Fecal Indicator Bacteria Management:

Reviewing the Latest Science on Bacteria Control for Watershed Managers

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Executive Summary:

A team convened by the Chesapeake Bay Program's Urban Stormwater Workgroup (USWG) reviewed recent research on fecal indicator bacteria (FIB) in urban watersheds, with an emphasis on how the new science can help craft better management strategies to restore bacteria-impaired waters. Some key messages based upon this review and past research include:

Current research continues to find most of the same urban water quality problems that were encountered in the past:

- Wet weather monitoring consistently shows that FIB levels are two to three orders of magnitude higher than the water quality standards established to protect human health.

- FIB levels sampled during dry weather tend to be lower and less variable in most urban watersheds, although standards are still exceeded in local hotspots that are influenced by human sewage.

- There is little hard evidence to show that FIB levels in urban watersheds have improved much in recent decades, except in situations where known sewage influences were successfully removed.

While recent research has improved our understanding of the dynamics of urban bacteria, it has not yet produced a solid consensus on which watershed strategies can best combat the urban bacteria problem.

- The presence of high bacteria concentrations is strongly associated with urban land use in a watershed, but it is very hard to isolate the specific sub-watershed factors that produce them.

- As a result, assigning a reliable "unit area" loading rate for FIB solely based on urban land use is not currently supported by available science. This is unfortunate, since managers rely heavily on urban land use to compute bacteria loads needed for local TMDLs.

- The nutrient and sediment accounting framework behind the Chesapeake Bay TMDL is not currently very helpful in crafting local bacteria TMDLs. Accurately simulating bacteria loads, delivery or treatment using the current generation of watershed simulation models is a challenge compared to other Bay pollutants.

Most bacteria problems are rooted in untreated wastewater discharges that are hidden in the urban landscape. A lot of detective work is needed to find (and fix) the spills, leaks, discharges, and overflows that are polluting urban waters. Most communities find that the best watershed strategy to manage bacteria relies more on "sleuthing" in the field than on desktop models in the office.

- New bacteria source tracking methods and synoptic stream/storm drain sampling can identify bacteria hotspots causing the greatest public health risk in urban watersheds.

- Managers need to supplement their tracking methods with detailed follow-up investigations to isolate the sewage leaks and other individual bacteria sources causing the bacteria hotspots.

Most urban best management practices (BMPs) show some ability to reduce bacteria, but not by enough to meet wet weather water quality standards. Much less is known about how they work during dry weather conditions.

- Urban BMPs must perform at an extremely high level (99+ % removal efficiency) to consistently reduce bacteria concentrations in incoming stormwater enough to meet water quality standards. Recent BMP performance data confirms that they cannot consistently meet such a high treatment standard.

- Some BMPs perform better than others, and recent research does show several design factors that could help improve bacteria removal.

This review suggests a few new directions for refining local bacteria management strategies in urban watersheds.

- Local stormwater and wastewater agencies should integrate their Illicit Discharge Detection and Elimination (IDDE), Infiltration/Inflow (I/I) and Sanitary Sewer Overflow (SSO) monitoring programs together to discover the worst bacteria sources in their community.

- Cooperative initiatives are recommended within the Chesapeake Bay region to help local managers to reduce bacteria to meet their local TMDLs.

Introduction:

Driven largely by the Chesapeake Bay Total Maximum Daily Load (TMDL), stormwater management in the Chesapeake Bay watershed has been very nutrient-centric over the past 10 years. However, elevated fecal indicator bacteria (FIB) levels remain the most frequent cause of water quality impairment in streams, rivers, lakes, estuaries, beaches and drinking water supplies across the U.S. Controlling bacteria represents a major challenge for state and local governments that seek to protect public health at the lowest cost for their citizens.

To date, there are few resources that quickly summarize data on bacteria source tracking and removal techniques in a way that can be easily applied by watershed planners and managers. The Chesapeake Bay Program's Urban Stormwater Workgroup (USWG) identified bacteria management as a priority and convened a small team to review and summarize the recent science and existing data for the workgroup (Table 1).

Table 1. List of Ad-Hoc Team Members and Their Affiliations

Team Member	*Affiliation*
Ted Brown	Biohabitats
Carrie Colbert	CSN
Luke Cole	D.C. Dept of Energy and Environment
Manasa Damera	AECOM
Dillon Goodell	D.C. Dept of Energy and Environment
Doug Griffith	Anne Arundel County
Tom Schueler	CSN
David Wood	CSN
*Ad hoc team members participated in the research review and provided guidance for summarizing the data. Final recommendations presented in the report are those of the Chesapeake Stormwater Network (CSN).	

Much of what we know about how to manage bacteria in urban watersheds was published over a decade ago (CWP 2007, Maestre and Pitt 2005, Schueler 1999). Reliable monitoring data for the presence of FIB in urban stormwater are scarce in comparison to other water quality parameters. As living organisms, microbes can grow and multiply over time, making sampling difficult. To get precise bacteria counts requires special sampling procedures and holding times, which are not easy to do with automated stormwater sampling devices[1].

The purpose of this review is to summarize what has been learned in the last 10-15 years and present the latest science in a way that is both accessible and actionable. The focus is on studies published post-2000, with additional emphasis on the most recent research. While some recommendations are provided, they do not represent the official position of the Urban Stormwater Workgroup.

This review summarizes the latest available information in three key areas:

- **Bacteria land use loading rates** – improve understanding of bacteria “hot spots” for source targeting efforts and determine if research exists to support land use loading rates that could serve as a potential baseline for well-defined BMP removal efficiencies.
- **Bacteria source analysis techniques** -- provide guidance on track-back efforts, monitoring techniques and other source identification and control strategies to more effectively target controllable bacteria sources that pose the greatest risk to the community.

[1] A wide variety of indicators have been used to characterize the risk of microbial contamination in surface waters (Schueler 1999). The two most commonly measured indicators are fecal coliform and *Escherichia coli*. While most researchers consider *E. coli* to be superior to fecal coliform as a risk indicator, most historic monitoring data utilizes fecal coliform, and some states continue to reference fecal coliform in their water quality standards.

- **Stormwater BMP performance** -- summarize data on bacteria removal performance of Chesapeake Bay Program-approved stormwater BMPs and source control techniques.

Bacteria Land Use Loading Rates

Literature Review

Public health authorities have tracked bacteria levels in urban waters for more than five decades. They continue to find it extremely difficult to interpret this imperfect, variable and idiosyncratic water quality indicator.

Tying land uses to bacteria loading rates has been a goal of stormwater managers for many years. The most comprehensive dataset available on bacteria loads and land uses comes from the National Stormwater Quality Database (NSQD). Originally released in 2001 and summarized in 2005 (Maestre and Pitt 2005), the data show high variability as well as concentrations consistently above EPA's primary contact recreation standard[2]. Residential land uses were generally found to be the highest loading, but there are large data overlaps (Table 2). While Table 2 was pulled from the 2005 NSQD, the more recent data continue to support similar trends. The full 2015 dataset can be downloaded here.

Table 2. Summary of Available Bacteria Concentrations in Stormwater Runoff Included in NSQD, version 1.1 (Pitt and Maestre, 2005)

	Fecal Coliform (mpn/100mL)		Fecal Streptococcus (mpn/100mL)		Total *E. Coli* (mpn/100mL)	
	median	# of observations	median	# of observations	median	# of observations
Mixed Industrial	3,033	79	11,000	59	2,467	14
Freeways	1,700	49	17,000	25	50,000	16
Mixed Freeways	2,600	20	19,000	16		
Open Space	7,200	23	24,900	22		
Mixed Open Space	3,000	86	21,000	75		
Residential	7,000	402	24,300	257	1,750	67
Mixed Residential	11,210	336	27,500	178	700	14
Commercial	4,600	253	12,000	201		
Mixed Commercial	5,400	116	11,900	95		
Industrial	2,400	315	12,000	189		

[2] EPA's recommended recreational water quality criteria standard is 126 cfu/100mL for *E.Coli*. While no longer recommended as an indicator, previous guidance for a fecal coliform standard was 200 MPN/100 ml.

Recent efforts to characterize land use loading rates for FIB have shown similar variability. A study in New Jersey collected runoff samples from three land use classes with varying impervious cover (IC): high-density residential (65% IC), low-density residential (17% IC), and landscaped commercial (15% IC) (Selvakumar and Borst 2006). High-density residential runoff had the highest concentration of bacteria, with numbers that, while variable within and between land uses, supported the findings in the NSQD.

Furthermore, there are concerns that studies linking bacteria loading rates to land uses risk oversimplifying the sources. A regression model created using variables obtained from GIS analysis, indicated that proximity to septic tanks and rainfall runoff from urbanized areas were important predictors of fecal coliform densities in a South Carolina estuary (Kelsey et al., 2004). However, the authors were clear that the findings may be a coincidental result of those same areas also being associated with higher density residential units and closer proximity to surface water.

When specifically targeting human sources of bacteria[3], Cao et al. (2017) found no discernable relationship between watershed land use and extent of human fecal contamination in the drainage network. This further suggests a complexity of human fecal pollution in urban environments that relates to specific site characteristics and management practices.

Research shows that factors like the percent impervious cover in the sub-watershed, percent of the population on sewer vs. septic, and physiographic region are helpful, but not definitive, indicators of subwatershed bacteria contamination. At this point, available literature still supports more site-specificity when quantifying baseline bacteria loads, but understanding which land uses contain potential "hot spots" can still be a useful exercise. For example, high impervious cover has been shown in multiple instances to be correlated with higher FIB concentrations (Paule et al., 2016; Sevakumar and Borst, 2006; Luckenbach et al, 2008; Mallin et al., 2001). Other studies have noted a correlation between high sediment yielding land uses and high FIB concentrations (Soupir et al. 2010, Tiefenthaler et al., 2011). These findings are likely related to the wash-off mechanisms for the different land surfaces.

Bacteria concentrations in wet weather runoff from impervious surfaces have been shown to spike later in a storm event than from pervious surfaces, possibly as animal fecal matter washes onto the pavement from adjacent turf grass and open space (Clary et al. 2014). In dry weather conditions, leaky septic systems can be the source of high bacteria concentrations in low density residential areas that are generally characterized by greater turf coverage. Sanitary sewer cross connections or leaks could be causing high concentrations in areas classified as an impervious cover. A more complete list of potential FIB sources in urban watersheds, is available in Appendix A.

[3] Human sources of FIB have been shown to pose a greater health risk and can be a more controllable load compared to more diffuse sources like wildlife (Nobel et al. 2005).

Management Implications

The lack of studies able to tie bacteria loads to specific urban land uses means that current approaches to defining baseline loads for implementation planning are likely to remain the norm for the foreseeable future. One common approach, used in Virginia, relies on source input data on human population, pet ownership, and wildlife population density to estimate a total watershed load. That load is then distributed to each land use to estimate a land use loading rate. Other states, like Maryland, currently encourage watershed managers to focus on source reduction programs, specifically prioritizing potential human sources.

The variability in land use loading data will also make it difficult to track progress using a comprehensive watershed modeling approach that is used to manage other Bay pollutants, such as nitrogen and phosphorus. Efficiency BMPs are dependent upon a good baseline land use loading rate in order to effectively demonstrate changes in loads over time. One of the biggest challenges with defining baseline loading rates for bacteria is simulating the growth, die-off and transport dynamics of FIB across a subwatershed. Persistence of FIB in storm drains, sediments and biofilms may obscure the progress, or lack there-of, achieved by source elimination and BMP implementation efforts. Implementation of stormwater BMPs for bacteria management or other water quality objectives should not be discouraged, but BMP performance will still likely require a bacteria-monitoring program to demonstrate reductions until enough data has been collected to better support average land use loading rates.

Managers can also use the information available to hone in on potential sources and hot spots (e.g., sewer leaks, manhole overflows, sewage exfiltration, untreated wastes, boat discharges, etc.). Residential land uses appear to be one of the highest loading land uses, whether because of leaking septic tanks, pet waste pick-up behavior, mulching habits or other contributing factors. It is also important to maintain consistent erosion control and turf management practices to reduce export of exposed sediments, which may carry bacteria. Additional resources on turf management, erosion and sediment control, and pet waste education and outreach programs can be found in Appendix B.

Bacteria Source Tracking

Literature Review

A lot of great work has already been done to support improved pollutant source tracking and analysis, often under the umbrella of illicit discharge detection and elimination (IDDE) programs. Multiple guides are available to assist local governments and citizen groups in developing monitoring and track-back methods (available in Appendix B). These guides tend to focus on how to collect samples and use co-indicators that can be used to pinpoint potential sources of the contamination. For example, optical brighteners -- often used in laundry detergents – can be used as an indicator of wash-water.

Meanwhile, much of the recent science on bacteria source tracking studies the effectiveness of various markers for determining the bacteria source. Using FIB, such as fecal coliform or *E. Coli*, is an imperfect system if the goal is to find and eliminate pathogens that pose the greatest human health risks. Multiple studies have shown that traditional FIB do not correlate well with the occurrence of pathogens, and they do not provide any indication of the contamination's source (Sauer et al. 2011, Sercu et al. 2009, McClellan and Eran 2015). FIB can colonize and regrow in the biofilms and fine sediments contained within the storm drain system, so the ability to track the original source of contamination is limited (Burkhart 2012).

Microbial source tracking (MST) methods help watershed managers hone in on the specific sources of bacteria. Techniques like Polymerase Chain Reactions (PCR) and Quantitative Polymerase Chain Reactions (qPCR) are used as part of an MST approach and are quick, cost-effective lab tests that generate significant information on the presence, quantity and source distribution of pathogens in a water sample. Human sewage contamination presents the greatest health risk, and is a controllable source, so it should generally be the first target of remediation efforts (Nobel et al. 2005).

New markers are being tested that are dependent upon the human biome and can't survive long when removed, making them better indicators of human sewage. For example, *Bacteroides sp*., specifically HF183, can identify human sources with high degrees of sensitivity and specificity (Boehm et al. 2013). That means they are reliably detected if they are present in the sample and have minimal cross-reactivity with animals, so managers can be more confident of the human source. When there is cross-reactivity, it is most often with dogs, which is another treatable source (Sauer et al. 2011).

Viruses and chemical tracers have also been used as human fecal indicators but should be used with caution as their use is still limited and their utility may be site-specific. Higher concentrations of caffeine and acetaminophen were indicative of human sewage contamination, but these chemical markers are more likely to degrade quickly and may only be useful for recent or ongoing raw sewage contamination (Staley et al. 2016). Quantification by PCR of DNA and RNA viruses has potential, but further study is needed to evaluate the correlation between viral indicators and specific pathogens (Gionnes et al. 2010).

Management Implications

The bottom line for urban watershed managers is that bacteria problems are best solved by field monitoring rather than desktop modeling. Many urban bacteria sources are hidden in existing infrastructure and a degree of track-back work will be required to find and eliminate them. PCR and qPCR methods are more accessible and inexpensive than ever before, and a number of the studies referenced above have shown that several markers can be reliably used to identify human fecal bacteria. That said, water body impairments are listed based upon FIB concentrations, and resources to develop and implement monitoring and source tracking programs are still limited.

Existing municipal programs, like IDDE, Infiltration/Inflow (I/I) and Sanitary Sewer Overflow (SSO) monitoring programs can be leveraged to improve bacteria management. Managers can identify priority catchments based on past bacteria monitoring efforts, age of existing development, or sewer maps. Outfall sampling can be conducted within the priority catchment, by either directly monitoring for FIB, or for other indicators that may point towards a human sewage source, such as ammonia or optical brighteners (CWP 2016).

Programs with sufficient resources have the option to target human sewage sources with a two-step approach. First, establish where FIB concentrations appear to be high based upon stream monitoring, then re-sample in those areas for PCR analysis to determine the presence and possible origins of human fecal pollution. This watershed/outfall prioritization approach can help effectively target pathogens that are both treatable and pose the greatest human health risk.

Priority watersheds and outfalls can then be the locations for track-back efforts, such as visual inspections of manholes, dye testing or thermal imaging.

BMP Bacteria Removal Performance

Literature Review

Communities have traditionally employed BMPs to remove stormwater pollutants that wash off from urban surfaces. They are the primary tool used to address other pollutants of concern, including nitrogen, phosphorus and sediment, which drive the Chesapeake Bay TMDL. While bacteria behave like a sediment particle in some ways, they are not inert and can persist and even grow in the sediments and vegetation of the urban storm drain network.

Previous efforts to summarize bacteria removal performance of BMPs have shown highly variable removal rates based upon fairly limited data (Table 3). Pollutant removal efficiency, usually represented by a percentage, specifically refers to the pollutant reduction from the inflow to the outflow of a system. A decade ago, we understood some of the mechanisms influencing bacteria removal performance, but not how they translated to field-scale applications. Variable soil types, storm intensities and influent concentrations were known to influence bacteria removal rates, but not enough field-studies had been conducted to begin to explain the effect of those factors on performance variability (CWP 2007).

Table 3. Percent removal of fecal indicator bacteria by stormwater BMPs, summarized from the National Pollutant Removal Database, v. 3 (CWP 2007)

	Wet Pond	Wetland	Filtration Practices	Bioretention	Infiltration Practices	Open Channel
Median	70	78	37	N/A	N/A	-25
Min	-6	55	-85	N/A	N/A	-100
Max	99	97	83	N/A	N/A	-25
Q1	52	67	36	N/A	N/A	-63
Q3	94	88	70	N/A	N/A	-25
Number of studies	11	3	6	0	0	3

Understanding the ability of stormwater BMPs to effectively remove bacteria and pathogens from surface runoff is key to a watershed manager developing an effective implementation plan. Recent reviews of BMP removal studies and international databases confirm that most BMPs successfully remove bacteria on average, but their performance varies from storm to storm. During individual storm events, many BMPs occasionally have higher effluent concentrations than influent concentrations. Dry weather bacteria discharges from BMPs are poorly studied but may be also be a cause for concern in some situations (e.g., waterfowl and ponds).

Research on bacteria removal performance shows results that are often site-specific, and difficult to compare with other studies because of methodological differences. The original intent of this review was to provide removal efficiencies for each Chesapeake Bay Program approved BMP for the purposes of co-benefit analysis. Many BMPs still lack sufficient monitoring data, however, to determine their definitive bacteria removal performance.

In addition, there are different questions that watershed managers may seek to answer when looking into BMP performance data. Besides pollutant removal efficiency, there is the question of whether stormwater BMPs are capable of reducing effluent concentrations below water contact recreation standards.

In this summary, available data will be presented so that watershed managers can sort through it and apply those that are useful and relevant for their needs.

<u>Bioretention</u>

Bioretention is the BMP with the most available research on its bacteria removal performance in recent years. Summary statistics from the International BMP Database (Clary et al. 2017) included seven bioretention areas monitored for *E. Coli*. The median influent *E. coli* concentration was reduced by 80% to a median effluent concentration of

240 MPN/100mL, just above the EPA recommended recreational water quality criteria standard (RWQC) of 126 cfu/100mL[4].

Nine additional studies were reviewed that evaluated bacteria removal performance of bioretention areas, though only four were field-studies, with the remaining involved test columns in a lab setting (Table 4).

There is some evidence that bioretention can reduce bacteria levels below water contact recreation standards (Hunt et al. 2008, Hathaway et al. 2009), but this depends on the influent concentrations to the practice. High BMP removal efficiency does not always guarantee attainment of bacteria standards when inflow concentration are high, even though bioretention does generally perform well at most inflow concentrations.

Table 4. Summary of Bioretention Bacteria Removal Performance**

Study	Fecal Coliform		*E. coli*			
	% concentration removal	effluent concentration*	% concentration removal	effluent concentration*	Lab Study?	Design Notes
Bratieres et al. 2008			98%		Yes	wet antecedent soil condition
			69%		Yes	dry antecedent soil condition
Hathaway et al. 2009	89%	258 col/100ml	92%	20 col/100ml	No	
Hunt et al. 2008	69%	4500 CFU/100ml	71%	273 MPN/100ml	No	
Kim et al. 2012			88%		Yes	shrub vegetation
			57%		Yes	highway grass seed mix vegetation
			48%		Yes	native grass seed mix vegetation
			76%		Yes	bermuda grass vegetation
			97%		Yes	no vegetation
Rusciano and Obropta 2007	96%				Yes	
Youngblood et al. 2017			87%	810 MPN/100mL	No	5% fly ash amended media
			35%	310 MPN/100mL	No	5% fly ash amended media
			43%	2000 MPN/100mL	No	5% fly ash amended media
Zhang et al. 2010			84%		Yes	traditional soil media
			99%		Yes	iron oxide-coated fine grain sand
			87%		Yes	iron oxide-coated coarse grain sand
			56%		Yes	traditional soil media fine grain sand
			69%		Yes	traditional soil media coarse grain sand
Zhang et al 2011			81%		Yes	2-month old bioretention
			96%		Yes	5-month old bioretention
			99%		Yes	9-month old bioretention
			100%		Yes	13-month old bioretention
			100%		Yes	18-month old bioretention
Zhang et al. 2012	-83%	36% did not meet RWQC standard	-197%	32% did not meet RWQC standard	No	
	69%	20% did not meet RWQC standard	34%	22% did not meet RWQC standard	No	
* EPA recommended RWQC standard is 126 cfu/100mL for *E. coli* and 200 cfu/100mL for fecal coliform						
** Full dataset can be downloaded from Appendix C						

[4] Most Probably Number (MPN) analyses estimates the number of organisms in a sample using statistical probability tables. While not a direct representation of colony forming units (cfu), it is considered an appropriate enumeration method for roughly 1:1 comparison.

The literature also presents several potentially significant factors that impact the bacteria removal performance of bioretention. Hydraulic retention time (HRT) seems to be positively correlated with *E. coli* removal (Kim et al. 2012). Two major removal mechanisms of bacteria from bioretention facilities include straining and sorption, and as a result, the length of HRT achieved in bioretention may be a useful and practical parameter to predict bacteria removal (Zhang et al. 2010, Kim et al. 2012).

While it has been documented that sunlight exposure can increase bacteria removal (Hathaway et al. 2009, Clary et al. 2014), temperature does not seem to impact initial bioretention removal. Lower temperatures do appear to favor long term survival of *E. coli* (Zhang et al. 2012), as it may influence the growth and survival of bacteria predator populations within the soil media.

Bacteria removal performance of bioretention appears to improve over time as the soil media settles (Zhang et al. 2011, Rusciano and Obropta 2007). In multiple studies, the first storm would show a removal efficiency as low as 50% but before increasing to over 95% after 6 months of sampling. Decreased porosity and increased hydrodynamic dispersion observed in mature bioretention areas appear to promote better physical straining and adhesion of bacteria cells, and allow for more time to establish larger protozoan colonies that prey on bacteria.

Efforts have been made to improve bioretention removal performance using soil amendments. Iron-coated sand amendments show promise to improve removal rates due to their greater surface roughness and positive charge that improves sorption. However, bacteria die off rates within the column were lower due to reduced predatory protozoan activity (Zhang et al. 2010). Fly-ash amendment has also been tested and performed favorably compared to traditional bioretention media, though more study is still required (Youngblood et al. 2017).

<u>Constructed Wetlands</u>

Constructed wetlands also have a substantial amount of literature on their bacteria removal performance. Summary statistics from the International BMP Database (Clary et al. 2017) included six constructed wetland basins monitored for *E. Coli*. The median influent *E. coli* concentration was reduced by 64% to a median effluent concentration of 1,000 MPN/100mL. The same database shows a reduction of 93% in median fecal coliform concentration across five studies. The 900 MPN/100mL effluent concentration is above the recommended RWQC for fecal coliform (200 cfu/100mL).

Four additional studies were reviewed that evaluated bacteria removal performance for constructed wetlands, as well as two literature reviews. The comparative results for these studies are summarized in Table 5.

Table 5. Summary of Constructed Wetland Bacteria Removal Performance**

Study	Fecal Coliform		E. Coli			
	% concentration removal	effluent concentration*	% concentration removal	effluent concentration*	Lab Study?	Design Notes
Davies and Bavor, 2000	79%	3600 cfu/100mL			No	
					No	
Hathaway et al. 2009	98%	184 col/100mL	96%	106 col/100mL	No	shallow wetland with little vegetation
	56%	3874 col/100mL	33%	864 col/100mL	No	
					No	
					No	
Tilman et al. 2011***	71%				No	
Birch et al. 2004	76%	41369 cfu/100mL (weighted avg concentration)			No	
Vymazal 2005****	92%	929000 cfu/100mL			No	free water surface
	86%	42900 cfu/100mL			No	horizontal subsurface flow
	99%	45800 cfu/100mL			No	vertical subsurface
Humphrey et al. 2014			59%	367 MPN/100mL	No	

* EPA recommended RWQC standard is 126 cfu/100mL for E. coli and 200 cfu/100mL for fecal coliform

** Full datased can be downloaded from Appendix C

*** Literature review study. Values presented are from Bavor et al. 2001.

**** Literature review study. Values presented are mean reductions for 60 constructed wetlands.

The wetland design components that seem to have the biggest impact on bacteria removal are closely tied to known bacteria treatment mechanisms. For example, shallow wetlands with greater light exposure seemed to perform the best in the field (Hathaway et al. 2009). Wetland vegetation itself may also play a significant role in bacteria removal in constructed wetlands. There is growing evidence that wetland plants are part of the explanation for why constructed wetlands are more effective at removing bacteria than unplanted ponds (Vymazal 2005).

This phenomenon may be caused by two factors: (1) presence of additional oxygen in the water column of free water surface wetlands or in the rhizospere of subsurface flow wetlands and (2) the presence of compounds released by the plant with antimicrobial properties (Vymazal 2005). In addition, sediment-bound bacteria can be resuspended back into the water column by high velocities during storms. Macrophytes in wetlands can stabilize bottom sediments, thereby reducing resuspension and increasing bacteria die-off rates (Davies and Bavor 2000).

Despite the effect of the macrophytes, the literature suggests that bacteria removal efficiency in constructed wetlands is still influenced by the intensity of the storm event. While high removal efficiencies are seen during moderately intense high-flow events (~1.0 mm of rain per hour), performance was substantially reduced during periods of intense rainfall (>4.0 mm of rain per hour) (Birch et al. 2004). This is likely tied to the resuspension of sediment-bound microbes at the bottom of a shallow constructed wetland.

There is also evidence that hydraulic loading rate and resultant hydraulic residence time (HRT) play a primary role in bacteria removal performance. The longer HRT allows more time for bacteria to be exposed to unfavorable conditions that cause mortality (Vymazal 2005). A study in New Zealand increased HRT from 2 days to 7 days and found a corresponding increase in removal rate from 76.2% to 95.3% (Tanner et al. 1995).

Despite these findings, there is still a high amount of monitoring variability caused in part by different wetland designs and experimental methods. More research is still needed to confirm which constructed wetland design features have the greatest impact on bacteria removal performance.

Stormwater Ponds

Retention ponds (wet ponds) and detention basins (dry ponds) are the only other BMP that have a substantial amount of new literature to characterize their bacteria removal performance. Summary statistics from the International BMP Database included 12 retention ponds and 15 detention basins. The retention ponds reduced the median fecal coliform concentration by 59% to 1,400 MPN/100mL, while the detention basins reduced the median fecal coliform concentration by 64% to 640 MPN/100mL.

Four additional studies on stormwater pond performance were reviewed which included several retention ponds and one detention basin, and results are summarized in Table 6.

Table 6. Summary of Stormwater Pond Bacteria Removal Performance**

Study	Fecal Coliform		E. Coli			
	% concentration removal	effluent concentration*	% concentration removal	effluent concentration*	Lab Study?	Design Notes
Retention Pond (Wet Pond)						
Rushton 2006	53%	145 cfu/100mL			No	Pond was shallower than typical design standards. Influent was pretreated by MTD
Hathaway et al. 2009	70%	2703 col/100mL	46%	1153 col/100mL	No	
					No	
Krometis et al. 2010	-34%	57677 MPN/100mL	0%	5904 MPN/100mL	No	
	29%	51519 MPN/100mL	41%	4193 MPN/100mL	No	
					No	
					No	
					No	
					No	
Mallin et al. 2002	59%	43 col/100mL			No	
	86%	70 col/100mL			No	
Davies and Bavor 2000	-2%	8100 cfu/100ml			No	
Detention Basin (Dry Pond)						
Hathaway et al. 2009	-45%	2873 col/100mL	-22%	1121 col/100mL	No	
	-20%	1590 col/100mL	0%	658 col/100mL	No	
* EPA recommended RWQC standard is 126 cfu/100mL for E. coli and 200 cfu/100mL for fecal coliform						
** Full datased can be downloaded from Appendix C						

The biggest takeaway from the pond literature review is the amount of variability in the performance data. The factors contributing to this variability are not yet well understood, though land use in the contributing drainage area, pond depth and weather conditions are all likely to play a role. For example, FIB concentrations both entering and exiting stormwater ponds were highly correlated to whether or not rainfall occurred on the day of sampling (Mallin et al. 2002). As discussed earlier, high flow events are likely to cause resuspension of microbes bound to fine sediments at the bottom of ponds.

Since ponds lack macrophytes, they are prone to bacterial resuspension during storms. Further support for this finding was provided by Krometis et al. (2010) who found that settleable microorganisms were removed at higher rates relative to the total bacteria concentration. This suggests that sedimentation is an important removal mechanism, but one that is dependent upon design and weather. In many cases, the benefit of bacteria treatment due to sunlight in shallower ponds may be offset by the potential for disturbance of bottom sediments during high flow events.

It is also important to note that even well-performing ponds are unable to meet water contact recreation standards after some storm events (Hathaway et al. 2009, Krometis et al. 2010). While retention ponds could perform well when receiving low influent *E. Coli* concentrations, they were not as effective at higher inflow concentrations.

<u>Performance of other Stormwater BMPs</u>

Limited data is available to draw broad conclusions about bacteria reduction rates for other common stormwater BMPs. Based on our current understanding of bacteria removal mechanisms for bioretention, it is theoretically possible to extrapolate removal rates to other LID practices such as permeable pavement. The authors, however, did not feel comfortable making that leap in this report.

Other BMPs that could potentially remove bacteria but are supported by little or no monitoring data include erosion and sediment controls, street cleaning and storm drain clean-outs, and the elimination of nutrient discharges from gray infrastructure (Erosion and Sediment Control Expert Panel 2014, Nutrient Discharges from Gray Infrastructure Expert Panel 2014, Street Cleaning Expert Panel 2016).

Several other LID practices that utilize vegetation had some limited monitoring data to characterize their potential capability to reduce bacteria (characterized as reductions in median concentrations unless otherwise noted):

- **Grass Swales:** Prior research summaries have shown that grass swales exhibit low to negative removal rates for bacteria (CWP 2007). The International BMP database supports this finding, with negative removals in the range of ~ -10% to -35% (Clary et al. 2017). Other BMP review studies have come to the same conclusion about grass swales: -338% average bacteria removal (Rifai 2006) and -25% average bacteria removal (Pennington et al. 2003).
- **Filter strips/buffers:** Some research indicates these BMPs have bacteria removal potential, but it tends to be extremely variable. A study by Coyne et al. (1995) showed 74% fecal coliform removal from soil surface runoff on one plot,

but only 43% on a second plot. Literature review studies for vegetated filters report average removal rates of 37% (Pennington et al. 2003) and 32% (Rifai 2006), respectively.

Modeling studies have shown that filter strip performance is sensitive to the parameters of soil, vegetation, and weather (Guber et al 2009). Fecal coliform reductions also did not improve with increased filter strip length (Srivastava et al, 1996). Nunez-Delgado et al. (2002) found that bacteria can be re-suspended after being temporary stored in the filter by subsequent rainfall events.

- **Tree filters:** Urban tree filters were monitored by Shifman et al (2016) and these bioretention design variants exhibited substantial reductions in *E. coli*. During a field tracer study, they observed 99.1% and 99.2% removal for conventional tree filter (sand/shale media) and modified tree filter (with added wood chips), respectively. During natural conditions, the conventional tree filter removed 86% and the modified tree filter removed 90% of *E. coli*.

  While this study is encouraging and suggests the potential of using treated wood chips as a "performance enhancer" for tree filters, it is a single study and needs to be replicated in other urban settings and bacteria loading conditions.

Management Implications

Traditional stormwater BMPs can certainly play a key supporting role in a watershed bacteria management strategy. While BMPs alone cannot reliably achieve bacteria levels that meet water contact recreation standards, they can be combined with source controls, outreach and other measures as part of a comprehensive watershed plan.

As noted in the preceding section, most BMP data is quite variable and site-specific, which makes it difficult to select a single BMP solution to incorporate into a watershed management plan. In general, both bioretention and constructed wetlands show strong potential to achieve significant reductions. Wet ponds and filter strips are highly variable, while dry ponds and swales seem to be the least effective. Given our growing understanding of the BMP removal mechanisms for both nutrients and bacteria, it should be possible to continually improve our designs to achieve more reliable treatment of both pollutants.

More field monitoring is needed to better quantify reductions for a range of practices and site conditions. As MST techniques are further refined, it may also be worth working to better understand how monitored reductions in FIB correlate to specific pathogen reductions. In the meantime, the desire to achieve co-benefits with nutrient and sediment BMPs in the Chesapeake Bay watershed will continue to drive bacteria reduction research in the hope that managers will be able to address multiple pollutants of concern with their implementation efforts. Researchers should also focus on how watershed managers can refine their illicit discharge detection and elimination programs to identify and control key bacteria sources in their watersheds.

Conclusions

Recent science suggests new directions to craft better strategies to reduce bacteria in urban watersheds, but managers still face many key data gaps when it comes to making local water quality decisions.

While bacteria are routinely detected in stormwater, it makes sense to treat bacteria sources well before they become entrained in runoff. Finding and fixing the untreated sewage sources that contain human pathogens should continue to be a major local management priority.

Data variability among bacteria reduction research is higher than most other pollutant constituents and presents a challenge for watershed managers. Trends from the available literature can help point to land uses that are commonly correlated with higher FIB loads. A growing body of research also shows that some BMPs have more bacteria removal performance than others. However, the variability and site-specificity are not yet fully explained, making it difficult to apply average land use loading rates and pollutant removal efficiencies to the watershed scale.

A multi-pronged approach will likely be the most effective management option for communities in the near-term. Combining implementation of some of the more promising traditional stormwater BMPs, like bioretention, with more bacteria-focused adaptations to IDDE programs can help to address both source elimination and stormwater treatment.

For communities with greater resources, two-tiered screening can be an effective option to identify high FIB-loading outfalls, which can then be targeted by more source-specific MST methods. These watersheds could also be targeted for greater BMP implementation or education and outreach campaigns depending on the bacteria source. Smaller, more resource-limited watersheds could focus outreach efforts and outfall screening based on desktop surveys. Identifying potential hotspots like older residential developments, particularly those on septic systems or near surface waters, as well as dog-walking corridors or homeless encampments can assist in future track-back work.

Better approaches are still needed to help address FIB in a way that is protective of public health while recognizing the resource limitations of local governments and the variability and controllability of FIB loads. However, resources are available to help managers make the best possible decisions based on the current state of the science. Balancing source control, education, and stormwater BMP implementation will help to reduce risk and provide more opportunity for program success.

Next Steps

The Chesapeake Bay Program's Urban Stormwater Work Group discussed some key regional cooperative initiatives that could be launched to help local managers in reducing bacteria to meet their local TMDLs. These include:

- Better defining the magnitude of the "local" bacteria reduction co-benefits associated with installing urban BMPs to meet the Bay-wide nutrient and sediment TMDL.
- Showcasing innovative bacteria detection and reduction strategies pioneered by other MS4s along the east coast, such as the coordinated watershed investigations done in greater Charlotte, NC and Boston, MA.
- Convening a small team to isolate the key design factors that could improve bacteria removal rates for the next generation of stormwater BMPs.

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Appendix A. Potential Sources of FIB in Urbanized Areas - From Clary et al. 2014

Table 3-1. Potential Sources of FIB in Urbanized Areas and Adjoining Watersheds

General Category	Source/Activity
Municipal Sanitary Infrastructure (piped)	Sanitary sewer overflows (SSOs)
	Combined sewer overflows (CSOs); regulated under NPDES/LTCP
	Leaky sewer pipes (Exfiltration) (see Sercu et al. 2011)
	Illicit Sanitary Connections to MS4
	WWTPs (if inadequate treatment or upsets); regulated under NPDES
Other Human Sanitary Sources (some also attract urban wildlife)	Leaky or failing septic systems
	Homeless encampments
	Porta-Potties
	Dumpsters (e.g., diapers, pet waste, urban wildlife)
	Trash cans
	Garbage trucks
Domestic Pets	Dogs, cats, etc.
Urban Wildlife (naturally-occurring and human attracted)	Rodents/vectors (rats, raccoons, squirrels, opossums)
	Birds (gulls, 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)
	Piers/docks
Urban Non-stormwater Discharges (Potentially mobilizing surface-deposited FIB)	Power washing
	Excessive irrigation/overspray
	Car washing
	Pools/hot tubs
	Reclaimed water/graywater (if not properly managed)
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
Recreational Sources	Bathers and/or boaters
	RVs (mobile)
Agricultural Sources (potentially including ranchettes within MS4 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
	Irrigation tailwater
	Slaughterhouses (NPDES-regulated)
Natural Open Space/Forested Areas	Wildlife populations
	Grazing
Other Naturalized Sources	Beach wrackline (flies, decaying plants), plants/algae, sand, soil (naturalized FIB)

Note: this table builds upon previous work by San Diego County (Armand Ruby Consulting 2011).

Appendix B. Additional Resources

Resource Title	Link
Be a Chesapeake Bay Retriever: Designing Effective Outreach Programs to Reduce Pet Waste	http://chesapeakestormwater.net/2017/08/be-a-chesapeake-bay-retriever-designing-effective-outreach-programs-to-reduce-pet-waste/
Safe Waters, Healthy Waters: A Guide for Citizen Groups on Bacteria Monitoring in Local Waterways	https://owl.cwp.org/mdocs-posts/safe-waters-healthy-waters-a-guide-for-citizen-groups-on-bacteria-monitoring-in-local-waterways/
Illicit Discharge Detection and Elimination Field Guide for the Coastal Plain: How to Identify and Quickly Report Pollution Problems	https://www.hrpdcva.gov/uploads/docs/Final_IDDE Field Guide_HRPDC.pdf
IDDE: A Guidance Manual for Program Development and Technical Assessments	https://www3.epa.gov/npdes/pubs/idde_manualwithappendices.pdf
Profile Sheet for Nutrient Discharges from Gray Infrastructure	https://chesapeakestormwater.net/download/6483/
Identification of High Risk Lawns for Water Quality: Guidance for Chesapeake Bay Communities	http://chesapeakestormwater.net/wp-content/uploads/dlm_uploads/2015/12/Identification-of-High-Risk-Lawns-Guidance-for-Chesapeake-Bay-Communities_FINAL.pdf

Appendix C. Complete BMP Bacteria Reduction Data Set

The full set of BMP data collected by the ad hoc team is available to view.

Download the spreadsheet here.