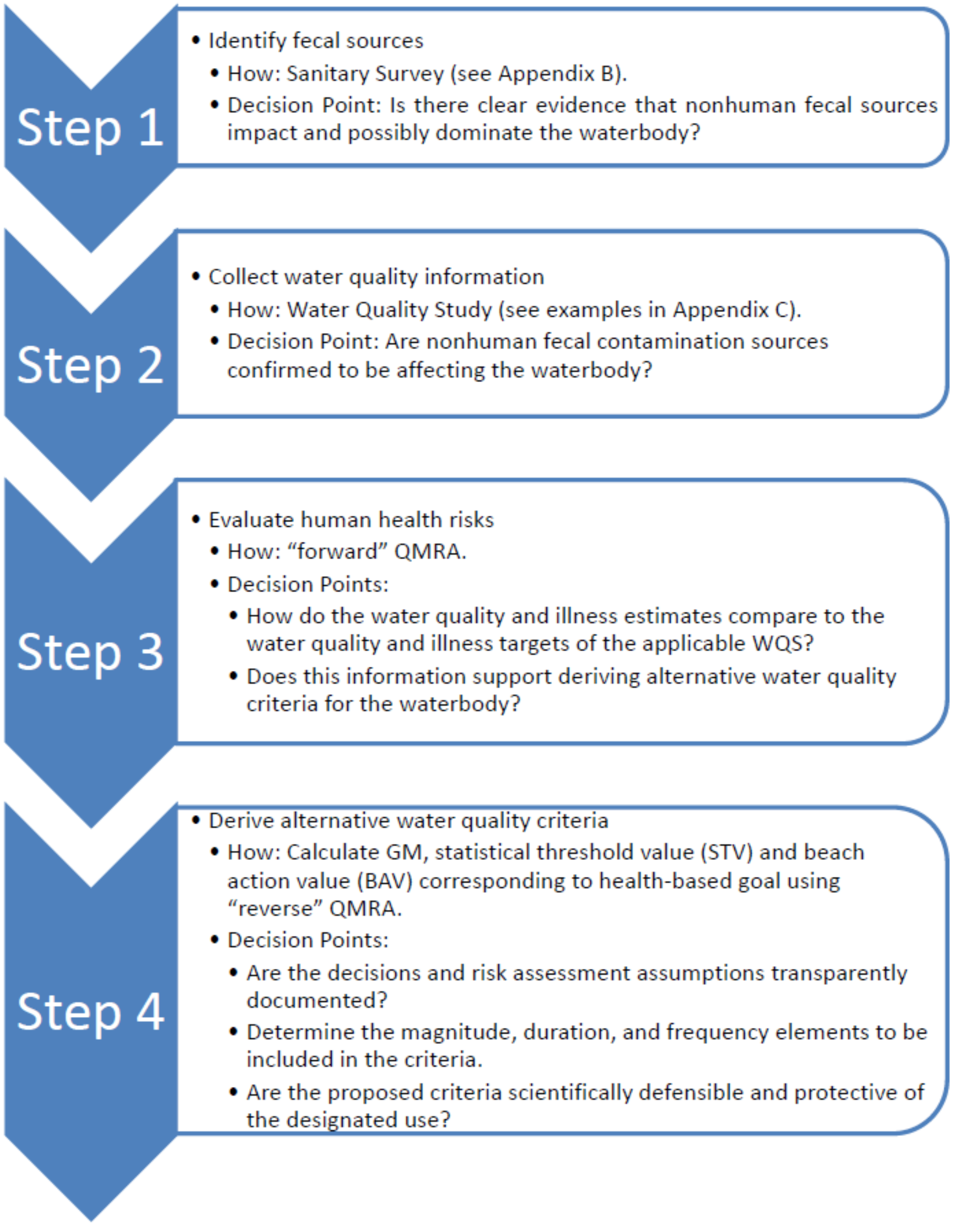


Figure 26. Flow Diagram for Considering QMRA in Developing Site-specific Alternative Criteria (Source: EPA 2024)

Although Colorado is not currently actively engaged in developing such site-specific criteria, some of the concepts described in the TSM are nonetheless useful for TMDL implementation planning and communicating relative risk to the public. For example, EPA's introduction to the TSM explicitly recognizes the limitations of a "one size fits all" approach to recreational water quality criteria and acknowledges different levels of human health risk, depending on sources. EPA (2024) states:

> A key recommendation from the Expert Workshop was to develop more flexible recreational water criteria because "one size fits all" criteria would be inadequate for both public health protection and Clean Water Act (CWA) compliance

activities (U.S. EPA, 2007a,b). There is recognition that a single indicator measured to gauge water quality may derive from many sources (i.e., humans, animals [agricultural and wildlife], and environmental) and the health risks to humans vary depending on which of these sources is contributing to the indicator being measured and the pathogens that can cause illness. Public health warning systems based on the single indicator approach do not provide an equal level of health risk protection in all recreational waters. Notification and remediation activities, such as beach postings, listings, and total maximum daily load (TMDL) determinations, are not necessarily focused on the recreational waters representing the greatest potential health risk. These activities occur in recreational waters where indicator levels exceeding standards can result from "natural" or environmental sources and processes (U.S. EPA, 2007b).

7.3.2.3 Practical Considerations for Monitoring to Support QMRA

QMRA is generally considered a potentially useful approach in moderately urbanized watersheds where significant compliance efforts have already been implemented and where initial source tracking results demonstrate an absence (or near absence) of human fecal contamination. Streams that are relatively close to meeting TMDL WLAs and underlying EPA RWQC and which have had investments previously directed to controlling anthropogenic sources are considered potentially good candidates for QMRA as described in Figure 26.

The general premise of QMRA is based on concepts of equivalent risk and the fact that risk varies based on sources of FIB. If the sources of FIB are relatively low risk, then a higher (less restrictive) water quality standard for FIB can be implemented while still protecting human health. Risk is based on exposure and potency. Exposure includes concentration of pathogens and ingestion rate, whereas potency is based on documented dose-response rates of illness in published literature. Simply described, the key steps involve:

1) Monitoring for <u>both</u> FIB and pathogens to develop a data set suitable for conducting QMRA.

2) Calculating expected illness rates associated with measured pathogen concentrations using QMRA methods.

3) Comparing calculated illness rates to EPA's tolerable illness levels (TILs) (e.g., 36 illnesses/1,000 exposures).

4) Either determine existing FIB levels are acceptable (delist the impairment) or develop site-specific criteria to match the tolerable illness levels

For examples of QMRA studies, see Rijal et al. 2011, Petropolou et al. 2008, Soller et al. (2010b), Schoen (2010), Ashbolt et al. (2010), Wuertz et al. (2011), Soller et al. (2016), Schiff et al. (2016) and others.

Communities considering QMRA should be aware that the identification of human sources of FIB during step 1 can be an unanticipated finding that causes a QMRA study to be abandoned, at least until human sources are removed. There are multiple examples of sanitary surveys where human sources have been found in storm drain systems. For example, Sercu (2009, 2011) identified leaking sanitary sewer lines into storm drains as sources of human markers in Santa Barbara, California. A study by Sauer (2011) identified human markers in at least one sample collected at all 45 outfalls monitored in a Milwaukee study. In Los Angeles, human markers were detected in half of Los Angeles River dry weather storm drain samples (CREST 2008). Divers (2013) and Bradbury (2013) found leaking sewers to be pervasive in Pittsburg, Pennsylvania and Madison, Wisconsin, respectively. Recent source tracking studies performed in multiple California watersheds including Cowell Beach in Santa Cruz, California (Russell et al. 2013), Doheny State Beach in Dana Point, California (Layton et al. 2015), and the Monterey Bay region (Schriewer et al. 2010) have detected human markers in samples collected from the surf.

For communities considering QMRA for purposes of an alternative recreational water quality standard, a potential cost range for a single stream reach or beach site could be on the order of $1,000,000 to $2,000,000 for precedent-setting studies. Costs would vary depending on the number of sample locations included and whether the study addressed both wet and dry weather conditions. It is expected that costs may decrease as regulator comfort level grows, and the number of laboratories and consultants experienced in performing these studies grows.

A full QMRA to develop alternative criteria approved by a regulatory agency would be costly, likely requiring hundreds of samples over multiple years. In contrast, a QMRA "Screening" Study could allow for health risk estimates to be made at a much lower cost, but without the step of seeking regulator review and approval. Such health risk estimates could be used to communicate actual recreational risks with the public, show regulatory agencies, NGOs, and other parties that MS4s are being proactive in protecting public health, and shed light on the viability of a full QMRA in the future.

7.3.3 Alternative Indicators or Methods

EPA anticipates that scientific advancements will provide new technologies for enumerating fecal pathogens or FIB. New technologies may provide alternative ways to address methodological considerations, such as rapidity, sensitivity, specificity, and method performance. As new or alternative indicator and/or enumeration method combinations are developed, states may want to consider using them to develop site-specific alternative criteria for adoption in water quality standards (WQS) or as the basis for notification when a state does not plan to modify existing WQS. The TSM, Site-Specific Alternative Recreational Criteria Technical Support Materials for Alternative Indicators and Methods, describes a process for comparing enumeration methods that may allow users to take advantage of the rapid and continuing advancements in the science of microbial water quality.

New methods and additional improvements to currently available methods, platforms, and chemistries may also be developed in the future. Examples of possible alternative indicators include, but are not limited to *Bacteroidales*, *Clostridium perfringens*, human enteric viruses, and coliphages. These possible alternative indicator organisms could be used with new methodologies or methodologies similar to those recommended by the 2012 RWQC. For example, in one case, *Bacteroidales* measured by qPCR were highly correlated with Enterococcus spp. and *E. coli* when either culture-based methods or qPCR methods were used (Wuertz et al., 2011). The pathogens norovirus GI and GII have also been shown to be predictors of the presence of other pathogens such as adenovirus measured by qPCR (Wuertz et al., 2011).

Coliphage (viruses that infect *E. coli*) continue to be evaluated by the EPA as an alternative indicator of fecal contamination due to their fate and transport properties that may be more similar to human viruses in the environment (http://www.epa.gov/wqc/microbial-pathogenrecreational-water-quality-criteria#Review of Coliphages). As an example, Price, Blackwell and Noble (2023) compared EPA-approved coliphage detection methods (Method 1642) with molecular MST markers (including HF183) and FIB in recreational waters. The research assessed how well viral indicators and quantitative

MST methods perform under stormwater-influenced conditions. Results showed that correlations between coliphages, FIB, and MST markers were weak, and that EPA Method 1642 is cumbersome and may be poorly suited for stormwater-dominated systems.

If a state adopts WQS using alternative indicator/method combinations, EPA will review those standards, including any technical information submitted to determine whether such standards are scientifically defensible and protective of the primary contact recreation use. Due to the highly technical nature of the alternative indicators discussion, readers are directed to EPA's 2014 TSM on this topic (http://www.epa.gov/sites/production/files/2015-11/documents/sitespecific-alternative-recreational-indicators-methods.pdf).

8 CONCLUSIONS

Reduction of *E. coli* loading in urban areas is challenging and costly. This Toolbox was developed to support communities, particularly MS4s, working towards attainment of instream recreational water quality standards by providing a concise overview of regulations driving TMDLs and MS4 permit conditions and then focusing on approaches to understanding sources of *E. coli*, potential non-structural and structural BMPs, and regulatory alternatives, particularly those resulting from EPA's 2012 update of its *Recreational Water Quality Criteria*. A summary of key points from this Toolbox includes:

1. There are many potential sources of *E. coli* in urban areas. In order to effectively control these sources and select appropriate abatement practices, it is important to develop a reasonable understanding of sources. In urban areas, the highest priority from a human health risk perspective is human sources, particularly persistent leaking sanitary infrastructure.

2. Tools for identifying sources of *E. coli* have expanded as communities around the country have gained experience implementing *E. coli* TMDLs. These tools range from relatively simple techniques to advanced microbial methods. Some of the advanced methods, though relatively expensive, have become more accessible for use to quickly determine whether human sources of fecal pollution are present so that follow-up actions are better targeted to the source(s).

3. The foundation of *E. coli* load reduction plans is source controls, which are non-structural measures that help to reduce the *E. coli* source and/or flow sources that are transporting *E. coli* to the storm drainage systems. Effective implementation of source control practices typically involves coordination with multiple local government departments and public outreach.

4. Structural stormwater practices, such as those described in Volume 3 of the *Urban Storm Drainage Criteria Manual*, are key tools to help reduce *E. coli* loading in urban runoff. Because existing performance data indicate that consistent attainment of primary contact limits at outfalls from BMPs is unlikely, volume reduction is a key approach for bacteria load reduction. Green infrastructure approaches should be considered. Other BMP types with performance data indicating potential ability to reduce *E. coli* concentrations include retention (wet) ponds, media filters, bioretention facilities and subsurface flow wetlands. Site-specific constraints, cost and sustainability (ability to maintain over time) affect selection of BMPs suitable for any particular site.

5. Active treatment, either through diversion of dry-weather low flows to the sanitary sewer system or active disinfection (e.g., UV) at the end of pipe, is generally a last resort for controlling *E. coli* discharges to receiving waters. This approach is impractical at a watershed scale with many outfalls.

6. EPA's 2012 update of its *Recreational Water Quality Criteria* resulted in several options for site-specific recreational water quality standards. Although application of these approaches requires significant technical expertise, the potential eventual application of these approaches is an important consideration for communities.

7. Research projects in Colorado that may be good candidates for coordinated regional collaboration include:

    a. Additional BMP performance monitoring for current MHFD-recommended BMP designs and other innovative designs.

    b. Characterization of instream concentrations and standards exceedance frequencies in reference (natural) watersheds along the Front Range.

- Continued sharing of lessons learned among individual permittees such as through the Colorado *E. coli* Symposium hosted by Colorado Stormwater Council in 2019.

9 References

Afrooz, A.R.M.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, 2160.

Ahmed, W., Hamilton, K., Toze, S., Cook, S., Page, D. (2019). A review on microbial contaminants in stormwater runoff and outfalls: Potential health risks and mitigation strategies. Science of The Total Environment Volume 692, 20 November 2019, Pages 1304-1321. https://www.sciencedirect.com/science/article/pii/S0048969719331687

Ahmed, W., Hughes, B., & Harwood, V. J. (2016). Current status of marker genes of *Bacteroides* and related taxa for identifying sewage pollution in environmental waters. *Water, 8*(6), 231. https://doi.org/10.3390/w8060231

Alderisio, K.A., DeLuca, N. (1999). "Seasonal enumeration of fecal coliform bacteria from the feces of ring-billed gulls (*Larus delawarensis*) and Canada Geese (*Branta canadensis*)." *Applied and Environmental Microbiology*. 65(12), 5628-5630.

American Society of Civil Engineers. (2025). *2025 report card for America's infrastructure:* https://infrastructurereportcard.org/

American Water Works Association Research Foundation and U.S. Environmental Protection Agency (AWWARF and U.S. EPA). (2006). *Development of Event-Based Pathogen Monitoring Strategies for Watersheds*. IWA Publishers.

Armand Ruby Consulting (ARC). (2011). "Source Prioritization Process for Bacteria." Draft. December 12, 2011.

Arnold, J. G., Kiniry, J. R., Srinivasan, R., Williams, J. R., Haney, E. B., & Neitsch, S. L. (2012). Soil & Water Assessment Tool: Input/Output documentation (Version 2012) (TR-439). Texas Water Resources Institute. Available at: https://swat.tamu.edu/media/69296/SWAT-IO-Documentation-2012.pdf

Ashbolt, N. J., Schoen, M. E., Soller, J. A., Roser, D. J. (2010). Predicting pathogen risks to aid beach management: the real value of quantitative microbial risk assessment (QMRA). *Water Res.* 2010, *44* (16), 4692–4703.

Barfield, B. J., Harp, S.L., Hayes, J.C., Chalavadi, M., Yeri, S., Brown, G. A., and Stevens, E. (2010). "Filtration and Sorption BMP Modeling for Water Quantity and Quality." *2010 21st Century International Water Quality Conference, American Society of Biological and Agricultural Engineering*, Earth University, Costa Rica.

Barrett, M. E. (2003). "Performance, cost, and maintenance requirements of Austin sand filters." J. *Water Resour. Plan. Manage*., 129 (3): 234–242.

Berg, J.M., Hedges, S.C. and Jakubowski, S.D. (2009). "Evaluating Irrigation Effectiveness – Effects of runoff-reducing weather based irrigation (Smart Timers)." *Water Efficiency*. July-August.

Bicknell, B. R., Imhoff, J. C., Kittle, J. L., Donigian, A. S., & Johanson, R. C. (2001). Hydrological Simulation Program—FORTRAN (HSPF): User's manual for release 12. U.S. Environmental Protection Agency.

Boehm, A. B., & Soller, J. A. (2020). Microbial risk analysis 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. https://doi.org/10.1016/j.mran.2020.100139

Boehm, A. B., Ashbolt, N., Colford, J., Dunbar, L., Fleming, L., Gold, M., Hansel, J., Hunter, P.R., Ichida, A., McGee, C., Soller, J.A., Weisberg, S.B. (2009). "A Sea Change Ahead for Recreational Water Quality Criteria*." Journal of Water and Health,* 7(1), 9-20.

Boehm, A. B., Graham, K. E., & Jennings, W. C. (2018). Can we swim yet? Systematic review, meta-analysis, and risk assessment of aging sewage in surface waters. *Environmental Science & Technology, 52*(17), 9634–9645. https://doi.org/10.1021/acs.est.8b01948

Boehm, A. B., Soller, J. A., & Shanks, O. C. (2015). Human-associated fecal quantitative polymerase chain reaction measurements and simulated risk of gastrointestinal illness in recreational waters contaminated with raw sewage. Environmental Science & Technology Letters, 2(10), 270–275. https://doi.org/10.1021/acs.estlett.5b00219

Boehm, A.B., Bell, C.D., Fitzgerald, N.J.M., et al. (2020). Biochar-augmented biofilters to improve pollutant removal from stormwater – can they improve receiving water quality? Environmental Science: Water Research & Technology, 6, 1520–1537. DOI:10.1039/D0EW00027B.

Bowen, J.L., and Valiela, I. (2004). "Nitrogen Loads to Estuaries: Using Loading Models to Assess the Effectiveness of Management Options to Restore Estuarine Water Quality." *Estuarine Research Federation,* 27, 482-500.

Bradbury, K. R., Borchardt, M. A, Gotkowitz, M., Spencer, S. K., Zhu, J., Hunt, R. J. (2013). Source and transport of human enteric viruses in deep municipal water supply wells. *Environ. Sci. Technol.* 2013, *47* (9), 4096–4103.

Brady, A. and Plona, M. (2012). Development and Implementation of a Regression Model for Predicting Recreational Water Quality in the Cuyahoga River, Cuyahoga Valley National Park, Ohio 2009-11. U.S. Geological Survey Scientific Investigations Reports 2012-5074.

Bratieres K, Fletcher T.D., Deletic A, Alcazar L, Coustumer S.L., Mccarthy D.T. (2008). Removal of nutrients, heavy metals and pathogens by stormwater biofilters. 11th International Conference on Urban Drainage. Edinburgh, Scotland, UK.

Burton, G.A. Jr., and R. Pitt. (2002). *Stormwater Effects Handbook: A Tool Box for Watershed Managers, Scientists, and Engineers*. ISBN 0-87371-924-7. CRC Press, Inc., Boca Raton, FL. 2002. 911 pages. www.epa.gov/ednnrmrl/publications/books/handbook/index.htm

Byappanahalli, M.N., Nevers, M.B., Korajkic, A., Staley, Z.R., and Harwood, V.J. (2012). "Enterococci in the Environment Microbiol." *Mol. Biol. Rev.,* 76, 4685-706.

Cai, Y., Pitt, R.E., Togawa, N., McGee, K., Osei, K. and R. Andoh. (2014). "Full Scale Up-Flo Filter Field Verification Tests." *CHI Journal of Water Management Modeling* 2014; C365.

California Regional Water Quality Control Board, San Diego Region. (2020). Indicator bacteria in Tecolote Creek. https://www.waterboards.ca.gov/sandiego/water_issues/programs/tmdls/docs/tecolote/tecolote_bacteria.pdf

California Regional Water Quality Control Board, San Francisco Bay Region. (2012). *Total maximum daily load for bacteria in San Pedro Creek and at Pacifica State Beach: Final staff report*. Accessible at: https://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/pacificabacteria/Final%20Staff%20Report.pdf

Center for Watershed Protection and R. Pitt. (2004). *Illicit Discharge Detection and Elimination: A Guidance Manual for Program Development and Technical Assessments*. Center for Watershed Protection, Ellicott City, MD, and University of Alabama, Tuscaloosa, AL. https://www.epa.gov/sites/default/files/2015-11/documents/idde_manualwithappendices.pdf

Chandrasena GI, Deletic A, Ellerton J, McCarthy DT. (2012a). Evaluating Escherichia coli removal performance in stormwater biofilters: a laboratory-scale study. *Water Science & Technology*: 66.5.

Chandrasena GI, Filip S, Zhang K, Osborne CA, Deletic A, McCarthy DT. (2012b). Pathogen and Indicator Microorganism Removal in Field Scale Stormwater Biofilters. 7th International WSUD Conference, Melbourne, Australia, February 21-23.

Chandrasena GI, Pham T, Payne EG, Deletic A, McCarthy DT. (2014). *E. coli* removal in laboratory scale stormwater biofilters: Influence of vegetation and submerged zone. *Journal of Hydrology*. August 5.

Chandrasena, G.I., Deletic, A., & McCarthy, D.T. (2016). Biofiltration for stormwater harvesting: Comparison of Campylobacter spp. and Escherichia coli removal under normal and challenging operational conditions. Journal of Hydrology, 537, 248–259.

City and County of Broomfield. (2025). City awards $1.6M contract for trenchless stormwater pipe rehabilitation in four neighborhoods. April 21, 2025. Accessible at: https://citizenportal.ai/articles/6051393/Broomfield-City/Broomfield-County/Colorado/City-awards-16M-contract-for-trenchless-stormwater-pipe-rehabilitation-in-four-neighborhoods

City and County of Denver. (2015). Ultra-Urban Green Infrastructure Guidelines. Prepared by Muller Engineering, Stream Design and TetraTech. https://www.denvergov.org/Government/Agencies-Departments-Offices/Agencies-Departments-Offices-Directory/Department-of-Transportation-and-Infrastructure/Programs-Services/Green-Infrastructure/Ultra-Urban-Guidelines

City of Austin. (2008). *Scoop the Poop Education Campaign, Summary Report*.

City of San Diego. (2011). *Phase II Pet Waste Bag Dispenser Station Design and Implementation.*

City of Santa Barbara, Creeks Division, in Partnership with University of California, Santa Barbara. (2012). *Tools for Tracking Human Fecal Pollution in Urban Storm Drains, Creeks, and Beaches*. September 1, 2012.

Clark, L. (2003). “A review of pathogens of agricultural and human health interest found in Canada Geese.” In: *Proceedings of the 10th wildlife damage management conference*. K. A. Fagerstone and G. W. Witmer, eds., 6–9 April 2003; Hot Springs, AR. Fort Collins, CO: The Wildlife Damage Management Working Group of The Wildlife Society, 326-334.

Clark, S.E. and Pitt, R. (2012). “Targeting treatment technologies to address specific stormwater pollutants and numeric discharge limits.” *Water Research*, 46, 6715-6730.

Clark, S.E., Pitt, R., and Field, R. (1994). “Stormwater treatment: inlet devices and filtration.” Proc. Eng. Foundation Conf. Stormwater NPDES Related Monitoring Needs*. American Society of Civil Engineers*, Reston, VA. 641-650.

Clary, J., Jones, J., Leisenring, M., Hobson, P., Strecker, E. (2020). International Stormwater BMP Database: 2020 Summary Statistics. Water Research Foundation: Alexandria, VA. Accessible at: www.bmpdatabase.org

Cleaner Rivers through Effective Stakeholder-led TMDLs (CREST). (2008). *Los Angeles River Bacteria Source Identification Study: Final Report.* November 2007.

Colford, J.M., Schiff, K.C., Griffith, J.F., Yau, V., Arnold, B.F., Wright, C.C., Gruber, J.S., Wade, T.J., Burns, S., Hayes, J., McGee, C., Gold, M., Cao, Y., Noble, R.T., Haugland, R., Weisberg, S.B. (2012). “Using rapid indicators for Enterococcus to assess the risk of illness after exposure to urban runoff contaminated marine water.” *Water Research*, 46, 2176-2186.

Colorado Department of Public Health & Environment. (2025, November 20). MS4 permit renewal meeting #3 presentation. https://drive.google.com/drive/folders/199u1pkVsFkYktfFuKJ_zlpyPDQsoKLmx

Colorado Department of Public Health and Environment (CDPHE). Use Attainability Analysis (UAA) library and water quality standards. https://cdphe.colorado.gov/environment/water-quality/clean-water/water-quality-standards

Colorado Parks and Wildlife. (2014). “Canada Goose: Managing Human-Goose Conflicts in Urban and Suburban Areas.” Accessible at: http://cpw.state.co.us/learn/Pages/LivingwithWildlifeGoose.aspx

Colorado State University (n.d.) “eRAMS website tools, see https://erams.com/documentation/flow-analysis/.

Colorado Water Quality Control Commission. (2012). Regulation 31: The Basic Standards and Methodologies for Surface Water (amended 9/11/12, effective 1/31/13).

Colorado Water Quality Control Commission. (2016). Regulation 93: Colorado's Section 303(d) List of Impaired Waters and Monitoring and Evaluation List (amended 01/11/16, effective 03/01/16).

Colorado Water Quality Control Division. (2010). Low Risk Discharge Guidance: Discharges from Surface Cosmetic Power Washing Operations to Land, Water Quality Policy 27.

Colorado Water Quality Control Division. (2015). Natural Swimming Areas Compliance and Sampling Guidelines.

Colorado Water Quality Control Division. (2016). CDPS General Permit COR090000 Stormwater Discharges Associated with Municipal Separate Storm Sewer Systems (MS4s), Second Public Notice Version.

Colorado Water Quality Control Division. (2024). Section 303(d) Listing Methodology 2026 Listing Cycle. Accessible at: https://cdphe.colorado.gov/surface-water-assessment.

Corsi, S.R., Borchardt, M.A., Spencer, S.K., Hughes, P.E., and Baldwin, A.K. (2014). Human and bovine viruses in the Milwaukee River watershed: Hydrologically relevant representation and relations with environmental variables. *Science of the Total Environment*. 490: 849–860.

De Man, H., Van Den Berg, H. H. J. L., Leenen, E. J. T. M., Schijven, J. F., Schets, F. M., Van Der Vliet, J. C., Van Knapen, F., De Roda Husman, A. M. (2014). Quantitative assessment of infection risk from exposure to waterborne pathogens in urban floodwater. *Water Res.* 2014, *48* (1), 90–99.

DeVuono-Powell, S. (2013). "Homeless Encampments in Contra Costa County" *Contra Costa County Flood Control and Water Conservation District*. Summer 2013.

Divers, M. T., Elliott, E. M., Bain, D. J. (2012). Constraining nitrogen inputs to urban streams from leaking sewer infrastructure using inverse modeling: Implications for DIN retention in urban environments. *Environ. Sci. Technol.* 2012, *47* (412), 1816–1823.

Dolbeer, R.A. (1994). "Blackbirds." *The Handbook: Prevention and Control of Wildlife Damage*, Internet Center for Wildlife Damage Management, University of Nebraska - Lincoln DigitalCommons@University of Nebraska – Lincoln.

Dorevitch, S., Doi, M., Hsu, F.C., Lin, K.T., Roberts, J.D., Liu, L.C., Gladding, R., Vannoy, E., Li, H., Javor, M., Scheff, P.A. (2011). A Comparison of Rapid and Conventional Measures of Indicator Bacteria as Predictors of Waterborne Protozoan Pathogen Presence and Density. *Journal of Environmental Monitoring,* 13: 2427-2435.

Edwards, M.E., Brinkman, K.C., Watson, J.T. (1993). "Growth of soft-stem Bulrush (Scirpus validus) plants in a gravel-based subsurface flow constructed wetland." In: Constructed Wetlands for Water Quality Improvement. Moshiri, G.A. (ed.). CRC Press/Lewis Publishers, Boca Raton, FL.

Ellis, A., Newman, D., and Pitt, R. (1998). "The use of peepers to measure nutrient and bacteria stratification in urban sediments." Presented at the *34th Annual American Water Resources Association Conference: Applications of Water Use Information*. Point Clear, AL. November.

Erickson, A. J. (2018). *Maximizing stormwater BMPs for phosphorus removal* [Webinar]. Minnesota Pollution Control Agency. January 9.

Facility for Advancing Water Biofiltration (FAWB). 2009. Stormwater Biofiltration Systems: Adoption Guidelines; Planning, Design, and Practical Implementation. Version 1. June. (now accessible through https://wscaustralia.org.au/).

Field, R. (1996). "Stormwater Pollution Abatement Technologies." In: *The Control and Treatment of Industrial and Municipal Stormwater*, Editor: P. E. Moffa. Van Nostrand Reinhold, New York, NY. 151-237.

Fleming, R. and Fraser, H. (2001). "The Impact of Waterfowl on Water Quality." *Literature Review*. University of Guelph, Canada.

Francy, D.S., Gifford, A.M., Darner, R.A. (2003). *Escherichia coli beaches—distribution, sources, wastewater indicators, and predictive modeling*. US Geological Survey Water-Resources Investigations Report 02-4285. Columbus, Ohio.

French, L., and Parkhurst, J. (2009). "Managing Wildlife Damage: Canada Goose (*Branta canadensis*)." Virginia Cooperative Extension Publication 420-203.

Geosyntec Consultants and Wright Water Engineers. (2011). *International Stormwater Best Management Practices (BMP) Database Volume Reduction Technical Summary*. January. (accessible at www.bmpdatabase.org).

Geosyntec Consultants and Wright Water Engineers. (2012). *International Stormwater Best Management Practices (BMP) Database Addendum 1 to Volume Reduction Technical Summary (January 2011) Expanded Analysis of Volume Reduction in Bioretention BMPs.* Prepared under Support from WERF, FHWA, EWRI/ASCE and EPA. (accessible at www.bmpdatabase.org).

Geosyntec Consultants and Wright Water Engineers. (2014). *International Stormwater Best Management Practices (BMP) Database Statistical Summary.* Prepared under Support from WERF, FHWA, EWRI/ASCE and EPA. (accessible at www.bmpdatabase.org).

Geosyntec Consultants. (2008). A user's guide for the Structural BMP Prioritization and Analysis Tool (SBPAT v1.0): Technical appendices. Prepared for Heal the Bay, City of Los Angeles, and Los Angeles County Department of Public Works.

Geosyntec Consultants. (2010). *Dry Weather Source Characterization and Control Summary, Santa Monica Bay Beaches Bacteria TMDL Implementation*. Revised June, 2011.

Geosyntec Consultants. (2010). Final Performance Evaluation Report, Cienega Filtration Project Field Demonstration, Irvine, California. IRWD Project No. 10867. February 12, 2010.

Geosyntec Consultants. (2012). *San Diego River Watershed Comprehensive Load Reduction Plan, Attachment E: Non-Structural BMP Memo*. Prepared for the County of San Diego, the Cities of El Cajon, La Mesa, Santee, San Diego, and the California Department of Transportation.

Geosyntec Consultants. (2014). *Draft Task Order No. 24: Dry Weather Microbial Source Tracking Study Findings Report, San Diego River Watershed*. February 2014.

Ghavanloughajar, M., Borthakur, A., Valenca, R., et al. (2021). Iron amendment minimizes the first-flush release of pathogens from stormwater biofilters. Environmental Pollution, 281, 116989. DOI:10.1016/j.envpol.2021.116989.

Griffith, J.F., Layton, B.A., Boehm, A.B., Holden, P.A., Jay, J.A., Hagedorn, C., McGee, C.D., and S.B. Weisberg. (2013). *The California Microbial Source Identification Manual: A Tiered Approach to Identifying Fecal Pollution Sources to Beaches.* Technical Report 804 - December 2013. Prepared for the Southern California Coastal Water Research Project. Accessible at: http://www.waterboards.ca.gov/board_info/agendas/2014/jan/012114_11_804_sipp_mst_manual.pdf

Guillot-Le Goff, A., Cartier, Y., Vinçon-Leite, B., Boyaval, S., & Carmigniani, R. (2026). *Predicting microbiological contamination in urban rivers: An event-based indicator approach applied to the Seine River during the 2024 Paris Olympic and Paralympic Games*. Journal of Hydrology, 674, 135504. https://doi.org/10.1016/j.jhydrol.2026.135504

Harmel, R.D. (2016a). Monitoring to Support and Improve H/WQ Modeling. Presentation at CLEAN Center Workshop, Fort Collins, CO. February. Accessible at: https://erams.com/clean/wp-content/uploads/2016/02/Harmel_Daren_MonitoringToSupportAndImproveH-WQModeling.pdf

Harmel, R.D., Hathaway, J.M., Wagner, K.L., Wolfe, J.E., Karthikeyan, R., Francesconi, W., McCarthy, D.T. (2016b). Uncertainty in monitoring *E. coli* concentrations in streams and stormwater runoff. *Journal of Hydrology* 534 (2016) 524–533.

Hathaway, J.M., and Hunt, W.F. (2008). Urban Waterways: Removal of Pathogens in Stormwater. In: North Carolina Cooperative Extension Service. October.

Hathaway, J.M., Hunt, W.F. (2012). Indicator Bacteria Performance of Storm Water Control Measures in Wilmington, North Carolina. Journal of Irrigation and Drainage Engineering, 138(2). February.

Hathaway, J.M., Hunt, W.F., Graves, A.K., Wright, J.D. (2011). Field Evaluation of Bioretention Indicator Bacteria Sequestration in Wilmington, North Carolina. Journal of Environmental Engineering 137(12). December

Hathaway, J.M., Hunt, W.F., Wright, J.D., & Jadlocki, S.J. (2009). Field Evaluation of Indicator Bacteria Removal by Stormwater BMPs in North Carolina.

Hatt, B.E., Fletcher, T.D., & Deletic, A. (2008). Improving stormwater quality through biofiltration: Lessons from field studies. 11th International Conference on Urban Drainage (ICUD), Edinburgh.

Hayes, J.C., Barfield, B.J., Harp, S.L., Chalavadi, M., Stevens, E., Alexander, M.D., Bates, B.T. (2008). “Modeling Impacts of Post Development Water Quality BMP.” 2008 21st Century International Water Quality Conference, American Society of Biological and Agricultural Engineering, University of Concepcion University, Concepcion, Chile.

HDR. (2013). Technical Memorandum Re: Raccoon Storm System Controls - University Hill. Memorandum to B. Linenfelser, City of Boulder, October 29.

Huey, G., and Meyer, M. (2010). Turbidity as an Indicator of Water Quality in Diverse Watersheds of the Upper Pecos River Basin. *Water,* 2: 273-284.

Hunt, W.F., Smith, J.T., Jadlocki, S.J., Hathaway, J.M. (2008). Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C., Journal of Environmental Engineering, ASCE, May.

Hussong, D., Damare, J.M., Limpert, R.J., Sladen, W.J.L, Weiner, R.M., Colwell, R.R. (1979). "Microbial impact of canada geese (Branta canadensis) and whistling swans (Cygnus columbianus columbianus) on aquatic ecosystems." *Applied and Environmental Microbiology*, 37(1), 14-20.

Hynes, J. M., Beattie, R. E., Blackwood, A. D., Clerkin, T., Gallard-Góngora, J., & Noble, R. T. (2024). Using a combination of quantitative culture, molecular, and infrastructure data to rank potential sources of fecal contamination in Town Creek Estuary, North Carolina. *PLOS ONE, 19*(4), e0299254. https://doi.org/10.1371/journal.pone.0299254

Irvine Ranch Water District (IRWD) and Orange County Metropolitan Water District (OCMWD). (2004). *Residential Runoff Reduction Study*. Irvine Ranch Water District and Municipal Water District of Orange County. July.

Ishii, S. and Sadowsky, M.J. (2008). "*Escherichia coli* in the Environment: Implications for water quality and human health." *Microbes Environ*., 23, 101-108.

Kadlec, R.H. and Knight, R.L. (1996). *Treatment Wetlands*. Lewis Publishers, CRC Press, Inc. Boca Raton, Fla.

Kear, J. (1963). "The agricultural importance of wild goose droppings." *The Waterfowl Trust, 14th annual Report*, 1961-1962, 72-77.

Kim, H.J., Phenrat, T., Tilton, R.D., and Lowry, G.V. (2012). "Effect of kaolinite, silica fines and pH on transport of polymer-modified zero valent iron nanoparticles in heterogeneous porous media." Journal of Colloid and Interface Science. 370, 1-10.

Kirschner, A., Zechmeister, T., Kavka, G., Beiwl, C., Herzig, A., Mach, R., Farnleitner, A. (2004). "Integral Strategy for Evaluation of Fecal Indicator Performance in Bird-Influenced Saline Inland Waters." *Applied and Environmental Microbiology*, 70(12), 7396-7403.

Knopp, W. K., Klaus, J. K., Wilson, D. W., Vlah, M. V., Ross, M. R., & Thomas, E. T. (2026). *Advancing continuous in-situ quantification of microbial contamination in environmental waters using tryptophan-like fluorescence: Sensor design and validation*. Water Research, 302, 126099. https://doi.org/10.1016/j.watres.2026.126099.

Kolb, R. and Roberts, G. (2009). "Further Understanding of the Bacterial Dynamic, Lessons from Microbial Source Tracking." Powerpoint presentation prepared by Weston Solutions for the "Think Blue San Diego" Program. San Diego, CA.

Kranner, B.P., Afrooz, A.R.M.N., Fitzgerald, N.J.M., & Boehm, A.B. (2019). Fecal indicator bacteria and virus removal in stormwater biofilters: Effects of biochar, media saturation, and field conditioning. PLOS ONE, 14(9): e0222719.

Krumgalz, B.S., Fainshtein, G., Cohen, A. (1992). "Grain size effect on anthropogenic trace metal and organic matter distribution in marine sediments." *Sci. Total Environ*., 116, 15-30.

Layton, B. A., Raith, M. R., Griffith, J. F. (2015). Use of dye tracers and qPCR to identify human fecal contamination at Doheny State Beach, Dana Point, CA. Southern California Coastal Water Research Project. Technical Report 860 – April 2015. Accessible at: http://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/860_DyeTracersPCRForContamWCov.pdf

Leisenring, M., Barrett, M., Pomeroy, C., Poresky, A., Roesner, L. Rowney, A.C., and Strecker, E. (2013). *Linking BMP systems performance to receiving water protection, BMP performance algorithms*. WERF: Alexandria, VA.

Li, H., Davis, A.P. (2009). Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention. Journal of Environmental Engineering. August.

Li, Y.L., Deletic, A., Alcazar, L., Bratieres, K., Fletcher, T.D., McCarthy, D. (2012). Removal of Clostridium perfringens, Escherichia Coli and F-RNA Coliphages by Stormwater Biofilters. Ecological Engineering, 49. December.

Li, Y.L., Deletic, A., McCarthy, D.T. (2014a). Removal of *E. coli* from urban stormwater using antimicrobial-modified filter media. Journal of Hazardous Materials. January 26.

Li, Y.L., McCarthy, D.T., Deletic, A. (2014b). Stable copper-zeolite filter media for bacteria removal in stormwater. Journal of Hazardous Materials. March 16.

Lowry, S. A., Steele, J. A., Griffith, J. F., Schiff, K. C., & Boehm, A. B. (2026). Simulated gastrointestinal risk from recreational exposure to stormwater and relationship to the human-associated *Bacteroidales* marker HF183. *Environmental Science: Processes & Impacts*. Advance online publication. https://pubs.rsc.org/en/content/getauthorversionpdf/D4EM00577E

Manny, B.A., Wetzel, R.G., and Johnon, W.C. (1975). "Annual contribution of carbon, nitrogen and phosphorus by migrant Canada geese to hardwater lake." *Ver. Internat. Verein. Limnol*., 19, 949-951.

Marion, J.W., Lee, J., Lemeshow, S., Buckley, T.J. (2010). Association of Gastrointestinal Illness and Recreational Water Exposure at an Inland U.S. Beach. *Water Research* 44(16): 4796-4804.

McCarthy, D.T. (2009). "A traditional first flush assessment of *E. coli* in urban stormwater runoff." *Water Science and Technology*, 60(11), 2749–2757.

McKee AM and Couch A. (2024). Land use and dog park associations with Escherichia coli in the Chattahoochee River National Recreation Area watershed. Science Report. NPS/SR—2024/113. National Park Service. Fort Collins, Colorado. https://doi.org/10.36967/2302755

Mile High Flood District. (2025). Urban storm drainage criteria manual (Vol. 3). https://www.mhfd.org

Miller, M. (2009). Removal of Waterborne Pathogens Using an Antimicrobial Filter Media, Proceedings of the 2009 Georgia Water Resources Conference, University of Georgia, April 27 – 29.

Minton, G. and R. Sutherland. (2010). "Street Dirt: A Better Way of Measuring BMP Effectiveness." *Stormwater Magazine*. p. 12-22. March/April.

Mitchell, C.J., Jayakaran, A.D., & McIntyre, J.K. (2023). Biochar and fungi as bioretention amendments for bacteria and PAH removal from stormwater. Journal of Environmental Management, 327, 116915.

Mohanty, S. and Boehm, A. (2015). Effect of weathering on mobilization of biochar particles and bacterial removal in a stormwater biofilter. Water Research. August.

Mohanty, S.K., Cantrell, K.B., Nelson, K.L., & Boehm, A.B. (2014). Efficacy of biochar to remove Escherichia coli from stormwater under steady and intermittent flow. Water Research.

Mohanty, S.K., Torkelson, A., Dodd, H., Nelson, K., Boehm, A. (2013). Engineering Solutions to Improve the Removal of Fecal Indicator Bacteria by Bioinfiltration Systems during Intermittent Flow of Stormwater. Environmental Science & Technology.

Monroe, M. (2009). "A Multi-faceted Approach to Microbial Source Tracking within Secondary Environments." Master's Thesis, Colorado School of Mines.

Murray, J. and Steets, B. (2009). "Dry-weather Hydrology, DNA-based Microbial Source Tracking and Feasibility Analysis for the Laguna Watershed." In *Proceedings of StormCon 2009*, Los Angeles, CA.

Mwabi, J., Mamba, B., and Momba, M. (2012). Removal of Escherichia coli and Faecal Coliforms from Surface Water and Groundwater by Household Water Treatment Devices/Systems: A Sustainable Solution for Improving Water Quality in Rural Communities of the Southern African Development Community Region, International Journal of Environmental Research and Public Health, 4 Jan 2012.

NASSCO. (2025). NASSCO specification guidelines. https://nassco.org/resources/nassco-specification-guidelines/

New York City Department of Environmental Protection. (2004). *Final Environmental Impact Statement for the New York City DEP's Expanded Waterfowl Management Program.* April 13.

Noble, R. T., Blackwood, A. D., Griffith, J. F., McGee, C. D., & Weisberg, S. B. (2023). Integrating microbial source tracking with quantitative microbial risk assessment to evaluate site-specific risk-based thresholds at two South Florida beaches. Frontiers in Microbiology. https://www.frontiersin.org/articles/10.3389/fmicb.2023.1210192/full

Nolan, S., Jones, S., Landry, N. (2004). "Evaluating the Stormwater Treatment Performance of AbTech Industries Smart Sponge(R) Plus in Seabrook, New Hampshire." New Hampshire Estuary Project, University of New Hampshire, and New Hampshire Department of Environmental Services. August, 2004.

Oliver, B.G. and Cosgrove, E.G. (1975). "The disinfection of sewage treatment plant effluents using ultraviolet light." *The Canadian Journal of Chemical Engineering,* 53 (2): 170–174.

Orange County Municipal MS4 Permittees, 2020. Comprehensive Human Waste Source Reduction Strategy (CHWSRS) Work Plan. February 2020.

Palos Verdes Peninsula Watershed Management Group (Peninsula WMG). (2015). Draft Palos Verdes Peninsula Enhanced Watershed Management Program (EWMP). June.

Passeport, E., Hunt, W.F., Line, D.E., Smith, R.A., Brown, R.A. (2009). Field Study of the Ability of Two Grassed Bioretention Cells to Reduce Storm-Water Runoff Pollution, Journal of Irrigation and Drainage Engineering, ASCE, July/August.

Pendergrass, D., Hauck, L. and McFarland, A. (2013). Instream Bacteria Influences from Bird Habitation of Bridges. Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, Texas. Prepared for Texas State Soil and Water Conservation Board Temple, Texas.

Pendergrass, D., McFarland, A., Hauck, L. (2015). Instream bacteria influences from bird habitation of bridges. *J. Amer. Water Resources Assoc*. 51 (6), 1519–1533.

Petropolou, C., Tolson, J., DeFlaun, M., Lanyon, R., Granato, T., Rijal, G., Gerba, C., Lue-Hing C., Patterson Environmental Consultants. (2008). Disinfection vs. Non-disinfection Microbial Risk Assessment for Recreational Use of Chicago Area Waterways. WEFTEC 2008, October 21.

Pierce, R. (2001). "Managing Raccoon Problems in Missouri, University of Missouri Extension." Publication G9453.

Pitt, R. (2002). "Emerging stormwater controls for critical source areas." *Management of Wet-Weather Flow in the Watershed*. Sullivan, D. & Field R. (Eds). p. 14-16. CRC Press, Boca Raton, FL.

Pitt, R. and S. Clark. (2010). Evaluation of Biofiltration Media for Engineered Natural Treatment Systems. For Geosyntec Consultants and The Boeing Co.

Pitt, R., Clark, S. and Parmer, K. (1994). *Potential Groundwater Contamination from Intentional and Nonintentional Stormwater Infiltration.* EPA Office of Research and Development: Cincinnati, OH. EPA/600/SR-94/051.

Pitt, R., Lalor, M., Field, R., Adrian, D.D., and Barbe, D. (1993). *A User's Guide for the Assessment of Non-Stormwater Discharges into Separate Storm Drainage Systems*. U.S. Environmental Protection Agency, Storm and Combined Sewer Program, Risk Reduction Engineering Laboratory. EPA/600/R-92/238. PB93-131472. Cincinnati, Ohio. 87 pgs. January.

Prabhukumar, G. (2013). Development of Permeable Reactive Filter Systems (PRFS) for Treatment of Urban Stormwater Runoff, Dissertation. May.

Puigagut, J., Villaseñor, J., Salas, J.J., Bécares, E., García, J. (2007). "Subsurface-flow constructed wetlands in Spain for the sanitation of small communities: a comparative study." *Ecol Eng* 30:312–319.

PV & Associates, LLC. (n.d.). WinSLAMM documentation. https://winslamm.net/documentation.html

Rahman, M.Y.A., Ergas, S.J., & Nachabe, M.H. (2020). Biochar amended bioretention for E. coli and nitrogen removal from urban stormwater runoff.

Ran, Q., Badgley, B.D., Dillon, N., Dunny, G.M., and Sadowsky, M.J. (2013). "Occurrence, Genetic Diversity, and Persistence of Enterococci in a Lake Superior Watershed." *Appl. Environ. Microbiol*., 79(9), 3067-3075.

Read, J., Wevill, T., Fletcher, T., Deletic, A. (2008). Variation among plant species in pollutant removal from stormwater in biofiltration systems. Water Research 42, 893-902.

Rijal, G., Tolson, J. K., Petropoulou, C., Granato, T. C., Glymph, A., Gerba, C., Deflaun, M. F., O'Connor, C., Kollias, L., Lanyon, R. (2011). "Microbial risk assessment for recreational use of the Chicago Area Waterway System," Journal of Water and Health, January 9, 2011.

Rippy, M. (2015). Meeting the criteria: linking biofilter design to fecal indicator bacteria removal. WIREs Water 2015, 2:577-592. September/October.

Roseen, R.M. and Stone, R.M. (2013). Bioretention Water Quality Treatment Performance Assessment. August.

Roser, D. J., Davies, C. M., Ashbolt, N. J., Morison, P. (2006). Microbial exposure assessment of an urban recreational lake: A case study of the application of new risk-based guidelines. *Water Sci. Technol.* 2006, *54* (3), 245–252.

Rossman, L. A. (2015). Storm Water Management Model user's manual (Version 5.1) (EPA/600/R-14/413b, Revised September 2015). U.S. Environmental Protection Agency, Office of Research and Development. Available at: https://www.epa.gov/sites/production/files/2019-02/documents/epaswmm5_1_manual_master_8-2-15.pdf

Rusciano, G.M. and Obropta, C.C. (2007). Bioretention Column Study – Fecal Coliform and Total Suspended Solids Reductions. American Society of Agricultural and Biological Engineers.

Russell, T. L., Sassoubre, L. M., Wang, D., Masuda, S., Chen, H., Soetjipto, C., Hassaballah, A., Boehm, A. B. (2013). A Coupled Modeling and Molecular Biology Approach to Microbial Source Tracking at Cowell Beach, Santa Cruz, CA, United States. *Environ. Sci. Technol.* 2013, 47 (18), 10231–10239.

Sakamoto, G. and Cairns, W. L. (1997). "UV Dose-response Determination: Collimated Beam vs. Pilot Studies." In: *Proceedings of Hawaii Water Environment Association Conference*, Honolulu, HI.

Salmon, T.P., and Gorenzel, W.P. (2005). "Cliff swallows." Publication 7482. University of California Agriculture and Natural Resources, Davis, California, USA.

Sauer, E.P., VandeWalle J.L., Bootsma M.J., McLellan S.L. (2011). Detection of the human specific *Bacteroides* genetic marker provides evidence of widespread sewage contamination of stormwater in the urban environment. *Water Res*. 45(14):4081–91.

Schiff, K. C., Griffith, J. F., Steele, J. A., & Gonzalez-Fernandez, A. (2025). Summary of technical research: Quantifying sources of human fecal pollution in the lower San Diego River watershed (Technical Report No. 1380). Southern California Coastal Water Research Project Authority. https://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/1380_FecalPollutionSanDiegoRiver.pdf

Schiff, K. C., Griffith, J. F., Steele, J. A., & Zimmer-Faust, A. (2023). Dry and wet weather survey for human fecal sources in the San Diego River watershed. *Water, 15*(12), 2239. https://doi.org/10.3390/w15122239

Schiff, K. C., Steele, J. A., & Griffith, J. F. (2023). Developing novel indicators of sewage collection systems for wet weather source tracking. Environmental & Water Resources Institute (EWRI) Congress 2023, American Society of Civil Engineers.

Schiff, K., Griffith, J., Steele, J., Arnold, B., Ercumen, A., Benjamin-Chung, J., Colford, J. M. Jr., Soller, J., Wilson, R., & McGee, C. (2016). The surfer health study: A three-year study examining illness rates associated with surfing during wet weather (SCCWRP Technical Report 943). Southern California Coastal Water Research Project.

Schoen, M. E., Ashbolt, N. J. (2010). Assessing pathogen risk to swimmers at non-sewage impacted recreational beaches. *Environ. Sci. Technol.* 2010, *44* (7), 2286–2291.

Schoen, M. E., Soller, J. A., Ashbolt, N. J. (2011). Evaluating the importance of faecal sources in human-impacted waters. *Water Res.* 45(8): 2670-2680.

Schriewer, A., Miller, W. A., Byrne, B. A., Miller, M. A., Oates, S., Conrad, P. A., Hardin, D., Yang, H. H., Chouicha, N., Melli, A., et al. (2010). Presence of Bacteroidales as a predictor of pathogens in surface waters of the central California coast. *Appl. Environ. Microbiol.* 2010, *76* (17), 5802–5814.

Sejkora, P., Kirisits, M and Barrett, M. (2011). Colonies of Cliff Swallows on Highway Bridges: A Source of Escherichia coli in Surface Waters. *Journal of the American Water Resources Association*, 47 (6): 1275–1284.

Sercu, B., Van De Werfhorst, L. C., Murray, J. L. S., Holden, P. A. (2011). Sewage exfiltration as a source of storm drain contamination during dry weather in urban watersheds. *Environ. Sci. Technol.* 2011, *45* (17), 7151–7157.

Sercu, B.S., Van De Werfhorst, L.C., Murray, J.L.S., and Holden P.S. (2009). Storm drains are sources of human fecal pollution during dry weather in three urban southern California watersheds. *Environ. Sci. Technol.* 43(2):293-8.

Shergill, S.S. and Pitt, R. (2004). "Quantification of Escherichia coli and enterococci levels in wet weather and dry weather flows." Presented at the *77th Annual Water Environment Federation Technical Exposition and Conference*. New Orleans, LA. Oct 4 – 7.

Shingle Creek Watershed Management Commission (project page). Iron- and Biochar-Enhanced Sand Filters (field trials including pond bench retrofits and catch basin inserts).

Sinigalliano, C.D., Fleisher, J.M., Gidley, M.L., Solo-Gabriele, H.M., Shibata, T., Plano, L.R., Elmir, S.M., Wanless, D., Bartkowiak, J., Boiteau, R., Withum, K., Abdelzaher, A.M., He, G., Ortega, C., Zhu, X., Wright, M.E., Kish, J., Hollenbeck, J., Scott, T., Backer, L.C., Fleming, L.E. (2010). Traditional and Molecular Analyses for Fecal Indicator Bacteria in Non-Point Source Subtropical Recreational Marine Waters. *Water Research* 44(13): 3763-3772.

Sleytr, K., Tietz A., Langergraber, G., Haberl. R. (2007). "Investigation of bacterial removal during the filtration process in constructed wetlands." *Sci Total Environ* 380:173–80.

Smith, A.E., Craven, S.R. and Curtis, P.D. (1999). *Managing Canada Geese in Urban Environments.* Jack Berryman Institute Publication 16, and Cornell University Cooperative Extension, Ithaca, N.Y.

Smith, C.D. (2006). *Waterfowl Management in Stormwater Management Ponds*, Thesis, University of Waterloo, Waterloo, Ontario, Canada.

Soller, J. A., Bartrand, T., Ashbolt, N. J., Ravenscroft, J., Wade, T. J. (2010a). Estimating the primary etiologic agents in recreational freshwaters impacted by human sources of faecal contamination. *Water Res.* 2010, *44* (16), 4736–4747.

Soller, J. A., Eftim, S., Wade, T. J., Ichida, A. M., Clancy, J. L., Johnson, T. B., Schwab, K., Ramirez-Toro, G., Nappier, S., Ravenscroft, J. E. (2016). Use of quantitative microbial risk assessment to improve interpretation of a recreational water epidemiological study. *Microb. Risk Anal.* 2016, *1*, 2–11.

Soller, J. A., Schoen, M. E., Bartrand, T., Ravenscroft, J. E., Ashbolt, N. J. (2010b). Estimated human health risks from exposure to recreational waters impacted by human and non-human sources of faecal contamination. *Water Res.* 2010, *44* (16), 4674–4691.

Soller, J. A., Schoen, M. E., Varghese, A., Ichida, A. M., Boehm, A. B., Eftim, S., Ashbolt, N. J., Ravenscroft, J. E. (2014). Human health risk implications of multiple sources of faecal indicator bacteria in a recreational waterbody. *Water Res.* 2014, *66*, 254–264.

Southern California Coastal Water Research Project (SCCWRP). (2023). Quantitative microbial risk assessment for Cabrillo Beach (Technical Report No. 1068). https://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/1068_CabrilloQMRA.pdf

Steele, J. A. (2025). Linking HF183 to Human Health Risk in Southern California Stormwater. SCCWRP Symposium, March 4, 2025. https://ftp.sccwrp.org/pub/download/PRESENTATIONS/CTAGMeetings/25_03_04/Steele_HF183.pdf

Steele, J. A., Schiff, K. C., & Griffith, J. F. (2023). *Differentiating among sources of fecal contamination using biofilm microbial communities*. Southern California Coastal Water Research Project Symposium presentation. http://ftp.sccwrp.org/pub/download/PRESENTATIONS/CTAGMeetings/23_05_24/Steele_Biofilm.pdf

Steele, J., Ebentier-McCargar, D., Zimmer-Faust, A., Griffith, J., & Schiff, K. (2019). *Los Coches Creek microbial source tracking study* (Technical Report No. 1087). Southern California Coastal Water

Research Project. https://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/1087_LosCochesMST.pdf

Steets, B. (2013). “Lessons from California Bacteria TMDLs.” Presentation to Colorado *E. coli* Work Group, Denver, CO. January 2013.

Steets, B., Kampalath, R., Mansell, S. (2013). QMRA Screening Estimates for Southern California Water Bodies: Where Might QMRAs be Worth the Investment? Presentation at the 11th Annual Headwaters to Oceans (H20) Conference, San Diego, CA. May 2013.

Stinson, M.K. and Perdek, J.M. (2003). “Chapter Three: Management and Control of Pathogens.” In *Managing Urban Watershed Pathogen Contamination*, EPA/600/R-03/111, EPA Office of Research and Development, Cincinnati, OH.

Stoeckel, D. (2010). “Presentation: Microbial Source Tracking—Sources of *E. coli* in Upper Fountain Creek.” Colorado Dept. Public Health and Environment *E. coli* Work Group. April 6, 2010.

Strecker, E., Leisenring, M., Poresky, A., Pomeroy, C., Mattson, J., and Barrett, M. (2009). “Recommended Initial Set of Water Quality Constituents and BMPs to Address in BMP Algorithms - Task 3A Technical Memo of Linking BMP Performance to Receiving Water Protection to Improve BMP Selection and Design.” WERF Project SW1R06. Submitted to Project Issue Area Team August 24, 2009.

Sunger, N., Haas, C. N. (2015). Quantitative Microbial Risk Assessment for Recreational Exposure to Water Bodies in Philadelphia. *Water Environ. Res.* 2015, *87* (3), 211–222.

Swallow, M., Huffman, J., Van Why, K. and D’Angelo. G. (2010). *The Effect of Goose Management on Water Quality.* Northeast Wildlife DNA Laboratory, East Stroudsburg University, East Stroudsburg, Pennsylvania and USDA APHIS Wildlife Services. Harrisburg, Pennsylvania.

Sweeney, L.C., Knappenberger, T., Brantley, E.F., & Shaw, J.N. (2022). Zeolite amended bioretention media improves nitrogen removal from stormwater. Agricultural & Environmental Letters. DOI:10.1002/ael2.20060.

TetraTech, Inc. (2013). *San Diego River Watershed: Comprehensive Load Reduction Plan – Phase II*. Submitted to City of San Diego Transportation & Storm Water Department. July 24, 2013.

Texas Commission on Environmental Quality (TCEQ). (2013). *Implementation Plan for Seventy-Two Total Maximum Daily Loads for Bacteria in the Houston-Galveston Region.* January 30, 2013.

Till, D. G., McBride, G. B. (2004). Potential public health risk of Campylobacter and other zoonotic waterborne infections in New Zealand. In *Waterborne Zoonoses Identification, Causes, and Control*; Cotruvo, J. A., Dufour, A., Rees, G., Bartram, J., Carr, R., Cliver, D. O., Craun, G. F., Fayer, R., Gannon, V. P. J., Eds.; IWA Publishing, 2004; pp 191–207.

Torkelson AA, da Silva AK, Love DC, Kim JY, Alper JP, Coox B, Dahm J, Kozodoy P, Maboudian R, Nelson KL. (2012). Investigation of Quaternary Ammonium Silane-Coated Sand Filter for the Removal of Bacteria and Viruses from Drinking Water. Journal of Applied Microbiology.

Torkelson, A.A. (2015). Enhanced Granular Media Filtration of Waterborne Pathogens: Effect of Media Amendments for Treatment of Drinking Water and Stormwater. PhD Dissertation, University of California, Berkeley.

U.S. Department of Agriculture Animal and Plant Health Inspection Services, Wildlife Services. (2001). Assistance with waterfowl." Factsheet. United States Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services. November.

U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services. (2009). "Management of Canada goose nesting." August 2009. 8 pp. https://www.aphis.usda.gov/sites/default/files/canada_goose.pdf

U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services. (2010). "Assistance with waterfowl damage." Factsheet. United States Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services. May 2010. 3 pp.

U.S. Environmental Protection Agency (EPA). (2024). Approval of New York's wet weather designated recreational use subcategory at 6 NYCRR 701.26(a). https://www.epa.gov/system/files/documents/2025-04/ny_let_0012_122024_0.pdf

U.S. Environmental Protection Agency (EPA). (n.d.) Use Attainability Analysis and use revision process. https://www.epa.gov/wqs-tech/use-attainability-analysis-and-use-revision-process

U.S. Environmental Protection Agency. (1973a). *Hypochlorination of Polluted Stormwater Pumpage at New Orleans.* EPA-670/2-73-067, Office of Research and Development, Washington, DC.

U.S. Environmental Protection Agency. (1973b). *Microstraining and Disinfection of Combined Sewer Overflows - Phase II.* EPA-R2-73-124. Office of Research and Development, Washington, DC.

U.S. Environmental Protection Agency. (1993). *Subsurface Flow Constructed Wetlands for Wastewater Treatment: A Technology Assessment*, EPA 832-R-93-008.

U.S. Environmental Protection Agency. (1999). *Preliminary Data Summary of Urban Stormwater Best Management Practices*. U.S. EPA 821-R-99-012. Office of Water, Washington, D.C.

U.S. Environmental Protection Agency. (2001). *Protocol for Developing Pathogen TMDLs*. EPA 841-R-00-002. Washington, DC: US EPA Office of Water. https://www.epa.gov/tmdl/tmdl-support-documents

U.S. Environmental Protection Agency. (2007). *An Approach for Using Load Duration Curves in the Development of TMDLs*. EPA 841-B-07-006. United States Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds.

U.S. Environmental Protection Agency. (2009). *Review of Published Studies to Characterize the Relative Risk from Different Sources of Fecal Contamination*. Office of Water Health and Ecological Criteria Division. EPA 822-R-09-001. http://www.epa.gov/waterscience/criteria/recreation/pdf/fecalcontamrecreationalwaters.pdf

U.S. Environmental Protection Agency. (2010a). *Report on 2009 National Epidemiologic and Environmental Assessment of 60 Recreational Water Epidemiology Studies (NEEAR 2010 -*

Surfside & Boquerón). EPA-600-R-10-168. Available at: https://archive.epa.gov/neear/web/html/index.html

U.S. Environmental Protection Agency. (2010b). *Comparison and Evaluation of Epidemiological Study Designs of Health Effects Associated with Recreational Water Use*.

U.S. Environmental Protection Agency. (2011). "A grant-funded pilot program focusing on cleaning up Coyote Creek. Clean Creeks." *Healthy Communities Program Snapshot*. May 31.

U.S. Environmental Protection Agency. (2012a). Recreational Water Quality Criteria. EPA-820-F-12-058. Available for download at EPA's Science and Technology website on Surface Water Quality Standards and Guidance. Accessible at: http://water.epa.gov/scitech/swguidance/standards/criteria/health/recreation/upload/RWQC2012.pdf

U.S. Environmental Protection Agency. (2012b). Method 1611: Enterococci in Water by TaqMan® Quantitative Polymerase Chain Reaction (qPCR) Assay. EPA-821-R-12-008.

U.S. Environmental Protection Agency. (2013). "National Long-Term Vision for the Clean Water Act Section 303(d) Program."

U.S. Environmental Protection Agency. (2014). *Overview of Technical Support Materials: A Guide to Site-Specific Alternative Recreational Criteria TSM Documents*.

U.S. Environmental Protection Agency. (2015). CMOM guide for collection systems. https://www.epa.gov/sites/default/files/2015-10/documents/cmom_guide_for_collection_systems.pdf

U.S. Environmental Protection Agency. (2015). Memorandum from Benita Best-Wong, Director, Office of Wetlands, Oceans, and Watersheds to Water Division Directors, Regions 1 – 10 and Robert Maxfield, Director, Office of Environmental Measurement and Evaluation. Subject: Information Concerning 2016 Clean Water Act Sections 303(d), 305(b), and 314 Integrated Reporting and Listing Decisions, Region 1. August 13.

U.S. Environmental Protection Agency. (2024). *Technical support materials: Developing alternative recreational criteria for waters contaminated by predominantly non-human fecal sources* (EPA 822-R-24-013). Office of Water. https://www.epa.gov/system/files/documents/2024-07/tsm-nonhuman-sources-revised_073024_508c.pdf

U.S. Environmental Protection Agency. (n.d.). Boston Water and Sewer Consent Decree. http://www.epa.gov/sites/production/files/documents/bwsc-cd.pdf

Ulrich, B. (2023). Biochar selection for stormwater treatment applications: A case study on E. coli removal. Minnesota Biochar Summit presentation.

Ulrich, B.A., Weelborg, K., Haile, T.M., Singh, U.B., & Magner, J. (2024). Field evaluation of a biochar-amended stormwater filtration system for retention of nutrients, metals, and Escherichia coli. Environmental Science: Water Research & Technology.

United States Department of Agriculture, Natural Resources Conservation District. (1994). Part 633, National Engineering Handbook: Chapter 26 Gradation Design of Sand and Gravel Filters. October.

University of Nebraska – Lincoln. *The Handbook: Prevention and Control of Wildlife Damage*, Internet Center for Wildlife Damage Management. Editors, Scott E. Hygnstrom, Robert M. Timm, Gary E. Larson. (1994). University of Nebraska-Lincoln. 2 vols. Accessible at: http://icwdm.org/Handbook/index.asp

Urban Water Resources Research Council (UWRRC). (2014). *Pathogens in Urban Stormwater Systems*. Eds. J. Clary, B. Steets, and R. Pitt. August 2014.

Valenca, R., Borthakur, A., Zu, Y., Matthiesen, E.A., Stenstrom, M.K., & Mohanty, S.K. (2021). Biochar selection for Escherichia coli removal in stormwater biofilters. Journal of Environmental Engineering. DOI:10.1061/(ASCE)EE.1943-7870.0001843. (Program summary presentation).

Virginia Department of Health. (2017). Microbial source tracking and recreational water quality assessment report. https://www.vdh.virginia.gov/content/uploads/sites/12/2018/05/2017-VDH-Report-2.2.17.pdf

Wade, D. and Ramsey, C. 1986. Identifying and Managing Aquatic Rodents in Texas: Beaver, Nutria and Muskrats. Texas Agricultural Extension Service. http://wildlife.tamu.edu/files/2010/04/6_Idetifying_and_managing_Aquatic_Rodents.pdf

Wade, T.J., Calderon, R.L., Brenner, K.P., Sams, E., Beach, M., Haugland, R., Wymer, L., Dufour, A.P. (2008). High Sensitivity of Children to Swimming-Associated Gastrointestinal Illness – Results Using a Rapid Assay of Recreational Water Quality. Epidemiology 19(3): 375-383.

Wade, T.J., Calderon, R.L., Sams, E., Beach, M., Brenner, K.P., Williams, A.H., Dufour, A.P. (2006). Rapidly Measured Indicators of Recreational Water Quality Are Predictive of Swimming-Associated Gastrointestinal Illness. Environmental Health Perspectives 114(1): 24-28.

Wade, T.J., Sams, E., Brenner, K.P., Haugland, R., Chern, E., Beach, M., Wymer, L., Rankin, C.C., Love, D., Li, Q., Noble, R., Dufour, A.P. (2010). Rapidly Measured Indicators or Recreational Water Quality and Swimming-Associated Illness at Marine Beaches: A Prospective Cohort Study. Environmental Health 9: 66.

Wang, D., et al. (2023). Cross-method assessment of coliphage detection methods in the framework of EPA regulatory standards. Letters in Applied Microbiology, 76(7). https://academic.oup.com/lambio/article/76/7/ovad081/7227921

Water Environment Research Foundation (WERF). (2007). *Development of a Protocol for Risk Assessment of Microorganisms in Separate Stormwater Systems*. Prepared by Olivieri, A., Boehm, A., Sommers, C., Soller, J., Eisenberg, J., and Danielson, R. WERF publication No: 03-SW-2. Copublishers: WERF, Alexandria, VA, and IWA Publishing, Colchester, UK.

Weber, J.A., Kampalath, R., Ferguson D., and Steets, B. (2013). "MS4 Outfall Dry Weather Bacteria Source Tracking Study." Presented at *2013 CASQA Workshop*. Prepared by Geosyntec Consultants.

Weston Solutions, Inc. (2004). *Phase I Report for the San Diego River Kelp and Dog Waste Management Plan for Dog Beach and Ocean Beach*. Prepared for the City of San Diego.

Weston Solutions, Inc. (2009a). *San Diego River Source Tracking Investigation – Phase I, Final Report, Revision 1.* Prepared for the City of San Diego. December 2009.

Weston Solutions, Inc. (2009b). *San Diego County Municipal Copermittees 2007–2008 Urban Runoff Monitoring.* Prepared for the County of San Diego. January 2009.

Weston Solutions, Inc. (2010b). *Tecolote Creek Microbial Source Tracking Summary Phases I, II, and III.* Prepared for the City of San Diego. June 2010.

Wilkins, A., Wong, C., & Cizek, A. (2025). Biochar for Bioretention Systems: A Review of Biochar Use in Bioretentions, Biofilters, and Bioretention Soil Media. Center for Watershed Protection.

Williams, D.E. and Corrigan, R.M. (1994). "Pigeons (rock doves)." Pp. 87-96 in S. E. Hygnstrom, R.M. Timm, and G.E. Larson, eds., *Prevention and control of wildlife damage.* University of Nebraska, Lincoln, NE.

Wojtenko, I., Stinson, M.K., and Field, R. (2001). "Challenges of Combined Sewer Overflow Disinfection with Ultraviolet Light Irradiation." *Critical Reviews in Environmental Science and Technology,* 31(3), 223-239.

Wright Water Engineers and Geosyntec. (2010). International Stormwater Best Management Practices (BMP) Database Pollutant Category Summary: Fecal Indicator Bacteria, and 2014 statistical appendices. Project sponsors include: Water Environment Research Foundation, Federal Highway Administration, American Society of Civil Engineers Environmental and Water Resources Institute, U.S. Environmental Protection Agency and American Public Works Association. Accessible at: www.bmpdatabase.org

Wuertz, S., Bambic, D., Mcbride, G., Miller, W., Stott, R. (2011). *Quantification of Pathogens and Sources of Microbial Indicators for QMRA in Recreational Waters*. Water Environment Research Foundation, Project Number PATH2R08.

Xanthopoulos, C., and Hahn, H.H. (1990). "Pollutants attached to particles from drainage areas." *Science of the Total Environment*, 93, 441-448.

Young, D. R., Sercu, B., Holden, P. A., & Schiff, K. C. (2020). *Source identification of fecal indicator bacteria in stormwater discharges to southern California beaches*. Southern California Coastal Water Research Project.

Zhang L., Seagren, E.A., Davis, A.P., Karns, J.S. (2010). The Capture and Destruction of Escherichia coli from Simulated Urban Runoff Using Conventional Bioretention Media and Iron Oxide-coated Sand. Water Environment Research, 82(8): 701-714.

Zimmer-Faust, A. G., Steele, J. A., Xiong, X., Staley, C., Griffith, M., Sadowsky, M. J., Diaz, M., & Griffith, J. F. (2021). A combined digital PCR and next generation DNA-sequencing based approach for tracking nearshore pollutant dynamics along the Southwest United States/Mexico border. *Frontiers in Microbiology, 12*, 674214. https://doi.org/10.3389/fmicb.2021.674214

Appendix A. Additional Information on Bioretention/Media Filter Amendments and Subsurface Flow Wetlands (from 2016 *E. coli* Toolbox)

The 2016 *E. coli* Toolbox included two sections providing a detailed discussion for design considerations for biofilter (bioretention/media filter) enhancement and subsurface flow wetlands. Because these are both research-level topics, they have been moved to an appendix for the 2026 update of this Toolbox. Media research continues in Colorado at the CSU SPUR campus and nationally as described in Section 5.1.3 of this Toolbox. Subsurface flow wetlands are not currently likely to be implemented in Colorado so this discussion has also been moved to an appendix. Update of these sections was beyond the scope of the 2026 Toolbox update; however, the discussions below still contain useful information.

Biofilter Enhancements

Biofilter enhancements include media selection, vegetation type, outlet controls and incorporation of a saturated zone. The Facility for Advancing Water Biofiltration (FAWB) at Monash University in Australia, developed guidance for advanced biofilter implementation (FAWB, 2009). FAWB was integrated into the CRC for Water Sensitive Cities (CRCWSC), which published updated the “Facility for Advanced Water Biofiltration: Stormwater Biofiltration Systems Adoption Guidelines” in 2022 (https://wscaustralia.org.au/).

Information provided in the 2016 *E. coli* Toolbox is provided below for convenience, but the most current version of the guidance should be reviewed for potential changes.

Media Selection

Specialty media components currently being researched to determine their effect on biofilter FIB performance include metal-oxide coated sand, organosilane, zeolite, and biochar. Metal-oxide coated sands are not recommended due to Mohanty et al. (2013) raising concerns of fouling with the presence of NOM and remobilization of bacteria, as well as the potential for this media to export metals and toxicity. Organosilane is not recommended due to observed rapid fouling by Torkelson et al. (2012). Additional testing is required to determine the effectiveness of these media and necessary precautions to reduce maintenance and export of other pollutants. Zeolite is a natural mineral that has been shown to reduce FIB concentrations below recreational objectives in studies by Mwabi et al. (2012) and Prabhukumar (2013). Zeolite also reduced other pollutants such as metals and nutrients due to its ion exchange capability (Pitt and Clark 2010). The lab study performed by Mohanty et al. (2014) evaluated biochar for FIB removal and found consistent reduction in effluent concentration, but effluent concentrations were not consistently below recreational objectives, which may have been due in part to unrealistically high influent concentrations ($1.2 – 1.7 \times 10^6$ cfu/mL). The same study also found biochar has the potential to enhance other methods of treatment. Unlike other advanced media, biochar was less affected by the presence of NOM and was found to reduce the remobilization of FIB (Mohanty et al. 2014). Mohanty and Boehm (2015) also found that in biochar-augmented sand filters, dry-wet cycles (i.e., dry periods between storms) improved FIB reduction. The FAWB recommends keeping nutrients low to avoid leaching and a media depth range between 16 and 24 inches (FAWB 2009). MHFD’s recommendation of 18-inch media depth (MHFD 2015) aligns well with recommendation.

Vegetation Selection

In addition to media mixture recommendations, Chandrasena et al. (2012a) found in a laboratory study that the species of vegetation provided in the media also affects FIB removal. While the difference was not statistically significant, they found that *Lomandra longifolia* (basket grass) showed better FIB removal than *C. appressa* (tall sedge). Previous studies had shown the opposite relationship when treating for nutrients (Bratieres et al. 2008, Read et al. 2008). These findings indicate that preferable plant traits may differ when targeting various pollutants. Additionally, Chandrasena et al. (2012b) hypothesized that the creation of macropores and other changes in the soil structure may have resulted in improved performance. They also hypothesized that specific species may produce antibiotic root exudates within the submerged zone that may increase overall removal of FIB. Given the importance of using drought-tolerant plants in Colorado, it may be worthwhile to conduct research to determine how FIB removal may be affected by choice of plants.

The FAWB recommends contacting local plant experts to identify suitable species that promote pollutant removal and infiltration, are drought tolerant, include extensive root structures that penetrate through the entire filter depth, include dense linear foliage, are non-invasive and meet other climate-specific requirements. Although extensive root depth promotes infiltration, it is important to note that the root depths should be limited to the filter media depth and not extend into the drainage layer, which could clog the underdrain. FAWB also recommends selecting a variety of species to increase system robustness and selecting vegetation that is hardy and tolerant of infrequent wetting in the area farthest from the inlet and vegetation capable of tolerating frequent inundation near the inlet.

Outlet Control and Contact Time

To provide adequate contact time between the stormwater runoff and the media, it is necessary to provide outlet control at the discharge. When providing outlet control, the flowrate through the media alone (controlled by media conductivity) should be greater than the flowrate through the outlet so that the media is not limiting flow through the BMP. Additionally, adding outlet control allows for the selection of larger media particles, with larger pore spaces that will likely reduce clogging frequency and maintenance requirements. The available literature on FIB removal from stormwater includes data on biofilters with contact times from approximately 5 minutes (Li et al. 2014a, Passeport et al. 2009) to over 2 hours (Hunt et al. 2008 , Mohanty et al. 2014) including different media mixtures and outlet configurations. Overall, the available literature show a positive correlation between treatment of FIB and contact time. Pitt and Clark (2010) found that good removal of most pollutants can be expected from a system with approximately 10 to 40 minutes contact time. MHFD's bioretention design criteria are based on a 12-hour drain time (MHFD 2015). Additional research is needed to better understand the relationship between contact time and FIB removal in advanced biofilters.

Saturated Zone ("Internal Water Storage Zone")

Recent published studies have also shown that the presence of a fully saturated zone or internal storage zone, which will also result in increased contact time, can improve treatment of FIB (Passeport et al. 2009; Chandrasena et al. 2014; Li et al. 2012; Roseen and Stone 2013; Rippy 2015). The saturated zone is created in the BMP by raising the outlet elevation by approximately 12 to 18 inches from the bottom of the BMP drainage layer (FAWB 2009) to create a permanently saturated zone below this elevation (i.e., after the storm, the captured water will drain through the elevated outlet, leaving 12 to 18 inches of saturated media or gravel between storms).

Li et al. (2012) found that extended drying, resulting in decreased soil moisture, likely led to increased porosity and less optimal biofilm functionality resulting in less FIB reduction. Conversely, the presence of a saturated zone and a carbon source (e.g., wood chips, pea straw, etc.) maintained optimal *E. coli* removal after antecedent drying periods. Rippy (2015) cautions that the carbon source should be selected to minimize the export of dissolved organic matter, which may reduce FIB reduction in biofilters. Rippy suggests newspaper, wood chips, and sulfur-limestone as suitable carbon sources that release low concentrations of total carbon.

Additional data and field studies are required to conclusively evaluate the benefits of a saturated zone for purposes of FIB reduction. The only field experiment of the studies referenced above is Passeport et al. (2009) for two grassed bioretention cells with internal water storage zones in North Carolina. The results of this field study showed that three of the four samples from one cell and one of the seven samples from another cell exceeded the EPA standard limit of 200 cfu/100 mL for fecal coliform (influent concentrations for both cells ranged from 220 to greater than 20,000 cfu/100 mL).

In summary, the FAWB recommends a saturated zone of 12 to 18 inch thickness (preferably 18 inches), including a mix of medium to coarse sand and carbon mix or fine gravel and carbon (carbon source = 5% mulch and 5% hardwood chips).

Subsurface Flow Wetlands

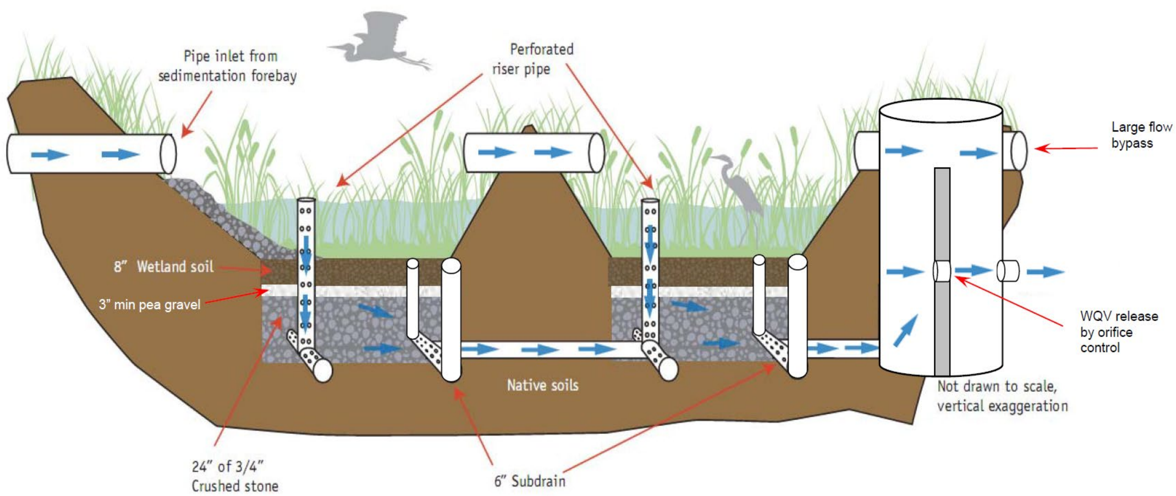
Water Rights and Wetlands in Colorado

Constructed wetlands in Colorado typically require a water right.

Subsurface flow wetlands are engineered, below-ground treatment wetlands that include many of the natural treatment processes of surface flow constructed wetlands as well as the filtration mechanisms of media filters. Water flows through a granular matrix, which typically supports the growth of emergent wetland vegetation on the surface. The matrix provides a significant surface area for the filtration of particulate-bound constituents and the growth of bacterial biofilms that metabolize and degrade pollutants. Due to the low flow rates required for treatment, an equalization basin is typically needed upgradient of the wetlands to handle peak flows and provide a near constant discharge to the facility, as well as provide solids removal to reduce maintenance frequency and associated cost for the subsurface flow wetland.

Currently, no subsurface flow wetland performance studies for FIB are included in the BMP Database; however, published research is available that suggests that subsurface flow wetlands may be effective at reducing FIB (Kadlec and Knight 1996, EPA 1993, Puigagut et al. 2007, Sleytr 2007, Edwards et al. 1993, Geosyntec 2010, Hathaway et al. 2008). Implementation of a subsurface flow wetland requires a consistent supply of water (and adequate water rights) to maintain aerobic conditions and support vegetation health; continuous water supply may not be available in all settings, particularly in semi-arid and arid climates. Additionally, adequate land area for equalization basins is needed. Subsurface flow wetlands are a treatment alternative often considered in Southern California TMDL plans (Geosyntec 2009, Peninsula WMG 2015). These plans show the typical cost for subsurface flow wetlands ranging from $40,000 to $68,000 per acre treated (including the cost of the equalization basin).

Figure A-1. Conceptual Subsurface Flow Wetlands
(Source: Geosyntec 2015)



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