International Stormwater Best Management Practices (BMP) Database

Pollutant Category Summary: Fecal Indicator Bacteria

Prepared by
Wright Water Engineers, Inc.
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Under Support From
Water Environment Research Foundation
Federal Highway Administration
Environment and Water Resources Institute of the
American Society of Civil Engineers

December 2010

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Acknowledgements

Report Preparation[1]

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POLLUTANT CATEGORY SUMMARY: BACTERIA

1 INTRODUCTION

As of 2010, pathogens were the top cause of stream impairments nationally, with over 10,000 stream segments identified as impaired, typically due to elevated concentrations of "fecal indicator bacteria" in waterbodies. This technical summary has been developed to assist federal, state and local governments, watershed organizations, environmental groups and other interested parties in selecting, designing and developing reasonable performance expectations for stormwater best management practices (BMPs) with regard to fecal indicator bacteria.

Although numeric effluent limits for stormwater discharges are not typically required in most communities, the implementation phase of Total Maximum Daily Loads (TMDLs) may result in National Pollutant Discharge Elimination System (NPDES) stormwater discharge permit requirements to address bacteria. Such requirements are typically based on BMPs; therefore, it is important to have a good understanding of sources of bacteria, treatment processes expected to be effective in reducing bacteria and the performance of BMPs. This technical summary addresses these topics:

- Regulatory context for pathogens in receiving waters
- Sources of pathogens and fecal indicator bacteria
- Fate and transport processes, removal mechanisms and associated BMP design considerations for fecal indicator bacteria and pathogens
- Overview and analysis of fecal indicator bacteria included in the International Stormwater BMP Database (BMP Database)
- Conclusions and recommendations

Basic Terminology
(Adapted from EPA 2001)

Fecal Indicator Bacteria: Bacteria present in the intestines or feces of warm-blooded animals that are used to indicate the potential presence of other organisms such as pathogenic bacteria and viruses. Fecal indicator bacteria are usually associated with the other organisms, but are more easily sampled/measured.

Pathogen: Disease-causing agent, especially microorganisms such as bacteria, protozoa, and viruses.

Bacteria: Single-celled microorganisms that lack a fully defined nucleus. Bacteria of the coliform group are considered the primary *indicators* of fecal contamination and are often used to assess water quality.

***Escherichia coli* ("*E. coli*") and enterococcus:** subgroups of fecal coliform bacteria that are part of the normal intestinal flora in humans and animals; used as indicators of fecal contamination in the 1986 EPA Ambient Water Quality Criteria.

***E. coli* 0157:H7:** An enteropathogenic strain of *E. coli* that can cause serious infection resulting in gastroenteritis. Presence of the *E. coli* subgroup does not necessarily mean that this pathogenic strain of *E. coli* is present.

Fecal Coliform: A subset of total coliform bacteria that are present in the intestines or feces of warm-blooded animals; historically used as indicators of the sanitary quality of water.

Total coliform bacteria: A group of bacteria found in the feces of warm-blooded animals; historically used as indicators of possible sewage pollution. Many common soil bacteria are also total coliforms.

Enteric: Of or within the gastrointestinal tract.

1.1 Regulatory Context

Under the federal Clean Water Act, the U.S. Environmental Protection Agency (EPA) establishes Ambient Water Quality Criteria (AWQC) for bacteria to protect human health (EPA 1986; Cabelli 1983; Dufour 1984). Currently, EPA uses *Escherichia coli* (*E. coli*) and enterococcus as indicators of fecal contamination of receiving waters. These fecal indicator bacteria are present in the intestines of warm-blooded animals and are easier to identify and enumerate in water quality samples than the broad range of pathogens in human and animal feces. Examples of human pathogens include species such as *salmonella* spp., *pseudonomas aeruginosa*, *staphylococcus aureus*, and *clostridium perfingens*. Prior to 1986, the AWQC relied upon fecal coliform as an indicator of fecal contamination. Total coliform and fecal streptococcus have also been used as indicator bacteria. EPA's currently applicable criteria were issued in 1986 (Table 1) and are scheduled to be updated in 2012. At the time of publication of this technical summary, significant research is underway to refine various aspects of the criteria based on the current state of scientific knowledge in the areas of microbiology, risk assessment, epidemiology, modeling, implementation considerations, and other related areas of practice.

Table 1. EPA Ambient Water Quality Criteria for Bacteria (EPA 1986)

Fecal Indicator	**EPA Primary Contact Criteria** (based on geometric mean[1])
E. coli (EPA-recommended for freshwater)	126/100 mL
Enterococcus (EPA-recommended for marine settings)	33/100 mL (freshwater) 35/100 mL (marine)
Fecal coliform (EPA-recommended prior to 1986)	200/100 mL

[1]EPA also provides recommendations for single-sample maxima for various uses; these single sample values are higher than the geometric mean values. States vary with regard to how or if single sample maxima are included in state water quality standards. Single sample maxima are required waters regulated under the BEACH Act.

States with delegated Clean Water Act authority rely on the AWQC to promulgate numeric standards to protect human health at streams with recreational use classifications. Such standards are also integrated into NPDES permits for wastewater treatment plants. Although EPA establishes minimum criteria for recreational water quality, there is significant variation among the states in how the criteria are adopted into state water quality standards. For example, some states use a geometric mean value as the standard, whereas other states use both a geometric mean value and some type of single sample maximum value. Similarly, some states specify a 30-day geometric mean of no less than five samples, whereas others do not have such a specification or use alternative specifications such as 60 days. States vary in terms of seasonal, wildlife and high flow exemptions, as well as with regard to how they categorize primary and secondary contact recreation. Variation also remains with regard to the type of fecal indicator bacteria used in the standard.

State standards are used to assess attainment of stream standards biennially, developing state "303(d) lists" of waters not attaining stream standards. States are required to initiate the TMDL process to address these impairments and assign pollutant load allocations to various sources discharging to the stream, including wasteload allocations (WLAs) for point sources and load allocations (LAs) for non-point sources. Municipal separate storm sewer systems (MS4s) are considered point sources.

Basic Form of a TMDL

The basic form of a TMDL calculation is:

$$\mathbf{TMDL = \Sigma WLA + \Sigma LA + MOS}$$

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)
- MOS= the margin of safety

1.2 Typical Sources of Pathogens and Fecal Indicator Bacteria

Sources of fecal indicator bacteria in streams vary widely and include animal, human and environmental sources. Representative sources of fecal indicator bacteria include sanitary sewer overflows (SSOs), combined sewer overflows (CSOs), wet weather (stormwater) discharges from MS4s, illicit connections to storm sewer systems (dry weather discharges), inappropriate discharges to storm sewer systems (e.g., powerwashing), failing or improperly located onsite wastewater treatment systems (septic systems), wastewater treatment plants, wildlife, domestic pets, agriculture and other sources (Table 2). Environmental sources of bacteria have gained increasing attention in recent years. For example, Skinner et al. (2010) summarize recent research indicating that biofilms (i.e., the "slime layer") in storm sewers provide a safe environment for enhanced bacterial replication; supply nutrients and water for biofilm bacteria; and offer protection against microbial predators, ultraviolet (UV) light, drying, and disinfectants (citing research by Coghlan 1996, Costerton et al. 1995, Donlan and Costerton 2002, Donlan 2002). Environmental sources of fecal indicator bacteria such as bacteria in sediments present in outfalls and streambeds have also received attention in various studies (e.g., Byappanahalli et al. 2003; Byappanahalli et al., 2006; Davies et al. 1995; Monroe 2009). Other studies have shown plant sources such as decaying kelp along beaches serving as the "perfect incubator for bacterial growth" (Kolb and Roberts 2009).

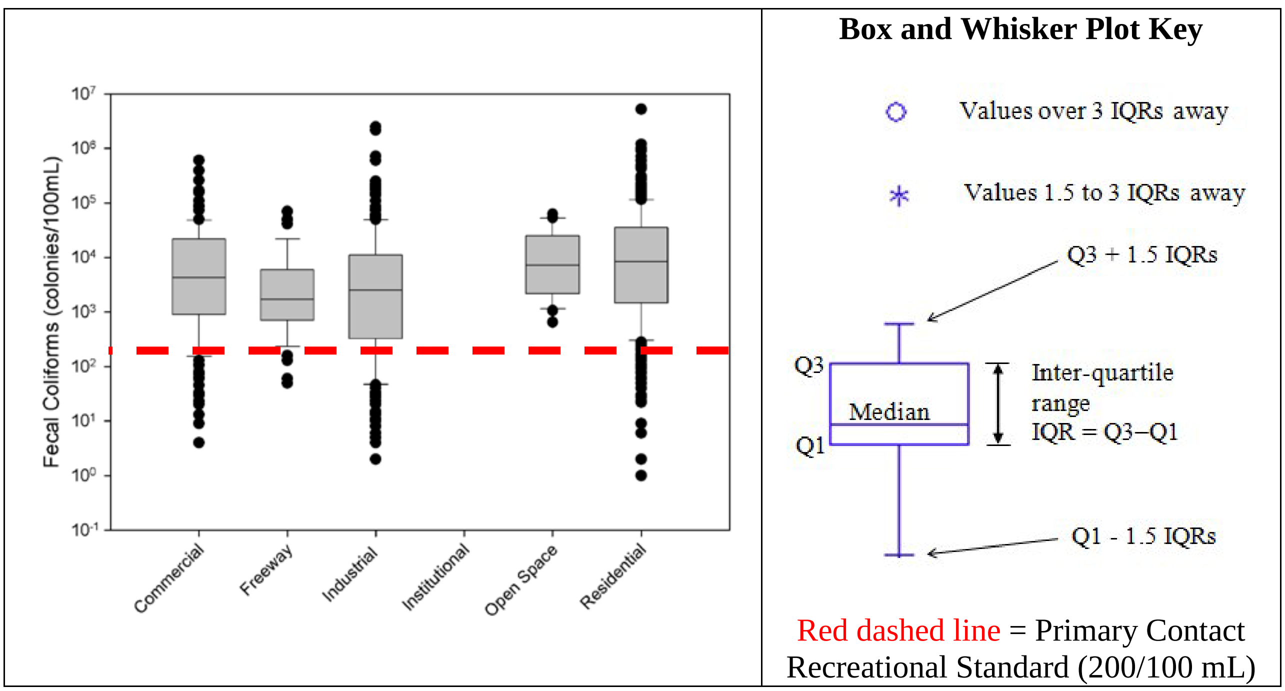
Regardless of whether the source is natural or human-caused, fecal indicator bacteria concentrations in urban stormwater are typically well above primary contact recreation stream standards, regardless of the land use (Figure 1) (Pitt, Maestre and Morquecho 2004). To target source controls, more detailed evaluation of sources or activities within various land uses is typically needed. Although some of these sources can be reasonably controlled (e.g., wastewater discharges, illicit connections), other sources are much more difficult to control such as raccoons and other animals in storm sewers, beavers, wildlife in open space areas, birds on bridges, and stream and storm sewer sediments and biofilms. When exploring source of fecal contamination that pose risks to human health, stormwater managers should also be aware that although significant concentrations of fecal indicator organisms are nearly ubiquitous in urban drainage, the relationship between fecal indicators and pathogens is unclear. For example, Schroeder et al. (2002) investigated the presence of human pathogens in urban storm drains in California and concluded, "Pathogens can be found in urban drainage, but there does not appear to be a relationship between the presence of pathogens and the concentration or presence of indicator organisms." Currently, water quality criteria do not differentiate risks to human health due to sources of fecal indicator bacteria. Expert panels convened by EPA (2007) and the Water Environment Research Foundation (WERF 2009) have generally agreed that human sources of bacteria are *expected* to pose a greater health risk than animals and environmental sources, but have also recommended additional research to better quantify this risk. In *Review of Zoonotic Pathogens in Ambient Waters*, EPA (2009) concludes "Contamination of recreational waters with feces from warm-blooded animals poses a risk of zoonotic infection of humans with some of the pathogens in those waters. Although the risk and severity of human illness due to contamination with animal feces and zoonotic pathogens is most likely lower than the risk and severity of illness from treated or untreated human sewage, currently available data are insufficient to quantify the differences." Consequently, EPA requires both natural and human-caused sources of fecal indicator bacteria to be addressed unless an epidemiological study has demonstrated that non-human sources do not pose a risk to human health (Barash 2009).

Understanding sources of bacteria is important in selecting appropriate BMPs targeted to these sources. Managing the source should be the first strategy implemented. A variety of guidance and techniques exist for conducting bacteria source tracking, ranging from relatively straightforward illicit discharge screening (CWP and Pitt 2004) to complex microbial source tracking (MST) studies (EPA 2005; WERF 2007). As one example, some communities have had success using quantitative polymerase chain reaction (qPCR) methods for human source *Bacteroides*. A discussion of MST and evolving microbiological methods is beyond the scope of this technical summary; nonetheless, stormwater managers should be aware that analysis and source identification methods are evolving. EPA's Recreational Water Quality Criteria website (http://water.epa.gov/scitech/swguidance/waterquality/standards/criteria/health/recreation/index.cfm) should be consulted to ensure that stormwater monitoring programs are consistent with the most currently recommended methods and criteria.

Table 2. EPA's Summary of Bacteria Sources, Possible Management Activities and Transport Processes[2] (Source: EPA 2001)

Source/land use	Operation/activity	Samples of management activity	Frequency	Transport process(es)
Agriculture	Livestock-feedlot Livestock-manure storage Crop-manure/sludge application Pasture	Manure removal Storage structures; leachate control Spreading schedules; storage Rotation	weekly variable variable variable	runoff; erosion runoff; erosion; seepage runoff; erosion runoff; erosion; direct
Urban/ Residential	Domestic pets Wildlife Septic systems Illicit connection Landfills	Waste pickup law Management; population control Pumpout; education Compliance Disposal	variable constant annual constant constant	runoff runoff; direct leaching; interflow direct runoff; leaching
Forest	Wildlife	Management; population control	constant	runoff; erosion; direct
Point Sources	WWTP Slaughterhouse CSOs; SSOs	Waste treatment Waste treatment Storage/transport redesign	constant variable variable	direct direct direct; rainfall-driven

Figure 1. Box and Whisker Plots of Fecal Coliform in Stormwater Data
(Source: Pitt, Maestre and Morquecho 2004)



[2] Additional sources not explicitly included in the EPA (2001) table include sediments and litter within storm sewer systems that can provide environments where bacteria can persist and be resuspended during runoff and/or potentially reproduce/grow. Researchers have not reached consensus on the relative roles of regrowth versus resuspension of bacteria deposited in sediments (WERF 2007).

2 TRANSPORT PROCESSES AND REMOVAL MECHANISMS[3]

Prior to evaluating BMP performance or selecting BMP strategies targeted to bacteria, it is important to understand basic fate and transport mechanisms and treatment processes anticipated to be effective for removing or inactivating fecal indicator bacteria and human pathogenic bacteria and viruses. This technical summary focuses on treatment and removal of fecal indicator bacteria from stormwater through the use of structural BMPs prior to flows entering MS4s or reaching receiving waters via direct overland flow. CSO, SSO and end-of-pipe disinfection are beyond the scope of this summary. Researchers should also be aware that the forms and behavior of pathogens and associated removal mechanisms may differ from fecal indicator bacteria (WERF 2007).

2.1 Overview of Fate, Transport and Pollutant Removal Mechanisms

Fecal indicator bacteria in urban stormwater originate from feces of warm blooded animals deposited on pervious and impervious surfaces. These bacteria may be directly deposited into the receiving water or transported in stormwater flows. Additionally, bacteria may persist for extended periods of time (outside of a warm-blooded host) in sediments, biofilms, and organic litter in stormwater facilities, pipes and media. Bacteria differ from the other conventional stormwater pollutants in two fundamental ways:

- Bacteria are living organisms and their primary effect on stormwater quality results from their life status rather than their simple presence. Bacteria can be controlled (i.e., inactivated) without being removed, but concentrations can also increase without further bacterial loading when conditions are conducive to natural population growth within stormwater conveyances, treatment facilities, and receiving waters.

- While sediment and organic litter represents a sink for most pollutants, bacteria may survive longer in sediments/organic litter than in the water column. Therefore, sediment or organic litter, if mobilized, could actually be an important source of bacteria, and removal of water column particulate-bound or free bacteria may not constitute a reliable permanent removal mechanism in some cases.

Removal mechanisms for bacteria in stormwater BMPs include both passive and active process. This technical summary focuses on passive stormwater treatment BMPs, which are briefly

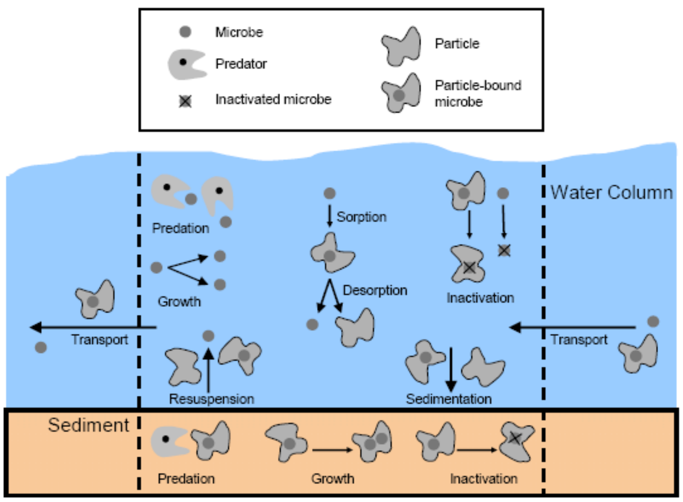
[3] Acknowledgements:
This section has been adapted from:
Strecker, E.; Leisenring, M.; Poresky, A.; Pomeroy, C.; Mattson, J., and Barrett, M. (2009). Recommended Initial Set of Water Quality Constituents and BMPs to Address in BMP Algorithms - Task 3A Technical Memo of Linking BMP Performance to Receiving Water Protection to Improve BMP Selection and Design. WERF Project SW1R06. Submitted to Project Issue Area Team August 24, 2009.
Significant portions of this section also rely upon work presented in:
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.

summarized in the remainder of this section. Active treatment mechanisms such as chlorination, ozonation, and active ultraviolet (UV) disinfection are excluded because no existing studies relying on active treatment are currently included in the BMP Database and application of active treatment practices for stormwater are not expected to be practical for most municipal applications. Currently, these types of installations are generally focused on treatment of dry weather flows from stormwater systems.

Based on a literature review conducted for the WERF Stormwater Challenge (Strecker et al. 2009), the dominant passive removal mechanisms for fecal indicator bacteria include natural inactivation, predation, inert filtration and sedimentation, sorption and chemical inactivation (via contacting products). Olivieri et al. (WERF 2007) graphically conceptualized some of these key removal mechanisms as shown in Figure 2.

Figure 2. The Possible Fates of Microbes (Fecal Indicators and Pathogens) in Environmental Water and Sediment

(Source: WERF 2007, as prepared by Olivieri et al.).



Strecker et al. (2009) and WERF (2007) describe these key passive pollutant removal processes that may be present in various BMP types:

- **Natural inactivation** is a general removal mechanism that refers to bacteria 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). In addition, bacteria bound to particulates have been found to be inactivated at slower rates as particulates are believe to provide both nutrients and shelter (WERF, 2007).

- **Predation** of pathogenic bacteria by other microorganisms is interrelated with natural inactivation and has been found to be a major removal mechanism. The most important predators of pathogenic bacteria are believed to be protozoa and other eukaryotic organisms. Studies have found that predation may account for approximately 90 percent of overall mortality rates of bacteria. Studies suggest that factors affecting natural inactivation rates such as sunlight and presence of particulates may have similar effects on predation rates by weakening bacteria or by sheltering them from predators, respectively (WERF, 2007).

- **Inert filtration[4] and sedimentation** of solids are mechanisms that would be expected to remove bacteria bound to particulates from the water column. The effectiveness of particle removal at reducing bacteria concentrations is a function of the partitioning of bacteria between particulate-bound and free-floating forms, and the association of bacteria across the particle size distribution. Once again, the removal of bacteria from the water column through sedimentation or filtration does not necessarily constitute an ultimate removal mechanism because the survival of bacteria is expected to be greater when bacteria are bound to sediment, and resuspension of communities of bacteria sheltered by sediment could represent a significant source of bacteria in some systems.

- **Sorption** (the bonding of microorganisms to the surface of particles) is believed to be controlled by steric, electrostatic, and hydrophobic interactions. As described in WERF (2007), steric interactions arise between macromolecules, electrostatic interactions are based on surface charge, and hydrophobic interactions result from the polarity and non-polarity of organic molecules. Researchers have found that some bonds are “irreversible” but that many bonds that occur between bacteria and particulates are reversible if conditions change or if physical forces such as fluid shear forces are applied. Even bonds considered to be irreversible can be broken under high turbulence and fluid shear. Partitioning of bacteria 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 bacteria 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 pathogenic bacteria without being consumed or dissipated and without producing toxic byproducts (Nolan, et al., 2004). It is presumed that effectiveness of BMPs 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 bacteria 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 devices.

  While inactivation through addition of chemicals such as chlorine and ozone is understood to be effective, its application is limited in stormwater because of the need to add chemicals, concerns about toxicity of byproducts, and the need to have greater control over these processes than typically allowed in operation of stormwater facilities.

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

2.2 Factors Influencing Pollutant Removal

Many factors affect survival of fecal indicator bacteria in the environment. Interactions between multiple factors make it difficult to transfer findings from one watershed to another. Primary characteristics and conditions expected to influence dominant removal mechanisms include:

- Sunlight (solar irradiation)
- Temperature
- Microbial community (predators)
- Turbidity
- Particle association/partitioning
- Flow rates
- Nutrient availability
- Other factors such as pH and salinity

2.2.1 Sunlight (Solar Irradiation)

Sunlight has been consistently observed to reduce the concentration of fecal indicator bacteria; however, different species have been observed to have different resilience to solar radiation and some studies have indicated that inactivation caused by sunlight may not be permanent; bacteria may be able to repair cell damage and regain colony forming potential when no longer exposed to sunlight (WERF, 2007).

BMP design characteristics influencing the solar radiation treatment process include depth of ponding, retention time, turbidity of water, and shading of the water surface. Turbidity, specifically, is important as it both blocks sunlight from passing through water and provides a place for bacteria to "hide."

2.2.2 Temperature

Microbial processes are controlled by temperature, thus it is no surprise that temperature has been found to be an important factor in natural inactivation of bacteria. Multiple studies (as summarized by WERF, 2007) have found that warmer water temperatures result in faster inactivation of bacteria. This is because warmer temperatures would cause faster metabolism and earlier natural inactivation, as well as increased activity (i.e., appetite) of predatory microorganisms. Colder temperatures would tend to "preserve" the vitality of bacteria by slowing metabolic processes. Solic and Krstulovic (1992) found that the time required for a 90 percent reduction in fecal coliforms decreased by 55 percent for each increase of 10^{o} C.

On the other hand, temperature effects on bacteria inactivation rates should not be confused with seasonal trends in bacteria concentrations or loadings. For example, studies of receiving waters along Colorado's Front Range have also shown that fecal indicator bacteria concentrations are typically greater in receiving waters during the summer, when temperatures are warmer (Colorado *E. coli* Work Group and WWE 2009). Hathaway et al. (2010) further explored the temperature paradox, also noting that field studies in North Carolina and other parts of the country have shown indicator bacteria concentrations in surface waters are higher during warmer parts of the year (citing Selvakumar and Borst 2006; McCarthy 2008; Young and Thackston 1999; Line et al. 2008; Schoonover and Lockaby 2006). Hathaway et al. (2010) suggest that the somewhat unexpected correlation between increasing temperature and indicator bacteria concentrations may be due to interactive effects between such factors as temperature and moisture, resulting in more complicated relationships. Based on their research and research by McCarthy et al. (2008), Crane and Moore (1986), and Tiefenthaler et al. (2009), Hathaway et al. (2010) suggest that possible explanations for the increase in indicator bacteria concentration with increased temperatures may include:

1. increased sources of indicator bacteria due to domestic and wild animal activity and

2. increased persistence due to seasonal variations in environmental conditions such as temperature, humidity, and rainfall patterns.

Hathaway et al. (2010) essentially conclude that temperature likely acts as a surrogate for seasonal variations and interactions among multiple factors.

2.2.3 Microbial Community

As previously noted, predation of bacteria from other microbes can reduce bacteria concentration in BMPs and runoff. Studies quantifying the condition of the predatory microbial community in stormwater BMPs are limited. When exploring the role of predation on bacteria reduction, it may be more constructive to characterize surrogate factors such as biochemical oxygen demand (BOD) or total organic carbon (TOC) to describe different levels of predation in different facilities.

2.2.4 Turbidity, Partitioning and Particle Association

As mentioned above, turbidity alone can affect the amount of sunlight passing through water, which can protect bacteria from the effects of UV radiation.

Estimates of partitioning and particle association for bacteria vary greatly between studies. Generally, greater amounts of bacteria are particulate bound when more particulate matter is present, and particulate-bound bacteria are expected to make up a significant fraction of total bacteria. Because studies have indicated better survival of bacteria associated with particles, the magnitude and fate of this fraction is important. Bacteria are generally negatively charged; thus, the presence of particulates with a positive charge on all or part of their surface would tend to result in greater partitioning of bacteria to the particulate-bound form. This would suggest that coating the sand in a media filter with iron would increase bacteria sorption because the iron would give the sand surface a positive charge allowing negatively charged bacteria to sorb.

When evaluating the role of partitioning for bacteria, it is also important to assess the strength of the bonds for the particle-associated bacteria. Based on studies that compared unagitated samples to agitated samples, it is apparent that physical agitation alone results in partitioning of particulate-bound bacteria into solution, indicating that bacteria-particulate bonds may be rather weak (Borst and Selvakumar, 2003 from WERF, 2007).

With regard to bacteria association with specific particle sizes, a limited number of studies exist. Results from these studies are wide-ranging and are not sufficient to confidently estimate the association of bacteria with specific particle size ranges.

2.2.5 Flow Rates

Filtration and sorption mechanisms are generally more effective at lower flow rates (Pitt, Clark and Parmer 1994). Similarly, sedimentation of particle-bound bacteria would be expected to be more effective in facilities with longer holding times, shallow depths, and longer flow paths. Wilkinson et al. (1994) summarize empirical studies that indicate the entrainment and deposition of fecal coliforms in streams and rivers is governed by the relationship between flow and the channel bed. Based on these studies, the researchers developed a model that assumes fecal coliform bacteria are associated with low density particles that are entrained when the flow rises and deposited when the flow recedes. A similar model was developed by Collins and Rutherford (2004) for pastoral lands that, in addition to accounting for deposition and entrainment associated with changes in flow, accounted for seepage in channel banks where excrement from grazing cattle and sheep may be transported to the surface waters.

2.2.6 Nutrients

Presence of nutrients in water may affect survival of bacteria, with several recent studies suggesting that nutrients may play a significant role. Researchers hypothesize that the greater survival of particulate-bound bacteria compared to free-floating bacteria is due in part to nutrients on the surfaces of particles. Nonetheless, recent studies vary with regard to the expected role that nutrients play in bacteria survival, with some studies showing strong positive correlations, with others showing no correlation. For example, Hathaway et al. (2010) note studies have shown varied correlations between nitrogen species and indicator bacteria. In particular, a study by Line et al. (2008) showed no correlation between fecal coliform concentrations and nitrate-nitrogen or ammonia-nitrogen in three watersheds in North Carolina. Conversely, McCarthy (2008) showed positive correlations between ammonia-nitrogen and *E. coli* for three out or four watersheds monitored in Melbourne, Australia. In California, Surbeck et al. (2009) found that fecal indicator bacteria concentrations were strongly positively correlated with dissolved organic carbon (DOC) concentration in runoff, and microcosm studies showed that the survival of *E. coli* and enterococci in runoff were strongly dependent on the concentration of both DOC and phosphorus.

2.2.7 Minor Factors

The following factors are expected to play minor roles in pollutant removal in stormwater BMPs:

- **pH**: Low and high pH are believed to decrease the survival of bacteria. While little research has been performed into effect of pH on survivability of stormwater pathogenic bacteria, one study noted that bacteria thrived near neutral pH (Solic and Krstulovic, 1992 from WERF, 2007). Wastewater literature states that most bacteria cannot tolerate pH levels above 9.5 or below 4.0, and thrive between 6.5 and 7.5 (Metcalf and Eddy, 2003). Therefore, under typical ambient conditions, pH is not a major factor.
- **Salinity**: Salinity has been demonstrated to affect the survival of bacteria; however, the range of salinity expected in stormwater runoff is relatively low compared to the range of salinities generally tested in studies of the effects of salinity on bacteria.

2.3 BMP Design Considerations

In summary, BMP designs that maximize exposure to sunlight, provide habitat enabling predation by other microbes, provide surfaces for sorption, provide filtration, and/or allow sedimentation should reduce bacteria concentrations in the water column. Practices that infiltrate stormwater will reduce bacteria loading (flow x concentration) by reducing the volume component of the load. Practices that infiltrate stormwater also typically provide treatment processes enabling sorption and filtration. Where infiltration is used, it is important to recognize that groundwater pollution can also occur, if adequate sorption and filtration do not occur prior to the infiltrated flows reaching groundwater.

3 GENERAL BMP PERFORMANCE DATA CHARACTERISTICS AND AVAILABILITY

3.1 Inventory of Available Data in Database

The BMP Database contains over 2,500 analysis results for indicator bacteria including fecal coliform, *E. coli*, fecal strep and total coliform. Of these, only *E. coli* and enterococcus are currently recommended for use by EPA. The majority of the data set is based on fecal coliform. Table 3 contains an overview of BMP studies in the database for each indicator. Attachment 1 to this memorandum provides basic inflow and outflow statistics for each of these studies, including number of samples, geometric mean, median, minimum, maximum, and 25th and 75th percentiles.

Table 3. Number of BMP Studies by Fecal Indicator Bacteria

Description	Entero-coccus	*E. coli*	Fecal Coliform	Fecal Strep	Total Coliform
Biofilter - Grass Strip		1	7		1
Biofilter - Grass Swale		5	13	1	
Bioretention	1	1	3		
Composite—BMPs in Series	1	3	2	1	
Detention Basin (Dry) - Concrete			1		
Detention Basin (Dry) - Grass-Lined	1	2	12		
Filter - Combination of Media			2		
Filter - Other Media			3		
Filter - Peat Mixed With Sand			2		
Filter - Sand	1	1	9		2
Green Roof		4	4		
Infiltration (Percolation) Trench			1		
Maintenance Practices - Street Sweeping					1
Manufactured Device (various types)	8	1	10	1	
Porous Pavement - Pervious Concrete			1		
Porous Pavement - Porous Asphalt			1		
Retention Pond (Wet) - Surface Pond		2	10	3	4
Wetland - Basin With Open Water Surfaces	1	5	2	1	1
Wetland - Channel With Wetland Bottom			3		1
Totals	13	25	86	7	10

After bacteria data at inflow and outflow locations for each BMP were retrieved from the Database (June 2010 Release), a series of screening decisions were made with regard to data sets considered appropriate for further analysis based on these criteria:

- Studies with less than five storm events monitored at the outflow from the BMP were excluded from the analysis. In part, the five storm threshold was selected since many states require a minimum of five sampling events for calculation of a geometric mean. Independent researchers may choose alternate thresholds, if desired. Ideally, for statistical hypothesis testing, many more sampling events based on event mean concentrations (EMCs) would be included; however, choosing a higher threshold would result in inclusion of a smaller number of studies in the analysis.

- No further analysis of total coliform or fecal strep data was conducted beyond the basic statistical summaries provided in Attachment 1. Relatively few BMP studies for these two fecal indicators are present in the BMP Database, and most of these studies also monitored fecal coliform or *E. coli*, so data analysis is focused on the more commonly reported indicator bacteria instead.

- Category-level comparison of BMP performance was determined to be inappropriate for enterococcus and *E. coli* due to the relatively small number of studies per BMP category. Category level analysis for fecal coliform was considered potentially appropriate for the detention basin, media filter, manufactured device, and retention pond categories.

In addition to these screening-level decisions, the following limitations of the data set are acknowledged:

- Because much of the bacteria data reported were based on grab samples, grab samples were included in this analysis. (Typically, the BMP Database analysis for other constituents is based on EMCs only.) EMCs developed based on samples collected through the duration of the storm hydrograph are considered most appropriate for characterizing stormwater pollutants. In the case of fecal indicator bacteria, EMCs are often not collected due to the recommended maximum 6-hour sample hold time for bacteria analyses. As a result, most of the data in the BMP Database are grab samples. Some sites may have one grab sample, whereas others may have multiple samples throughout the storm event. This increases uncertainty as to whether the samples are representative of the EMC for the storm, which in turn creates uncertainty when calculating loads or assessing load reduction due to infiltration-oriented practices. For sites where researchers reported multiple, uncomposited grab samples, the median of the samples was used to represent performance for the storm event.

- From a statistical analysis perspective, an additional complication relates to variation in upper and lower quantitation limits (censored data) both within and between BMP studies. Specifically, lab analysts seek a balance when diluting samples to provide characterization of high and low ends of the expected sample result range. Some analysts may reach “too numerous to count” at 2,400/100 mL, whereas other studies may reach this determination at 240,000/100 mL (or greater). These variations in quantitation limits make absolute characterization of influent and effluent concentrations more challenging.

- Stated more generally, sample collection, processing and culture-based analysis methods for fecal indicator bacteria have well known limitations. In addition to the holding time and dilution issues mentioned above, sample contamination can be an issue and culture-based test methods have short-comings. For example, culture-based methods generally involve collection of a water sample, filtering the water sample through a membrane, placing the membrane in a medium, incubating the sample, than counting and recording the number of bacteria colonies. Very small samples are taken (with respect to the storm and with respect to sample volumes for other constituents) and relatively large dilutions are typically needed to obtain a countable number of colonies. The small sample volumes are further split into much smaller subsamples (100 mL), then filtered and counted manually. The nature of the sampling, processing, and analysis methods are therefore subject to large variabilities. These are in addition to large variabilities expected between sites and among different antecedent conditions and storm-event properties.

- Widely varying sample results at the same sample location, even during the same day lead to large variation in data sets and wide confidence limits for measures of central tendency. These data set characteristics make statistical hypothesis testing challenging without much larger data sets (i.e., it is difficult to draw statistically significant conclusions with highly variable data sets). For guidance on how many samples may be needed to draw statistically significant conclusions at varying levels of confidence and power, see Appendix D of the *Urban Stormwater BMP Monitoring Manual* (http://www.bmpdatabase.org/MonitoringEval.htm). The number of sampling events needed will vary depending on study objectives and site-specific conditions.

- Seasonal distribution of samples may affect conclusions drawn related to BMP performance. For example, winter concentrations of fecal indicator bacteria may be lower than summer concentrations (Colorado *E. coli* Work Group and WWE 2010).
- All of the monitoring data in the BMP Database and the majority of the monitoring routinely conducted by most communities are targeted to fecal indicator bacteria. Much remains unknown with regard to the relationship of fecal indicator bacteria to the wide range of human pathogens that may be present in urban runoff (WERF 2007).
- Data sets for some BMP categories may be dominated by particular types of locations or be limited geographically. For example, the manufactured device studies reporting fecal coliform are limited to two locations: the Delaware Department of Transportation I-95 Service Plaza (6 BMPs) and California Department of Transportation (Caltrans) sites (3 BMPs).
- Users should be aware that certain types of BMPs are not currently represented in the BMP Database. In particular, advanced treatment methods such as UV and ozone disinfection have been successfully used in communities where frequent beach closures due to elevated fecal indicator bacteria occur. Studies in these communities have shown that these techniques can be highly effective at reducing bacteria concentrations in the discharges that they treat. These approaches are costly and are typically used where there is a definable point source discharge close to the swimming area that can be treated. Even when the discharge is effectively treated, the downstream receiving water may not necessarily attain recreational water quality criteria since new sources of bacteria (e.g., wildlife, birds) may be introduced following treatment (Murray and Steets 2009).

3.2 Graphical Summaries of Fecal Indicator Data by Individual Study

Box and whisker plots were developed to graphically illustrate the central tendencies and ranges of bacteria concentrations observed for the inflow and outflow for each BMP study for enterococcus (Figure 3), *E. coli* (Figure 4) and fecal coliform (Figures 5-10, plotted by BMP category).[5] In the box and whisker plots, the inflow is provided in the first box (in red) and the outflow is provided in the second box (in blue) above each BMP category. Conclusions that can be drawn regarding bacteria concentrations from visual observation of these data sets include:

[5] See Figure 1 for box and whisker plot key. See footnote on p. 14 for guidance in reading the plots on Figures 3-10; plot formats are constrained by formatting options available in the statistical software. Color printing recommended.

- Regardless of fecal indicator bacteria type, the available data set shows that concentrations in urban runoff typically exceed primary contact recreation standards, often by one or more orders of magnitude. (The red dashed line in each figure provides a benchmark for comparison based on EPA's geometric mean ambient water quality criteria.)

- Currently available data suggest that it is unlikely that conventional structural BMPs can consistently reduce bacteria concentrations in runoff to primary contact recreation standards.

- Bioretention, media filters and retention (wet) ponds appear to be able to reduce bacteria concentrations to some extent. 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 (dry) basins and grass swales do not appear to reduce bacteria concentrations in effluent. Instead, increases in effluent concentrations are apparent for some grass swales studies. (*Note: reductions in bacteria loading due to infiltration and evapotranspiration are not evaluated in this analysis*.)

- Inadequate data sets are available to evaluate the performance of permeable pavements, wetland basins, wetland channels and green roofs. An observation of the green roof data is that even with relatively few sources of bacteria (i.e., birds); sample results an order of magnitude above primary contact stream standards are not uncommon.

- The manufactured device category includes a range of proprietary devices which rely on various unit treatment processes; therefore, for most analyte types, performance should be evaluated on a unit treatment process basis, as opposed to a general category. The manufactured device studies currently included in the BMP Database did not result in fecal indicator bacteria effluent concentrations attaining stream standards. Significant overlap of interquartile ranges for inflows and outflows is present for the majority of the manufactured devices. The data set currently included in the BMP Database is limited; therefore, general conclusions about manufactured devices, or subcategories of manufactured devices, are not appropriate at this time.

- The concentration-based analysis does not account for load reductions that may result from reduced surface volumes discharged from the various BMP types.

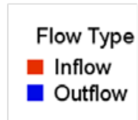


Figure 3. *E. coli* for All Studies

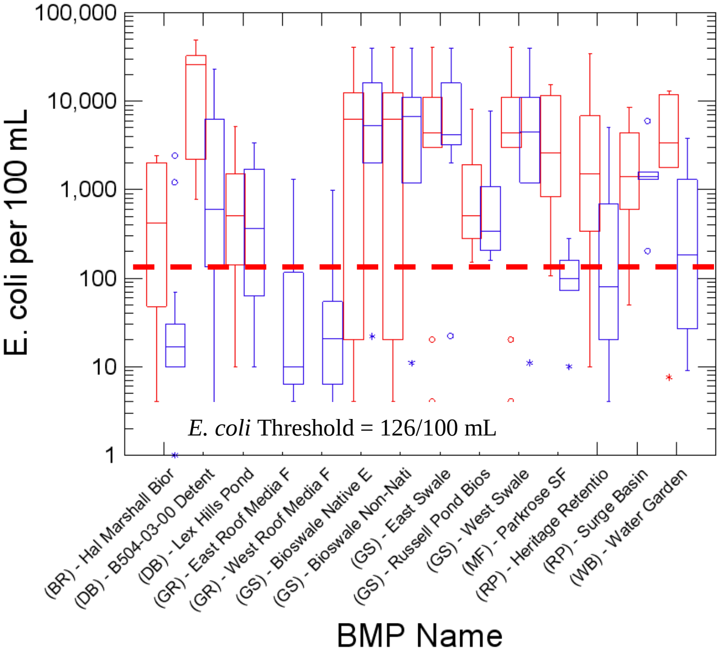


Figure 4. Enterococci for All Studies

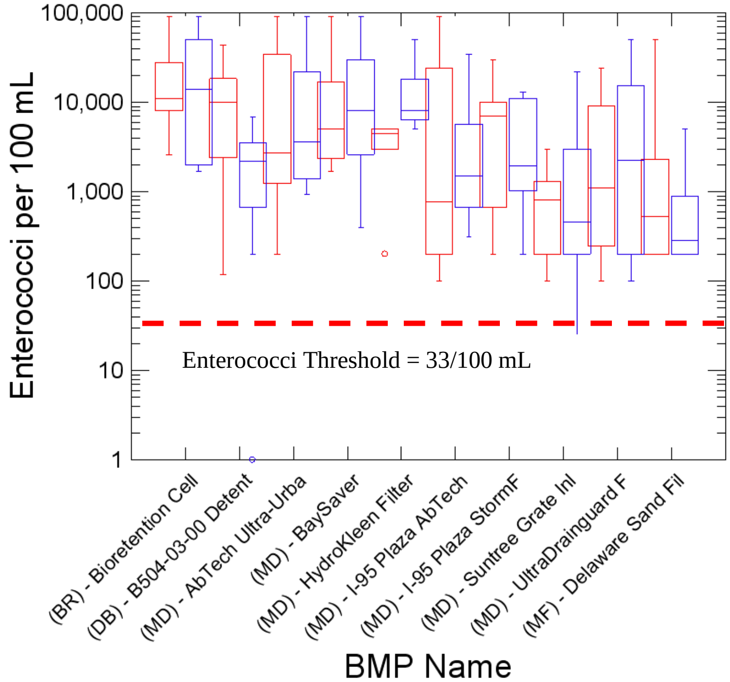


Figure 5. Fecal Coliform for Detention Basins

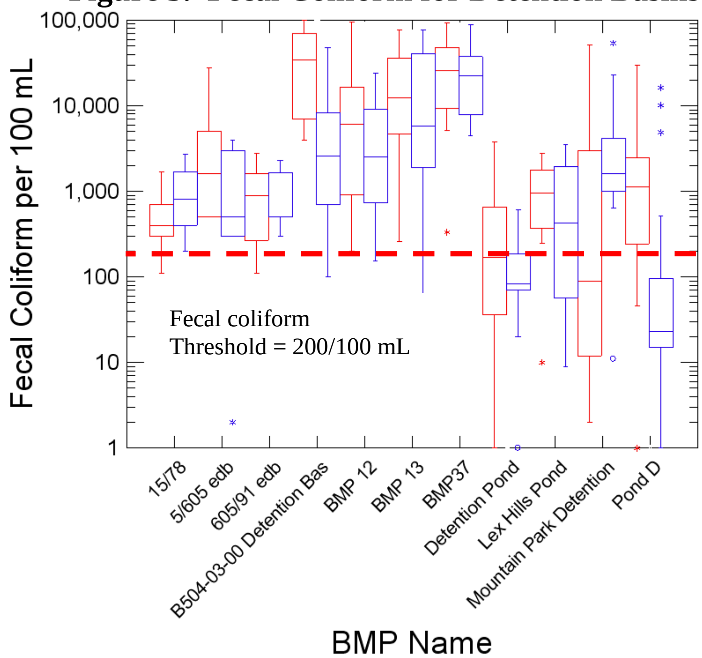
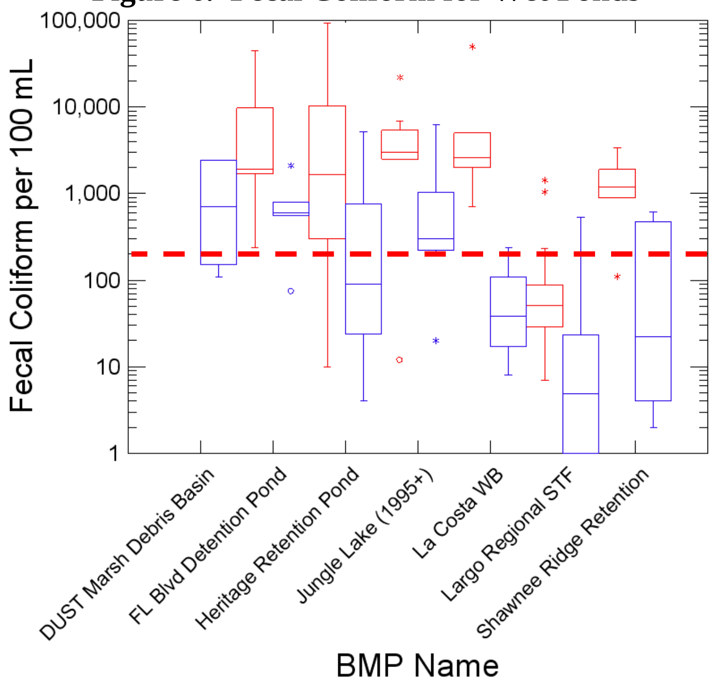


Figure 6. Fecal Coliform for Wet Ponds



Notes: Inflow and Outflow boxes "straddle" the X axis tick marks. X axis labels restricted to 24 characters; see Attachment 1 for full BMP Names. Red dashed line provides primary recreation stream standard as a benchmark for comparison. Note: for some BMPs, only outflow data are available (e.g,. DUST Marsh Debris Basin).
BR = Bioretention; DB = Detention Basin; GR = Green Roof, GS = Grass Swale; MF = Media Filter; RP = Retention Pond; WB = Wetland Basin.

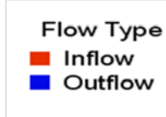


Figure 7. Fecal Coliform for Media Filters & Bioretention (***Bioretention Cell & Hal Marshall Bioretent.***)

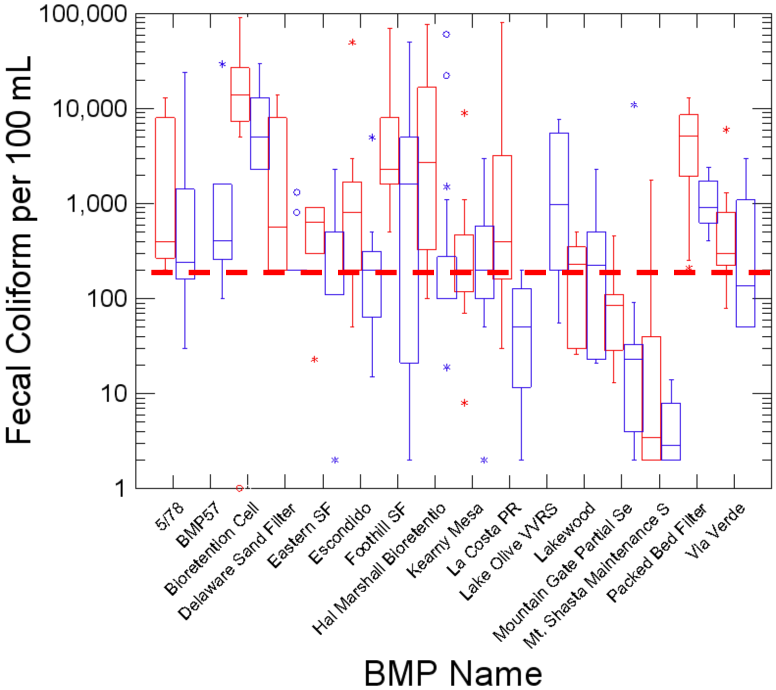


Figure 8. Fecal Coliform for Grass Swales & Strips

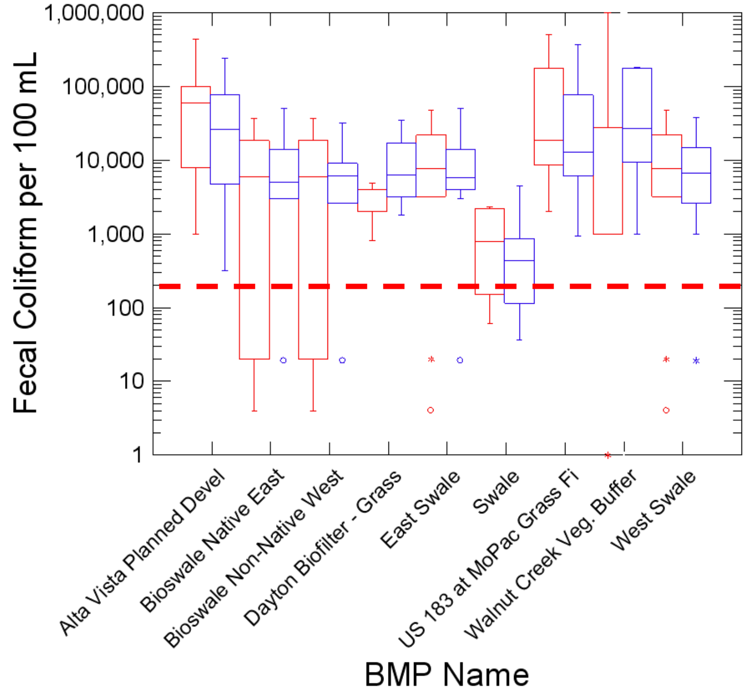


Figure 9. Fecal Coliform for Wetland Basins/Channels

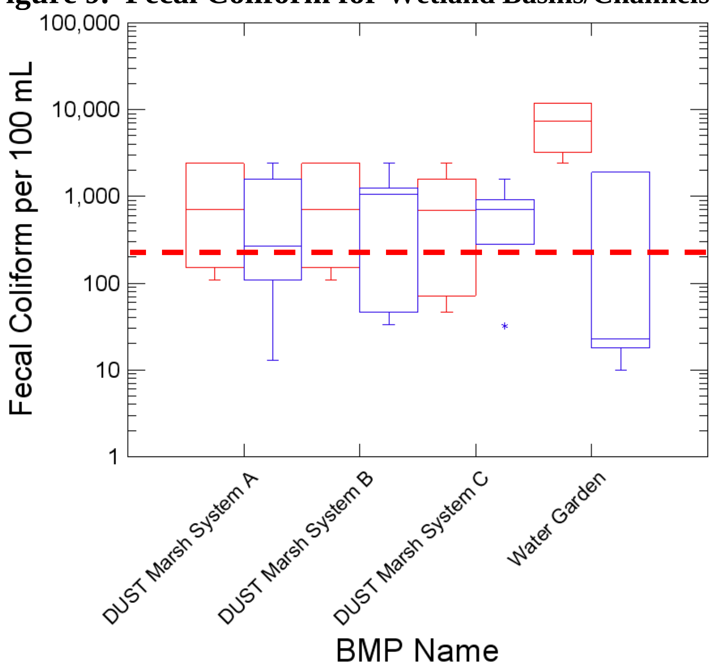
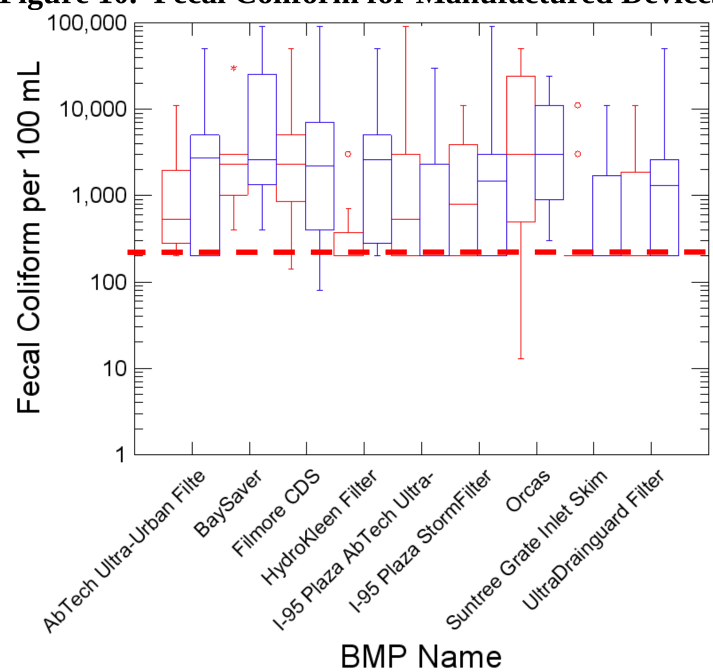


Figure 10. Fecal Coliform for Manufactured Devices



3.3 Category-level BMP Analysis for Fecal Coliform

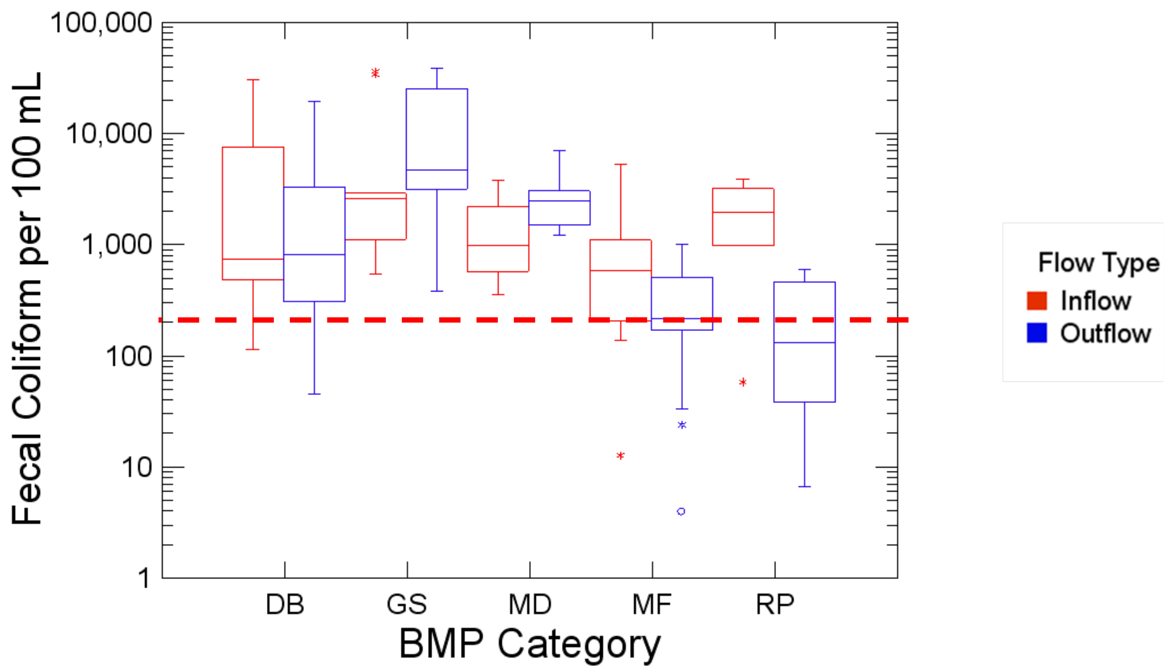
Additional statistical analysis was conducted for the fecal coliform data set for these BMP categories: detention basins, retention ponds, media filters and manufactured devices. Table 4 contains summary statistics based on the geometric mean of each study for these BMP categories ("BMP-weighted" statistics) and Figure 11 depicts these statistics graphically.

Table 4. BMP Category-level Summary Statistics for Selected BMP Categories (BMP-weighted) for Fecal Coliform

Type	Flow	# of Studies	Median	95% LCL[1] on Median	95% UCL[1] on Median	Lower 25th %	Upper 75th %
Detention Basin	Inflow	11	749	303	7563	460	10781
	Outflow	11	813	196	3647	298	3981
Grass Swale/Strip	Inflow	9	2628	1116	18620	1116	10772
	Outflow	9	4724	2852	18572	3095	26523
Manufactured Devices (various)	Inflow	9	993	499	2187	538	2310
	Outflow	9	2462	1438	3431	1476	3326
Media Filters (various)	Inflow	12	605	179	1112	209	1112
	Outflow	14	216	101	464	170	510
Retention Pond	Inflow	6	1971	521	2673	985	3212
	Outflow	7	133	35	411	37	500

[1]LCL = lower confidence limit and UCL = upper confidence limit

Figure 11. Box Plots of BMP Study Geometric Means for Fecal Coliform by Selected BMP Category



Notes: DB = Detention Basin; **GS** = Grass Strip/Swale; **MD** = Manufactured Device; **MF** = Media Filter; **RP** = Retention Pond

General observations from this analysis include:

- There is wide variation in the geometric mean inflow and outflow concentrations for most BMP categories, often spanning orders of magnitude.
- Although 95th percentile upper and lower confidence intervals are provided in Table 4, it may be appropriate to use alternative confidence limits such as the 80th or 90th percentiles, depending on the objectives of the researcher. Using 95% UCLs and LCLs, the only BMP category showing statistically significant reduction in bacteria is retention ponds; a different confidence interval may result in statistically significant differences for other BMP types such as media filters.
- Retention ponds and media filters have the lowest median geometric mean effluent concentrations and are the only BMP categories with median effluent concentrations lower than median influent concentrations.
- Detention basins, grass swales/strips and manufactured devices do not show clear reductions in bacteria at the category level and indicate export of fecal coliform frequently occurs in some cases, particularly for grass swales/strips.
- Retention ponds are the only BMP category with median effluent concentrations below the primary contact recreation standard; however, the confidence band for the retention pond effluent median is broad, spanning from 35/100 mL to 411/100 mL, which indicates this BMP type may not necessarily meet the standard on average.

3.4 Supplemental BMP Category-level Statistical Analysis

Due in part to the challenges associated with hypothesis testing for analytes exhibiting wide-ranging variability and disparities with upper and lower quantitation limits between studies, a supplemental statistical analysis approach was conducted for the fecal coliform BMP category-level analysis. Exceedance frequency distribution curves were developed for inflows and outflows for all storm events in each BMP category (i.e., individual storm events grouped by BMP type) to assess the percentage of inflow and outflow values exceeding a range of threshold values. Table 5 summarizes the percentage of inflow and outflow concentrations exceeding the primary contact threshold of 200/100 mL for fecal coliform. Figures 12 through 16 illustrate the results graphically for a broad range of threshold values.[6] For example, other threshold comparisons of interest could focus on secondary contact recreation standards, which are typically five times the primary contact standard (e.g., 2,000/100 mL for fecal coliform).

[6] For readability, the X axis in Figures 12-16 has been truncated at 20,000/100 mL, which is two orders of magnitude greater than the stream standard. Higher values have been observed in many studies, with about 15 percent of the overall data set exceeding 20,000/100mL, including several values over 1,000,000/100 mL in the data set .

Table 5. Percent of Inflow and Outflow Values Greater than Primary Contact Recreation Standard for Fecal Coliform

BMP Category	Threshold (Primary Contact Std.)	% Inflow Values Greater Than Threshold	% Outflow Values Greater Than Threshold
Detention Basin	200/100 mL	83% CI: 77% -90%	65% CI: 57% -73%
Grass Swale		85% CI: 77% -94%	93% CI: 87% -99%
Manufactured Device		98% CI: 94% -100%	99% CI: 97% -100%
Media Filter		74% CI: 65% -83%	59% CI: 49% -69%
Retention Pond		61% CI: 49% -74%	36% CI: 24% -48%

Key findings based on Figures 12-16 include:

- The results indicate that all of the BMP categories analyzed exceed the 200/100 mL threshold (*shown as a vertical red dashed line in the figures*) for the majority of stormwater inflows and outflows, with the exception of retention ponds. Retention ponds have the lowest overall effluent concentrations with approximately two-thirds of the effluent values meeting the threshold value. However, it should be noted that influent data for retention ponds tended to be lower than many BMP types.
- Detention basins show statistically significant reductions in the frequency of exceedances of the 200/100 mL threshold, but the median effluent frequency of exceedance is still relatively high (65%). At higher thresholds, the frequencies of exceedance do not significantly change between inflow and outflow (Figure 13). This suggests that detention basins may be effective at reducing fecal coliform exceedances when the thresholds are low (e.g., 200/100 mL), but may be unable to reduce exceedances when thresholds are high (e.g., 2000/100 mL). Additional analysis is needed to further evaluate the causes of the trends shown in Figure 13. For example, the flow conditions under which high bacteria concentrations are observed could be a confounding variable affecting the appropriateness of this type of conclusion. Additionally, as an overall BMP category, the detention basin data set is expected to include a wide range of BMP designs. For example, some of the detention basins may function primarily for flood control, with little control (detention) of smaller events. Better performing detention basins may be enhanced with design features that promote infiltration, as well as detention (e.g., Pond D, as shown in Figure 5). As the BMP database grows, researchers may choose to sub-categorize detention basins with similar designs and unit processes.
- Figure 13 shows little overlap in the 95% confidence limits for the inflows and outflows for media filters, indicating that reductions in fecal coliform outflow concentrations are

occurring relative to inflow concentrations. A different confidence limit (e.g., 90%) may have resulted in statistically significant differences.

- Grass swales and manufactured devices have significant overlap of confidence intervals, indicating that these overall categories of BMPs are not demonstrating significant bacteria removal. In fact they appear to frequently cause increases in exceedances indicating these BMP types may be exporting fecal coliform bacteria either from entrainment of previously deposited bacteria or from new sources (e.g., animal excrement). Also, even at higher thresholds (e.g., 2,000/100 mL), grass swales and manufactured devices typically have high exceedances of water quality standards at the outflow (i.e., ~85% for swales and ~55% for manufactured devices).

Figure 12. Exceedance Frequency Distribution for Detention Basins

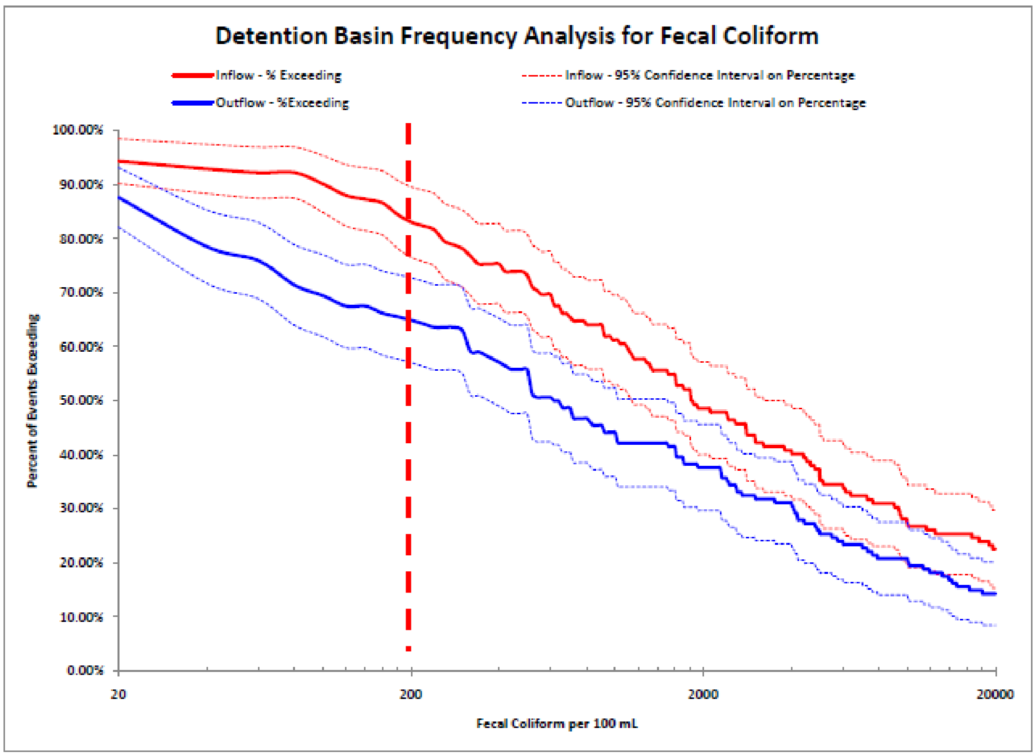


Figure 13. Exceedance Frequency Distribution for Media Filters

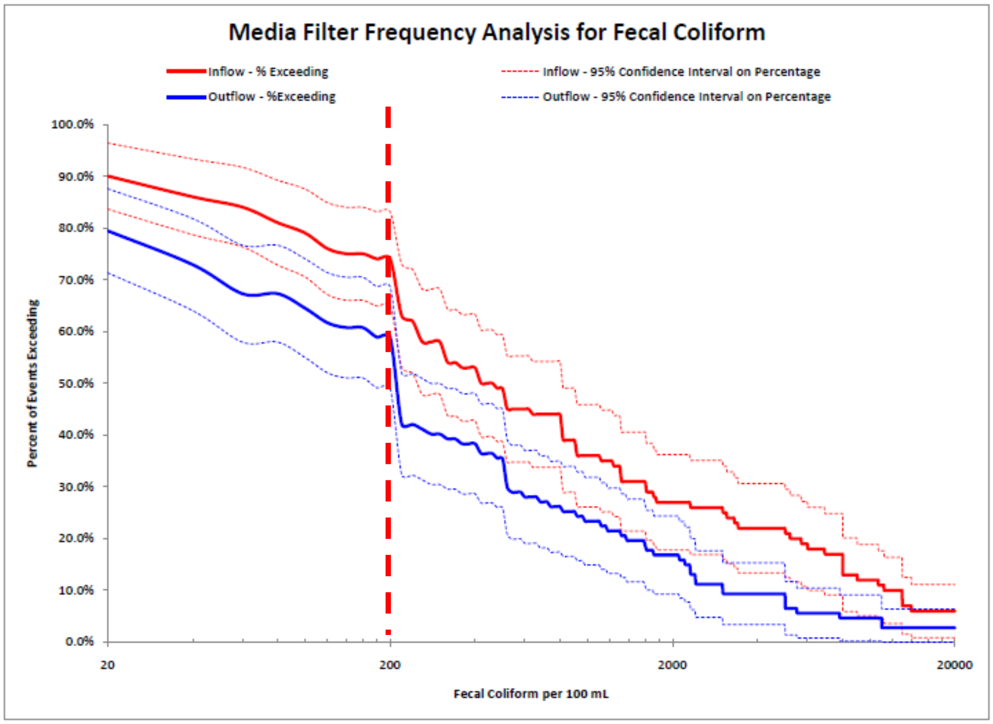


Figure 14. Exceedance Frequency Distribution for Manufactured Devices

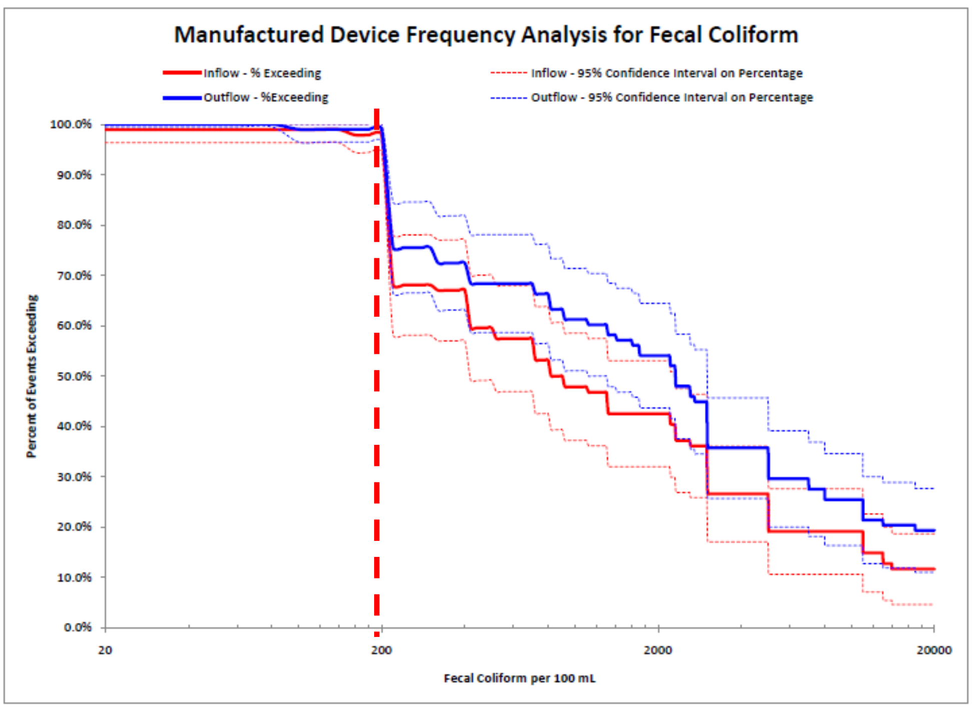


Figure 15. Exceedance Frequency Distribution for Grass Swales

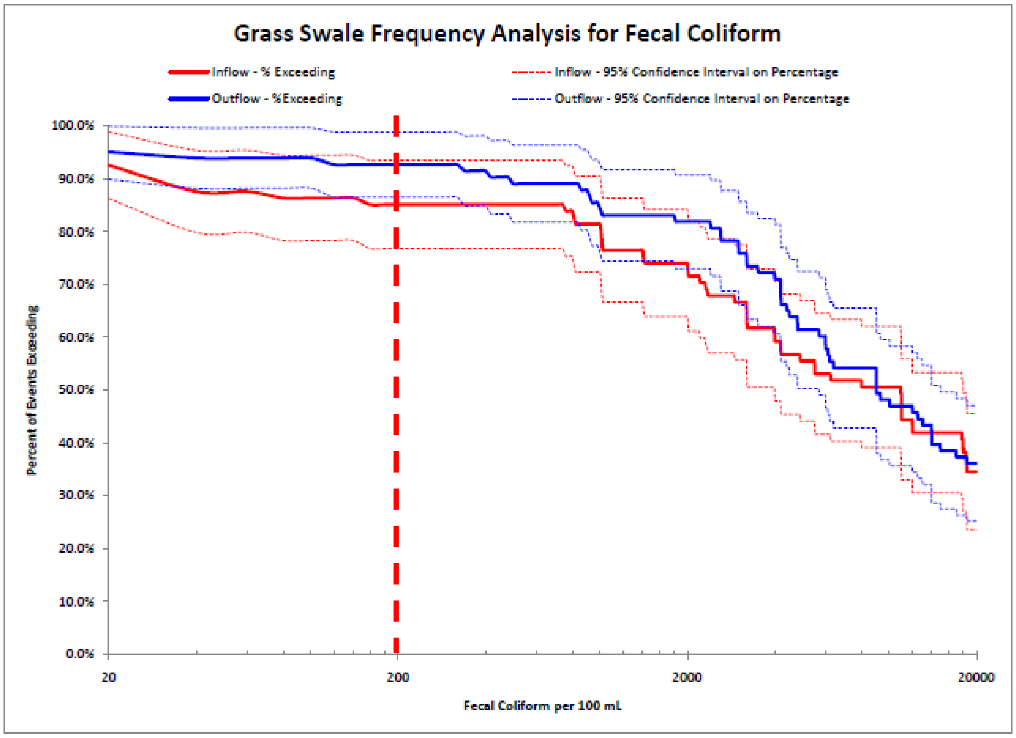
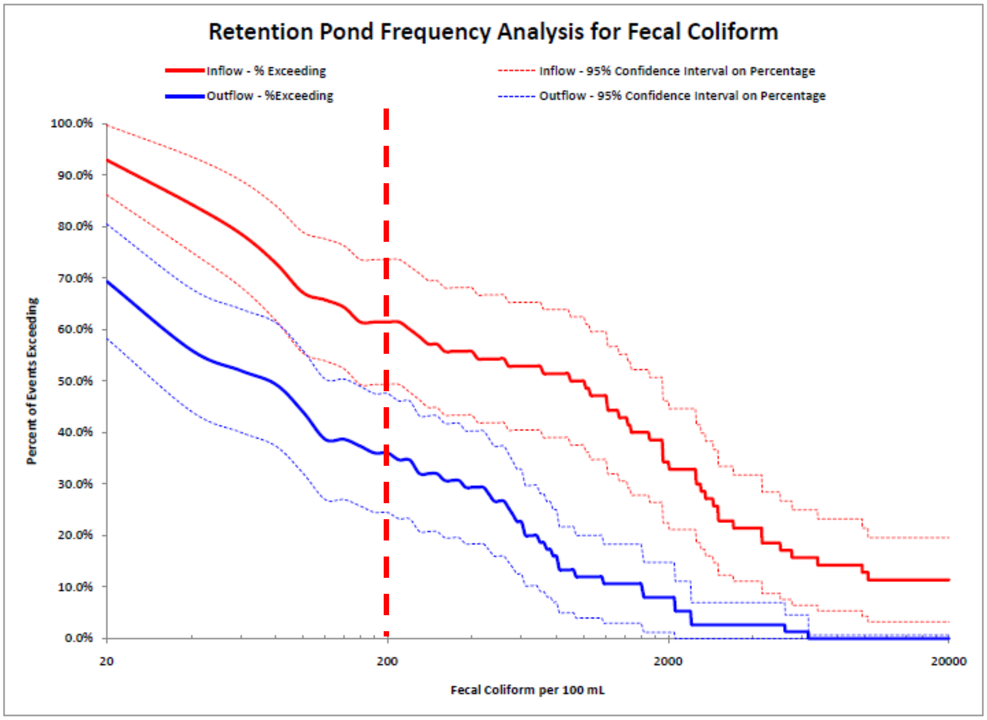


Figure 16. Exceedance Frequency Distribution for Retention Ponds



4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Recommendations for BMP Selection

Based on the performance data available to date in the BMP Database, only general inferences regarding BMP selection are appropriate at this time. General recommendations include:

- Those working to address pathogen impairments on streams should focus first and foremost on source controls. This requires clear identification of the primary sources of fecal indicator bacteria relative to site-specific conditions. Focusing on controllable sources of bacteria, particularly those of human origin, is believed to be the most important first step in protecting human health (Pitt 2004; Clary et al. 2009) although source control alone may not be sufficient to meet ambient water quality standards.

- The majority of conventional stormwater BMPs in the BMP Database do not appear to be effective at reducing fecal indicator bacteria concentrations to primary contact stream standards, which is the ultimate target of TMDLs. Because the data are limited, both in the number of data points and the representativeness of the data (i.e., grab samples, bias from quantitation limits, etc.), rigorous statistical conclusions cannot be drawn based on the available data. Significantly more studies and more representative data (i.e., flow-weighted composites and/or multiple grab samples during an event) are needed for all BMP types to increase the confidence of performance estimates with regard to bacteria.

- In terms of reducing overall bacteria *loads* to receiving waters, site designs and individual BMPs that reduce runoff volumes should reduce bacteria loading from urban runoff. (However, this does not necessarily mean that the receiving waters will attain stream standards if runoff is retained onsite.) BMP performance with regard to volume reduction is discussed separately in a companion technical summary.

- At the BMP category level, retention (wet) ponds, and various types of media filters may help to reduce bacteria concentrations, although not necessarily to instream standards. Individual bioretention studies also appear to reduce bacteria concentrations, but more studies are needed for this category of BMPs to draw category-level conclusions. Based on the unit treatment processes provided in retention ponds, media filters, and bioretention, bacteria reductions are expected, so the data, for the most part, support the theory.

- In general, grass swales/strips and detention basins do not appear to provide meaningful reduction in bacteria concentrations and often show net export of indicator bacteria. These BMP types may require enhancements to improve specific additional treatment processes such as filtration and sedimentation. However, it should be noted that volume reductions may be significant, so these BMPs may be effective at reducing bacteria loadings to receiving waters.

- The manufactured devices in the BMP Database include a range of unit treatment processes, requiring case-by-case evaluation of performance. As an overall category, the individual studies currently included in the Database do not demonstrate significant fecal indicator bacteria removal, regardless of the unit treatment process.

- Various individual BMPs may provide reductions in bacteria. Representative examples include individual bioretention studies, a wetland basin and a few detention basins. Care should be taken to understand both site-specific and BMP design characteristics in these studies before assuming that similar performance will occur at other locations.

4.2 Recommendations for Appropriate Uses of Data

- The BMP Database bacteria data set can be used for general characterization of BMP performance for selected BMP categories. Due to significant variability in the data sets, it is important that central tendency statistics (e.g., geometric mean, median) also include measures of variability such as the interquartile range or confidence limits associated with such estimates. Where possible, there may be a benefit to conducting further analyses on the data to select more locally appropriate data sets for evaluation. For example, it may be appropriate for investigate the design parameters for specific BMP types using a reduced set of data for the analyses based upon conformance to local design standards.

- Available data may be appropriate to support emphasis on TMDL strategies that first work to implement source controls, prior to relying on treatment from structural BMPs.

- For the purposes of bacteria modeling, the database team does not recommend relying solely on the empirical data summaries for estimating the effluent concentrations for BMPs for bacteria. Rather, this information may be used as a check on the reasonableness of results from more physically-based modeling approaches that consider bacterial decay and other unit treatment processes (e.g., sedimentation, filtration, etc.). When possible, regional or site-specific data should be used to calibrate and validate physically-based models.

4.3 Additional Research

- More studies with larger numbers of storm events and additional within-storm sample collection and analyses for EPA's currently recommended fecal indicator bacteria in a range of geographical locations would be helpful in drawing more statistically rigorous conclusions for all BMP types.

- Studies that document performance of BMPs under various hydraulic conditions to assess the effect of resuspension of sediment on bacteria concentrations in BMP effluent could be beneficial in BMP design enhancements. This could also include further exploration of the relationship between total suspended solids (TSS) and fecal indicator bacteria.

- Paired watershed studies of non-structural BMP practices such as pet waste controls, urban wildlife management programs, storm sewer cleaning, etc., could help to target source control BMPs that are most effective in urban watersheds.

- Continue to conduct studies that help to elucidate fate and transport related issues such as the relationship between fecal indicator bacteria and sediment sizes, various nutrients, presence of biofilms, and other factors.

- New research and sampling efforts should be sure to analyze samples for EPA's currently applicable Ambient Water Quality Criteria using the most current analysis methods. For example, researchers may want to consider using advanced microbial methods such as qPCR, as one example.

5 ATTACHMENTS

Attachment 1. Basic Statistical Summary and Analysis Data Set in Excel

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