Effectiveness of Best Management Practices for Bacteria Removal

Developed for the Upper Mississippi River Bacteria TMDL

June 2011

Primary Authors and Contributors

Emmons & Olivier Resources, Inc.
Lisa Tilman
Andrea Plevan
Pat Conrad

wq-iw8-08q

Table of Contents

EXECUTIVE SUMMARY

This literature review is intended to assist in guiding the selection of the most practical and effective implementation strategies to improve water quality in the Upper Mississippi River Bacteria Total Maximum Daily Load project area. The literature review evaluated research findings regarding the effectiveness of various best management practices to reduce bacteria loading to surface waters. The best management practices evaluated through literature were: wetland treatment systems, wet and dry detention ponds, biofiltration/filtration practices, hydrodymanic and manufactured devices, vegetated buffers/filter strips and swales, livestock riparian access control, manure management and pollution prevention and source controls.

Pollution prevention and source control are recommended as methods to reduce the load of bacteria to be managed by constructed best management practices and to limit the potential for bacteria to be transported to receiving waters. Of the best management practices reviewed in this study, wetland treatment systems, wet retention ponds, biofiltration/filtration practices, wide filter strips on permeable soils, and limitations on livestock access to riparian areas were identified as the practices that appear to have the most potential for effective reduction of bacteria loads. However, all of the methods reviewed display a level of variability in treatment effectiveness and careful consideration of design is necessary.

BACKGROUND

The study of best management practices (Best Management Practices, e.g. bioretention and bioswales) for removal of bacteria is well behind that of other constituents such as nitrogen, phosphorus, and heavy metals. However, a number of studies have been conducted to evaluate the removal of bacteria through best management practices. The following literature review is intended to assist in the selection of the most practical and effective implementation strategies to improve water quality in the Upper Mississippi River Bacteria Total Maximum Daily Load project area. This document provides a review of studies pertaining to the effectiveness of best management practices in removing bacteria from urban stormwater runoff and rural watershed runoff.

In Minnesota, as in many places throughout the world, fecal contamination of surface waters was measured using fecal coliforms as an indicator and is now measured using *E. coli* as the indicator organism. Studies evaluating the impact of best management practices on the concentration of bacteria entering surface waters tend to track reductions in one or both of these indicators as water moves through the treatment practice.

The survival of bacteria in water has been found to be affected by predation by microorganisms such as protozoa and by solar (UV) radiation (Sinton et al. 1994 and Burkhardt et al. 2000 cited in Mendez et al. 2009) with bacteria removal from the water column further enhanced by sedimentation and filtration (Bavor et al. 2005). The growth of bacteria can be further limited by factors such as cold water temperature, low nutrients, low pH, drying, and low carbon availability (Oliveri et al. 1977 cited in Schueler and Holland 2000). Stormwater best management practices could use these factors to reduce the concentration of fecal bacteria entering surface waters. Stormwater best management practices have historically been constructed for sediment and nutrient reduction, however, many studies on the impact of best management practices have evaluated their function for bacteria removal as well.

LITERATURE REVIEW METHODS

The literature search was not exhaustive, but covered a large and representative sample of existing literature to achieve the intended purpose of the literature overview.

Sources

Several methods were used to search available literature on the special study topics. United States Geological Survey scientific investigations reports were searched using the online United States Geological Survey database. The scientific literature was searched in several ways. Journal databases accessible through the University of Minnesota were searched from 1972 (chosen because of the Clean Water Act) to 2009 using the search rubric below. The literature collected in support of a planned guidance document on agricultural best management practices for the Minnesota Department of Agriculture was searched using the criteria of the second and third bullet points below. Finally, the works cited in some of the more relevant papers were checked for papers of interest to provide some additional literature.

Some articles provide a literature review or synopsis of the state of the science with regard to bacteria removal in urban and rural or agricultural best management practices and/or a summary of removal efficiency data of various best management practices studied throughout the United States (Appendix A). Research articles providing this type of synopsis or summary were reviewed in detail, while the remainder of the research articles were reviewed with a focus on the results presented. Much of the research reviewed was on buffers or filter strips and on constructed wetlands for wastewater and/or stormwater treatment. However, a number of other best management practices were evaluated in the reviewed literature including sedimentation ponds, biofiltration practices, filtration practices, vegetated buffers and swales, hydrodynamic devices, livestock riparian access management, manure management and source controls.

Search Rubric

Scientific journals were searched with the following search terms (parenthetical terms were searched in combination with those terms not in parenthesis):

- "best management practice"* (AND bacteria) (AND fecal) (AND Escherichia)
- "best management practice"* AND "agricultural" (AND bacteria) (AND fecal) (AND Escherichia)
- bacteria (AND "livestock riparian pasture") (AND "livestock access control") (AND "rotational grazing") (AND buffer) (AND filter strip) (AND "manure management") (AND "nutrient management")
- "treat bacteria" AND "storm water"**
- bacteria AND "water quality treatment" (AND "storm water"**) (AND urban)
- bacteria AND "storm water"** (AND treatment) (AND urban)
- "bacteria reduction" AND "storm water"**
- bacteria AND "storm water** treatment"
- bacteria AND "storm water"** AND sump
- bacteria (AND "Vortechs") (AND "sump water") (AND "detention pond") (AND "retention pond") AND ("storm water** pond") (AND "sumped manhole")
- bacteria AND urban (AND "filter strip) (AND grass) (AND bioretention) (AND raingarden) (AND "rain garden")

* "BMP" was also used as a replacement for this search term
** "stormwater" was also used as a replacement for this search term

EFFECTIVENESS OF URBAN AND RURAL BEST MANAGEMENT PRACTICES IN REMOVING BACTERIA

Wetland Treatment Systems

Wetland treatment systems consist of a wetland constructed with the purpose of treating wastewater or stormwater inputs. The wetlands may be vegetated, open water, or a combination of these. Primary research studies found average measured removal efficiencies for wetland systems of 79% (Bavor et al. 2001) in the studies reviewed. A subsurface flow wetland was found to have a 98% removal of bacteria (Gerba et al. 1999). Literature review studies cite wetland bacteria removal rates of 88.3% (Rifai 2006), -45% to 98% (Clary et al. 2008) and 78% (Pennington et al. 2003). On a storm by storm basis, Mendez et al. (2009) found that the efficiency ranged from -260% to 98% for three events measured individually. The *Minnesota Stormwater Manual* (MPCA, 2008) presents a median removal for bacteria of 75 % for wetland treatment systems based on less than five studies identified in the International BMP Database. Negative removals indicate that the wetland was releasing more bacteria than had been present in the inflow. While the exact reasons for these occurrences are not clear, it is estimated that accumulated sediment with adsorbed bacteria may be washed out of the system during a storm (Schueler and Holland 2000; Zhang and Lulla 2006; Clary et al. 2010) and/or that bacteria may multiply in the sediment (Schueler and Holland 2000) or that other sources such as wildlife are present (Clary et al. 2010). Wildlife and waterfowl are suspected to act as sources of bacteria in wetlands and other water bodies, however this contribution was not quantified in the studies reviewed.

Settling of sediments is often considered to be the method for bacteria reduction through wetland systems, however Boutilier et al. (2009) found that up to 50% of bacteria were adhering to small particles that are difficult to capture through settling (2009).

More effective wetland designs were found to have larger volumes in proportion to the contributing drainage area and longer flow paths resulting in a longer detention time and fewer overflow events (Mendez et al. 2009). Other features of more effective designs were open water areas between the vegetated areas (Mendez et al. 2009). The open water areas are presumed to allow exposure of the bacteria to ultraviolet radiation in sunlight, therefore reducing the bacteria population (Boutiliera et al. 2009). Natural die-off may also contribute to the decrease in bacteria populations in treatment wetland effluent (Boutiliera et al. 2009).

Detention and Retention Ponds

Sedimentation ponds, also called detention, retention, or stormwater ponds, are open water ponds constructed to allow the settling of particles in stormwater and watershed runoff and the storage of water to limit flooding. Sedimentation ponds are not typically extensively vegetated although some vegetation may occur near the edges of the pond. Measured bacteria removal efficiencies in sedimentation or wet retenion ponds ranged from 15% to 20% (Krometis et al. 2009) to 56% and 86% (Mungasavalli and Viraraghavan 2006) to 42% to 99% (Clary et al. 2008). Literature review studies cite average sedimentation pond bacteria removal rates of 65% with a range of -5% to 98% (Schueler and Holland 2000) and 70% (Pennington et al. 2003). The *Minnesota Stormwater Manual* (MPCA, 2008) presents a median removal for bacteria of 70 % for wet retention ponds based on studies identified in the International BMP Database.

An alternative type of sedimentation pond, a dry detention pond, which stores water temporarily and drains dry, was found to have a 90% removal rate for bacteria based on one study identified through a literature review (Rifai 2006) and was found to have an average bacteria removal of 78% in another literature review (Pennington et al. 2003) and showed a range of -995% to 93% in a study by Clary et al. (2008). As with wetlands, negative removals indicate that the pond was acting as a source of bacteria. While the exact reasons for the best management practice to release more bacteria than were present in the inflow are not clear, it is estimated that accumulated sediment with adsorbed bacteria may be washed out of the system during a storm (Schueler and Holland 2000; Zhang and Lulla 2006; Clary et al. 2010) and/or that bacteria may multiply in the sediment (Schueler and Holland 2000) or that other sources such as wildlife are present (Clary et al. 2010). Wildlife and waterfowl are suspected to act as sources of bacteria in wetlands and other water bodies such as stormwater ponds, however this contribution was not quantified in the studies reviewed.

Biofiltration/Filtration

Biofiltration and filtration practices rely on the transport of stormwater and watershed runoff through a medium such as sand, compost, soil, or a combination of these in order to filter out sediment. Biofiltration systems, also called bioretention systems, are also vegetated. A specific study on one bioretention system indicated bacteria removal efficiencies of greater than 50% and a significant difference between inflow and outflow concentrations (Hathaway, 2009). Literature review studies, however, cite average filtration best management practice bacteria removal rates of 70% (Pennington et al. 2003) and 50% with individual practice removal rates ranging between -68% to 97% (Schueler and Holland 2000) and individual practice removal rates ranging between -146% to 96% (Clary et al. 2008)). In the laboratory, biofiltration systems were found to have an average bacteria removal rate of 92% ranging from 55% to over 99% (Rusciano and Obropta 2007). The *Minnesota Stormwater Manual* (MPCA, 2008) presents a median removal for bacteria of 35 % for filtration and bioretention systems based on fewer than five studies identified in the International BMP Database.

Hydrodynamic and Manufactured Devices

One study was identified that evaluated the effect of one type of proprietary hydrodynamic stormwater device. These devices capture sediment from stormwater by encouraging more rapid sedimentation through the swirling action of water moving through the device. The measured effectiveness for bacteria removal was 39% to 86% (Zhang and Lulla 2006) in a “Vortechs” device. Manufactured devices, including hydrodynamic devices, were identified in Clary et al. (2010) as having median inflow fecal coliform count per 100mL of 993 and outflow of 2,462 for the nine practices included in International Stormwater BMP Database.

Vegetated Buffers/Filter Strips/Swales

Vegetated buffers and filter strips are strips of vegetation next to an area of runoff. The runoff is allowed to flow evenly over the buffer or filter strip to allow capture of sediment by vegetation and to allow water to filter into the soil. Buffers and filter strips are used in numerous applications such as adjacent to streams and wetlands, along agricultural field boundaries, and around feedlots. Swales are similar to buffers but allow a more directed flow pattern in a shallow, vegetated ditch.

Bacteria removal rates were 75% in 14.7-foot wide buffer filter strips and were 91% in 29.5-foot wide buffer filter strips (Coyne et al. 1998). Filter strips of 118 feet (36 m) were found to provide reductions in bacteria concentration over the two years of the study (Young et al., 1980). A study by Fajardo et al. (2001) found bacteria reductions of 64% and 87% for two rainfall events, but found no reduction in the other two events studied. Literature review studies list average removal rates for vegetated filters of 37% (Pennington et al. 2003) and 32% (Rifai 2006).

Studies where much of the runoff through the buffer infiltrated into the soil showed higher efficiencies (Mankin et al, 2006; Roodsari, 2005). Mankin et al. (2006) found no discharge from the filter strips for 92 – 93% of rainfall events when the buffer adjacent to a feedlot was at least half the size of the contributing drainage area. Sites with buffer to drainage area ratios of less than 0.5 showed more variability in function (Mankin et al, 2006). Stout et al. (2005) found higher removal of bacteria from longer buffer strips in a scale model. However, other studies did not find this relationship. In one study, buffers were found to be effective in bacteria removal after one rainfall event, but with the next rainfall events bacteria were re-incorporated into the runoff after temporary storage in the buffer with no relationship to buffer length (Nunez-Delgado et al., 2002). The impact of raindrops and their splashing was found to transport bacteria and was also surmised as a possible method of transport of bacteria into streams (Boyer et al., 2008). Swales were identified as having bacterial removal rates of -338% (Rifai 2006), -25% (Pennington et al. 2003), and -58% (Schueler and Holland 2000). A study by Clary et al. (2008) idetified only six swales that showed a positive removal rate. In this study removal rates ranged from averages of -185% to 83% for 18 different sites.

An alternative method for filtration within a swale is to have the runoff also flow through compost filter socks, permeable rolls of compost laid on the ground across the flow. A study by Faucette et al. (2009) found a bacteria removal efficiency of 75%. With the addition of a floculant to the compost socks, the removal rate increased to 99%.

Livestock Riparian Access Control

Livestock with access to streams, lakes, and other riparian areas directly introduce fecal matter and bacteria into the waterway or waterbody. Limiting access to waterbodies would be expected to eliminate this direct source of bacteria. A study by Sheffield et al. (1997), as cited in Simpson and Weammert (2009), found that the amount of time cattle spent drinking from the stream and the time cattle spent in the stream area was reduced with the installation of watering troughs. The installation of watering troughs reduced by 89% the amount of time cattle spent drinking from the stream and reduced by 51% the time cattle spent in the stream area. The study did not quantify the impact of these changes on the actual transport of bacteria to the stream. A study by Monaghan et al. (2007) based on land use analysis found that the direct introduction of fecal matter into streams in the watershed contributed only 0.1% of the total annual load of *E coli* with 84% of the stream length fenced to exclude livestock access. A model used to evaluate the impact of best management practices in an agricultural watershed estimated an average 22% to 35% decrease in bacteria concentration (Collins et al., 2004) with the elimination of livestock access to riparian areas.

Manure Management

Manure management includes a variety of practices intended to store, treat, and use manure in a manner that limits the potential for the bacteria in manure to be transported to water bodies or waterways. Manure is often land applied to improve soil fertility. A study by Kern and Wolfe (2005) evaluated the application of liquid dairy manure in the spring and fall using four different methods. Three methods used surface application and one method applied the manure below the soil surface. The mean concentration of bacteria in runoff was lowest in the "undercut" method that applied the manure below the soil surface, but with the observed variability in all practices the difference was not statistically significant (Kern et al., 2005). After manure is land applied, it takes about 4 days for bacteria levels to reach background levels in the top 0.78 in (2 cm) of soil (Gessel et al., 2004). However, Muirhead et al. (2005) found that bacteria in cow pies grew for 6 to 14 days and did not follow the expected die off curve. In addition, bacteria was released into runoff in concentrations similar to that in the cow pies and most of the E. coli were in the runoff as single organisms not attached particulates (Muirhead et al., 2005). The study concludes "that E. coli cells in cowpats may not only survive for longer than currently anticipated but also may, during rainfall events, become deposited onto soil systems as highly mobile unattached cells. These findings may explain the occurrence of high "background" concentrations of fecal bacteria in runoff from agricultural land that has not been recently impacted with feces." (Muirhead et al., 2005).

Methods other than land application also exist for manure management. Reports not supported by cited research suggest that properly composting manure (Natural Resource Conservation Service, 1999), manure storage for two weeks, and treatment of manure in digesters at mesophilic temperature (Georgia Soil and Water Conservation Commission, 2007) may reduce the bacteria content of manure.

Pollution Prevention and Source Controls

Source controls focus on limiting the introduction of bacteria into locations in the landscape where bacteria could be transported to waterbodies. Source controls include efforts such as control of pet waste, street sweeping, septic system maintenance, wildlife management, livestock exclusion from riparian access, manure management and animal husbandry. Pollution prevention practices and source controls are expected to be valuable, but the impacts of all but livestock exclusion and manure management were not the main focus of this literature review and were not quantifiable in the relevant studies reviewed.

A study by Serrano and DeLorenzo (2008) found that 95% of residents responding to a survey in the study area were at least somewhat willing to change their behavior if the change would improve water quality. However, few of the respondents were following desired practices at the time of the survey. Only about 11% picked up pet waste daily and only about 11% had a vegetated buffer by the water body.

Other Considerations

Partitioning

Partitioning studies found that free-floating bacteria and particle-bound bacteria are often most highly associated with the smaller particles that are difficult to capture through sedimentation processes without an unduly long detention time (Boutilier et al. 2009; Characklis et al. 2005). These studies that focused on the partitioning of bacteria to sediment particles found that sedimentation would not be expected to be a large contributor to the removal of bacteria. A study by Boutilliera et al. (2009) on municipal and agricultural wastewater found that only 10% to 50%

of bacteria were associated with particles larger than 5 µm and settling velocities of particles with bacteria were too slow to likely be captured through sedimentation. Characklis et al. (2005) found 20% to 35% of bacteria were associated with settleable particles during baseflow conditions in urban streams and 30% to 50% of bacteria associated with settleable particles during storm events. It is likely that sedimentation along with other factors contributes to the removals observed.

Outflow Concentration

Three studies evaluated not only the overall removal of pollutants by the best management practices but also whether or not the resulting outflow concentration was low enough to meet a recreational contact standard. These three studies found that few practices will provide the reduction needed to meet standards.

In the study by Clary et al. (2008), of the 44 practices evaluated, five sedimentation ponds, two bioswales, and six filtration practices were discharging below the recreational contact standard. However, the inflow for two of these sedimentation ponds, one of the bioswales, and two of the filtration practices was already below the contact standard. Based on data from the International Stormwater Best Management Practice Database, Clary et al. (2010) reported median outflow fecal coliform count per 100mL of 813 for 11 dry detention basins with a median inflow of 749. For nine grass swales and buffers, the outflow fecal coliform count per 100mL was 4,728 with an inflow of 2,628. For 14 filtration facilities, the outflow fecal coliform count per 100mL was 216 with inflow of 605. For the six wet retention ponds in the database, the median outflow fecal coliform count per 100mL was 133 with inflow of 1,971.

The study by Schueler and Holland (2000) stated that most practices discharge in the range of 2,500 to 5,000 colonies per 100 mL, well above a recreational contact standard. The study asserts that even if stormwater practices are implemented throughout a watershed, bacteria concentrations may exceed the standard.

Big River Systems

Communication with practitioners working to reduce bacteria loads to another big river system, the Ohio River, indicated that their efforts have not yet extensively addressed non-point bacteria sources from urban and rural areas because their focus at this time is on addressing the over 1,000 combined sewer overflows within the watershed (J. Heath, personal communication, May 12, 2011)

Infiltration

It is presumed that infiltration practices would fully limit the transport of bacteria into surface waters for any rainfall event that is fully infiltrated since these practices eliminate or drastically reduce outflow. However, none of the studies specifically evaluated the impact of infiltration basins on bacteria removal. A number of reviewed studies suggest that bacteria are transported as individual cells in water or attached to very small particles, not always attached to larger particles that would be more easily trapped in a filter. Therefore, in areas where the bacterial concentration in shallow groundwater is of concern or where shallow groundwater contributes considerably to the water body, infiltration should be evaluated with consideration given to groundwater in addition to surface water runoff.

Summary and Recommendations

All of the methods reviewed display a level of variability in treatment effectiveness. The practices that appear to have the most potential for effective reduction of bacteria loads include wetland treatment systems, wet retention ponds, filtration practices including long filter strips with high levels of infiltration, and limiting livestock access to riparian areas.

Pollution prevention and source controls are recommended as a likely key component in reducing bacteria. Rural and agricultural source controls may include measures such as grazing management plans, animal waste management, and septic system maintenance. Urban source controls may include actions such as pet waste management, litter control, street sweeping, and complete separation of sanitary sewers and storm sewers. The effectiveness of various source controls is not well quantified in the literature; however, efforts to reduce the introduction of bacteria into the system are expected to assist in reducing the total bacteria load to the Mississippi River. In addition, limiting bacteria sources is expected to lower the concentration of bacteria entering a best management practice and increase the likelihood that the outflow from the best management practice will support water body standards. Guidance on a variety of residential, municipal and industrial/commercial pollution prevention methods can be found Chapter 12-1 of the *Minnesota Stormwater Manual* (MPCA, 2008). Guidance on agricultural source controls can be found through sources such as University of Minnesota Extension and their publication *Best Management Practices for Pathogen Control in Manure Management Systems* (Spiehs and Goyal, 2007).

Recommended best management practices are filtration practices including long filter strips with high levels of infiltration, wet retention ponds, wetland treatment systems and limiting livestock access to riparian areas. All best management practices are expected to be most effective when designed and constructed in a manner that is expected to maximize treatment potential. The *Minnesota Stormwater Manual* (MPCA, 2008) provides design guidance for a number of best management practices including filtration, biofiltration, wet retention ponds and wetland treatment.

The literature reviewed for this study suggests that filtration, biofiltration, wet retention ponds and wetland treatment practices are expected to be most effective when sized to limit overflows and designed to provide the longest flow path from inlet to outlet and limit resuspension of sediments. Based on the studies evaluated for this literature review, buffers and filter strips are expected to be most effective when infiltration into the soil is high and when a long flow path is provided over the buffer or filter strip. One study specifically identified high functioning buffers when the buffer to drainage area ratio was 0.5 or greater (Mankin et al, 2006). Limiting livestock access to riparian areas has a variety of methods that are expected to be effective. Literature reviewed suggests that providing watering systems (troughs, etc.) away from the riparian area can reduce the time livestock spend in the riparian area and suggests that fencing to keep livestock out of the riparian area can reduce bacterial loads to the waterbody. Guidance such as the Minnesota Department of Agriculture handbook *Managing Grazing in Stream Corridors* (2007) could assist in designing an effective riparian access plan.

APPENDIX A. CITATIONS AND BACKGROUND LITERATURE

The following articles were reviewed to prepare this literature review. The reviewed documents include manuals and guides prepared by government agencies, published studies and white papers that provide a synopsis of the state of the science with regard to bacteria treatment in best management practices and/or a summary of removal efficiency data of various best management practices, and published studies reporting on primary research regarding the function of best management practices with respect to bacteria removal.

Citation	Topic of Study	Location of Study	Number of Sites Included in Study
Akhand, N., D. R. Lapen, E. Topp, M. J. Edwards,L. Sabourin, B. R. Ball Coelho, F. W. Duenk, M. Payne, N. Gottschall. 2008. Using Macro to Simulate Liquid Sewage Biosolid Transport to Tile Drains for Several Land Application Methods. Transactions of the ASABE; 51(4): 1235-1245.	• Land application of manure methods	Ontario, Canada	1
Bavor, H. J., C. M. Davies, K. Sakadevan. 2001. Stormwater treatment: do constructed wetlands yield improved pollutant management performance over a detention pond system? Water Science and Technology. 44(11-12): 565-570.	• Constructed wetland removal efficiency • Detention basin removal efficiency	Sydney, NSW, Australia	2
Board of Water and Soil Resources. 2006. *Public Drainage Ditch Buffer Study*. Prepared in Partnership with Minnesota State University, Mankato, Water Resources Center and University of Minnesota Water Resources Center.	• Buffers	Minnesota	N/A
Boutilier, L., R. Jamieson, R. Gordon, C. Lake, W. Hart. 2009. Adsorption, sedimentation, and inactivation of E. coli within wastewater treatment wetlands. Water Research. 43(17): 4370-4380.	• Constructed wetland treatment mechanisms including E. coli inactivation, adsorption and settling	Nova Scotia, Canada	2
Boyer, D. 2008. Fecal coliform dispersal by rain splash on slopes. Agricultural & Forest Meteorology; 148(8/9):1395-1400	• Transport of bacteria by raindrop splash	N/A (laboratory study)	1
Characklis, G. W., M. J. Dilts, O. D. Simmons, C. A. Likirdopulos, L-A. H. Krometis, M. D. Sobsey. 2005. Microbial partitioning to settleable particles in stormwater. Water Research. 39(9): 1773-1782.	• Partitioning behavior, in particular, settleable particles in stormwater	Chapel Hill, North Carolina	n/a

Citation	Topic of Study	Location of Study	Number of Sites Included in Study
Clary, J. J. Jones, B. Urbonas, M. Quigley, E. Strecker, T. Wagner. 2008. Can Stormwater BMPs Remove Bacteria? New Findings from the International Stormwater BMP Database. Stormwater Magazine. 9(3). Including corresponding bacteria data from International Stormwater BMP Database 2008.	• Bioretention removal efficiency • Bioswale removal efficiency • Green roof removal efficiency • Retention pond removal efficiency • Detention pond removal efficiency • Sand filter removal efficiency • Filter strip removal efficiency • Media filter removal efficiency • Manufactured device removal efficiency • Wetland removal efficiency	various	73
Clary, J. M. Leisenring, and J. Jeray. 2010. Pollutant Category Summary: Fecal Indicator Bacteria. International Stormwater Best Management Practices Database.	• Bioretention removal efficiency • Biofilter removal efficiency • Green roof removal efficiency • Retention pond removal efficiency • Detention pond removal efficiency • Sand filter removal efficiency • Filter strip removal efficiency • Media filter removal efficiency • Infiltration removal efficiency • Maintenance practice removal efficiency • Manufactured device removal efficiency • Porous pavement removal efficiency • Wetland removal efficiency	various	141
Collins, R and K. Rutherford. 2004. Modelling bacterial water quality in streams draining pastoral land. Water Research.38(3):700-713	• Livestock grazing • Riparian access	New Zealand	1
Coyne, M. S., R. A. Gilfillen, A. Villalba, Z. Zhang, R. Rhodes, L. Dunn, R. L. Bevins. 1998. Fecal bacteria trapping by grass filter strips during simulated rain. Journal of Soil and Water Conservation. 53(2): 140-145.	• Grass filter strip removal efficiency (poultry fecal waste)	Kentucky	1

Citation	Topic of Study	Location of Study	Number of Sites Included in Study
Davies, C. M. and H. J. Bavor. 2000. The fate of stormwater-associated bacteria in constructed wetland and water pollution control pond systems. Journal of Applied Microbiology. 89(2): 349-360.	• Constructed wetland: fate of bacteria • Water pollution control pond: fate of bacteria • Treatment mechanisms including adsorption • Factors affecting performance including survival in sediments	Sydney, Australia	2
Davies, C. M., V. G. Mitchell, S. M. Petterson, G. D. Taylor, J. Lewis, C. Kaucner, N. J. Ashbolt. 2008. Microbial challenge-testing of treatment processes for quantifying stormwater recycling risks and management. Water Science and Technology. 57(6): 843-847.	• Constructed wetland removal efficiency • Retention pond removal efficiency • Biofiltration removal efficiency • Storage tank removal efficiency • UV disinfection removal efficiency	Australia	3
Davies, C. M., Z. Yousefi, H. J. Bavor. 2003. Occurrence of coliphages in urban stormwater and their fate in stormwater management systems. Letters in Applied Microbiology. 37(4): 299-303.	• Constructed wetland removal efficiency • Detention pond removal efficiency • Treatment mechanisms including settling	Sydney, NSW, Australia	2
Davis, A. P., W. F. Hunt, R. G. Traver, M. Clar. 2009. Bioretention technology: overview of current practice and future needs. Journal of Environmental Engineering. 135(3): 109.	• Bioretention: state of the science • Bioretention: research needs	various	0
Dietz, M. E., J. C. Clausen, K. K. Filchak. 2004. Education and changes in residential nonpoint source pollution. Environmental Management. 34(5): 684-690.	• Non-structural BMPs • Homeowner education as factor • Paired watershed study	Branford, Connecticut	1
Fajardo, J. J., J. W. Bauder, S. D. Cash. 2001. Managing nitrate and bacteria in runoff from livestock confinement areas with vegetative filter strips. Journal of Soil & Water Conservation. 56(3):1-1	• Filter strip efficiency	Bozeman, Montana	1
Faucette L. B., F. A. Cardoso-Gendreau, E. Codling, A. M. Sadeghi, Y. A. Pachepsky, D. R. Shelton. 2009. Storm Water Pollutant Removal Performance of Compost Filter Socks. Journal of Environmental Quality. 38(3): 1233-1239.	• Compost filter sock removal efficiency • Flocculation as treatment mechanism	N/A (laboratory study)	1
Garbrecht, K., G. A. Fox, J. A. Guzman, D. Alexander. 2009. E. coli transport through soil columns: implications for bioretention cell removal efficiency. Transactions of the ASABE. 52(2): 481-486.	• Bioretention removal efficiency • Soil media as factor	N/A (laboratory study)	1

Citation	Topic of Study	Location of Study	Number of Sites Included in Study
Georgia Soil and Water Conservation Commission. 2007. *Best Management Practices for Georgia Agriculture: Conservation Practices to Protect Surface Water Quality*. Manual. Athens, GA: The Georgia Soil and Water Conservation Commission.	• Manure management	N/A	N/A
Gerba, C. P., J. A. Thurston, J. A. Falabi, P. M. Watt, M. M. Karpiscak. 1999. Optimization of artificial wetland design for removal of indicator microorganisms and pathogenic protozoa. Water Science and Technology. 40(4-5): 363-368.	• Constructed wetland removal efficiency (duck-weed covered pond, multi-species subsurface flow and multi-species surface flow wetlands) • Treatment mechanisms	Tucson, Arizona	3
Gessel, P. D., N. C. Hansen, S. M. Goyal, L. J. Johnston, J. Webb. 2004. Persistence of zoonotic pathogens in surface soil treated with different rates of liquid pig manure. Applied Soil Ecology. 25(3)237-242	• Bacterial survival in soil	Morris, Minnesota	12
Gilley, J. E, J. R. Vogel, E.D. Berry, R.A. Eigenberg, D.B. Marx, B.L. Woodbury. 2009. Nutrient and bacterial transport in runoff from soil and pond ash amended feedlot surfaces. Transactions of the ASABE; 52(6):2077-2085	• Feedlot runoff	Clay Center, Nebraska	12
Guber, A. K, J.S. Karns, Y.A. Pachepsky, A.M. Sadeghi, J.S. Van Kessel, T.H. Dao. 2007. Comparison of release and transport of manure-borne Escherichia coli and enterococci under grass buffer conditions. Letters in Applied Microbiology. 44(2):161-167	• Grass Filter Strip	N/A (laboratory study)	1
Harmel, R. D., C.G. Rossi, T. Dybala, J. Arnold, K. Potter, J. Wolfe, D. Hoffman. 2008. Conservation Effects Assessment Project research in the Leon River and Riesel watersheds. Journal of Soil & Water Conservation. 63(6):453-460	• Watershed modeling for bacteria	Reisel, Texas	28
Hathaway, J. M., W. Hunt, S. Jadlocki. 2009. Indicator Bacteria Removal in Storm-Water Best Management Practices in Charlotte, North Carolina. Journal of Environmental Engineering. 135(12):1275-1285	• Wet pond efficiency • Storm-water wetlands efficiency • Dry detention basins efficiency • Bioretention area efficiency • Proprietary devices	Charlotte, NC	9
Hunt, W. F., J. T. Smith, S. J. Jadlocki, J. M. Hathaway, P. R. Eubanks. 2008. Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, NC. Journal of Environmental Engineering - ASCE. 134(5): 403-408.	• Bioretention removal efficiency	Charlotte, NC	1

Citation	Topic of Study	Location of Study	Number of Sites Included in Study
Karpiscak, M. M., C. P. Gerba, P. M. Watt, K. E. Foster and J. A. Falabi. 1996. Multi-species plant systems for wastewater quality improvements and habitat enhancement. Water Science and Technology. 33(10-11): 231-236.	• Macrophytic plants as treatment mechanism • Constructed wetland removal efficiency • Removal efficiency of aquatic system covered with duckweed	Pima County, Arizona	2
Kelly, R. F. and M. Ruby. Bacterra™ Advanced Bioretention Technology: A best management practice for stand alone stormwater treatment for bacteria removal. Filterra® Bioretention Systems.	• Bacterra™ Advanced Bioretention Technology removal efficiency • Treatment mechanisms	Marina Del Ray, California	1
Kern J. D. and M. L. Wolfe. 2005. Cover crop/dairy manure management systems: water quality and soil system impacts. Transactions of the ASAE. 48(4):1333-1341	• Land application methods	Virginia	16
Khatiwada, N. R. and C. Polprasert. 1999. Kinetics of fecal coliform removal in constructed wetland. Water Science and Technology. 40(3): 109-116.	• Removal efficiency in constructed wetland • Temperature, solar radiation, sedimentation, adsorption and filtration as factors/mechanisms	Bangkok, Thailand	7
Kidd, S., J. Miller, K. Reininga, R. Kapur, T. Walsh, F. Wildensee. 2005. Storm water BMP effectiveness workgroup report.	• ACWA Stormwater BMP Effectiveness Database summary • Filters (leaf/sand/other) effluent concentration • Non-structural BMPs • Land-use based bacteria concentrations	various	not available
Kirby-Smith W.W. and N.M. White. 2006. Bacterial contamination associated with estuarine shoreline development. Journal of Applied Microbiology. 100(4):648-657	• Shoreline disturbance impact on bacteria	North Carolina	1
Krometis, L. A. H., P. N. Drummey, G. W. Characklis, M. D. Sobsey. 2009. Impact of Microbial Partitioning on Wet Retention Pond Effectiveness. Journal of Environmental Engineering - ASCE. 135(9): 758-767.	• Wet detention basin anticipated effectiveness • Wet detention basin locating • Partitioning and relative concentrations in the stormwater transport chain • Partitioning as factor • Sedimentation as treatment mechanism	Northeast Creek watershed, North Carolina	2
Li, H. and A. P. Davis. 2009. Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention. Journal fo Environmental Engineering - ASCE. 135(8): 567-576.	• Bioretention removal efficiency	Maryland	2

Citation	Topic of Study	Location of Study	Number of Sites Included in Study
Mallin, M. A., S. H. Ensign, T. L. Wheeler, D. B. Mayes. 2002. Pollutant removal efficacy of three wet detention ponds. Journal of Environmental Quality. 31(2): 654-660.	• Wet detention pond removal efficiency • Wet detention pond design	Wilmington, North Carolina	3
Mankin, K. R., P.L. Barnes, J.P. Harner, R.K. Kalita, J. Boyer. 2006. Field evaluation of vegetative filter effectiveness and runoff quality from unstocked feedlots. Journal of Soil & Water Conservation.61(4):209-217	• Filter strip efficiendy	Kansas	4
Mendez, H. P. M. Geary, R. H. Dunstan. 2009. Surface wetlands for the treatment of pathogens in stormwater: three case studies at Lake Macquarie, NSW, Australia. Water Science and Technology. 60(5): 1257-1263.	• Constructed wetland removal efficiency (surface wetland) • Trash rack removal efficiency • Gross pollutant trap removal efficiency	Lake Macquarie, Australia	3
MN Department of Agriculture. 2007. *Managing Grazing in Stream Corridors*. Edited by Howard Moechnig.	• Livestock riparian access	Southeast Minnesota	N/A
Monaghan, R.M, R.J. Wilcock, L.C. Smith, B. Tikkisetty, B.S. Thorrold, D. Costall. 2007. Linkages between land management activities and water quality in an intensively farmed catchment in southern New Zealand. Agriculture, Ecosystems & Environment. 118(1-4):211-222	• Livestock exclusion • Subsurface drainage	New Zealand	1
Monaghan, R.M, C.A.M. de Klein, R.W. Muirhead. 2008 Prioritisation of farm scale remediation efforts for reducing losses of nutrients and faecal indicator organisms to waterways: A case study of New Zealand dairy farming. Journal of Environmental Management. 87(4):609-622	• Ag BMP prioritization	New Zealand	4
Muirhead, R.W., R.P. Collins, P.J. Bremer. 2005. Erosion and Subsequent Transport State of Escherichia coli from Cowpats. Applied & Environmental Microbiology. 71(6):2875-2879	• Bacteria release from cow fecal matter	New Zealand	n/a
Mungasavalli, D. P. and T. Viraraghavan. 2006. Constructed wetlands for stormwater management: A review. Fresenius Environmental Bulletin. 15(11): 1363-1372.	• Constructed wetland removal efficiency • Design as factor	various	not available
Natural Resources Conservation Service. 1999. *Agricultural Waste Management Field Handbook*. Edited by James N. Krider.	• Manure management	N/A	N/A

Citation	Topic of Study	Location of Study	Number of Sites Included in Study
Núñez-Delgado, A., E. López-Periago, F. Dıaz-Fierros Viqueira. 2002.Chloride, sodium, potassium and faecal bacteria levels in surface runoff and subsurface percolates from grassland plots amended with cattle slurry. Bioresource Technology. 82(3):261-271	• Filter strip efficiency	Spain	2
Oberts, Gary, and Andrea Plevan. 2001. Benefits of Wetland Buffers: A Study of Functions, Values and Size. Prepared for the Minnehaha Creek Watershed District by Emmons & Olivier Resources, Inc.,	• Wetland buffers	Minnesota	N/A
Pennington, S. R., M. D. Kaplowitz, and S. G. Witter, 2003. Reexamining Best Management Practices for Improving Water Quality in Urban Watersheds. Journal of the American Water Resources Association. 39(5): 1027-1041.	• Dry pond removal efficiency • Wet pond removal efficiency • Wetland removal efficiency • Filtering practices removal efficiency • Infiltration practices removal efficiency • Swales removal efficiency	Detroit, Michigan	not available
Rifai, H. 2006. Study on the effectiveness of BMPs to control bacteria loads: Final quarterly report no.1. Prepared for the Texas Commission on Environmental Quality.	• Dry basin removal efficiency • Grassy swale removal efficiency • Vegetative filter strip removal efficiency • Wet basin removal efficiency • Wetland removal efficiency • Treatment mechanisms • Factors	Harris County and Houston, Texas	82
Roodsari, R. M. D.R. Shelton, A. Shirmohammadi, Y.A. Pachepsky, A.M. Sadeghi, J.L. Starr. 2005. Fecal coliform transport as affected by surface condition. Transactions of the ASAE. 48(3):1055-1061	• Filter strip efficiency	N/A (laboratory study)	1
Rusciano, G. M. and C. C. Obropta. 2005. Efficiency of Bioretention Systems to Reduce Fecal Coliform Counts in Stormwater. Proceedings of The North American Surface Water Quality Conference and Exposition, Orlando, Florida, July 18-25, 2005. Forrester Communications, Inc., Santa Barbara, CA.	• Bioretention removal efficiency • Filtration, adsorption, pH and predation as factors/mechanisms	N/A (laboratory study)	1
Rusciano, G. M. and C. C. Obropta. 2007. Bioretention column study: Fecal coliform and total suspended solids reductions. Transactions of the ASABE. 50(4): 1261-1269.	• Bioretention removal efficiency • Treatment mechanisms	N/A (laboratory study)	1

Citation	Topic of Study	Location of Study	Number of Sites Included in Study
Schueler, Thomas R. and Heather K. Holland (Eds.). 2000. Microbes and Urban Watersheds: Ways to Kill `Em, Article 67, The Practice of Watershed Protection. Center for Watershed Protection, Ellicott City, MD. 3(1): 566-574.	• Bacteria mortality causes • BMPs, stream buffers and source controls: state of the science • Design guidance	various	24
Serrano L., M. E. DeLorenzo. 2008. Water quality and restoration in a coastal subdivision stormwater pond. Journal of Environmental Management. 88(1): 43-52.	• Stormwater pond as source • Education and outreach as factor • Pond management as factor	South Carolina	1
Simpson, T. and S. Weammert. 2009. Developing Best Management Practice Definitions and Effectiveness Estimates for Nitrogen, Phosphorus and Sediment in the Chesapeake Bay Watershed. Prepared for the University of Maryland Mid-Atlantic Water Program.	• Livestock riparian access	n/a	n/a
Sonstrom, R. S., J. C. Clausen, D. R. Askew. 2002. Treatment of parking lot stormwater using a StormTreat system. Environmental Science & Technology. 36(20): 4441-4446.	• Structural BMP (StormTreat) removal efficiency • Factors	East Hartford, Connecticut	1
Spiehs, M. and S. Goyal. 2007. Best Management Practices for Pathogen Control in Manure Management Systems. Prepared for University of Minnesota Extension.	• Animal management • Manure management	N/A	N/A
Stout, W. L., Y.A. Pachepsky, D.R. Shelton, A.M. Sadeghi, L.S. Saporito, A.N. Sharpley. 2005. Runoff transport of faecal coliforms and phosphorus released from manure in grass buffer conditions. Letters in Applied Microbiology. 41(3):230-234	• Grass buffer efficiency	N/A (laboratory study)	1
Struck, S. D., M. Borst, A. Selvakumar. 2006. Performance of stormwater retention ponds and constructed wetlands in reducing microbial concentrations. EPA Rep. No. 600/R-06/102, Washington, D.C.	• Constructed wetland removal efficiency • Retention pond removal efficiency • Temperature, sunlight, salinity, predation, sedimentation, filtration, sorption, pH, and BOD as factors/mechanisms	Edison, New Jersey	2
Struck, S. D., A. Selvakumar, M. Borst. 2008. Prediction of effluent quality from retention ponds and constructed wetlands for managing bacterial stressors in storm-water runoff. Journal of Irrigation and Drainage Engineering. 134(5): 567.	• Constructed wetland removal efficiency • Retention pond removal efficiency • Accumulation in BMP sediments • Turbidity as indicator of bacteria treatment effectiveness • Water temperature, light and other environmental factors as factors	Edison, NJ	2

Citation	Topic of Study	Location of Study	Number of Sites Included in Study
Young, R. A., T. Huntrods, and W. Anderson. 1980. Effectiveness of Vegetated Buffer Strips in Controlling Pollution from Feedlot Runoff. Journal of Environmental Quality. 9(3): 483-487.	• Buffer efficiency	Stevens County, Minnesota	6
Zhang, X. and M. Lulla. 2006. Distribution of Pathogenic Indicator Bacteria in Structural Best Management Practices. Journal of Environmental Science and Health Part A. 41: 1421-1436.	• Bacteria survival in sump water and sediment of structural BMP (Vortechs)	Providence, Rhode Island	2
Zhang, X. Q. and M. Lulla. 2006. Evaluation of pathogenic indicator bacteria in structural Best Management Practices. Journal of Environmental Science and Health Part A-Toxic/Hazardous Substances & Environmental Engineering. 41(11):2483-2493.	• Structural BMP (Vortechs) removal efficiency • Structural BMP (Vortechs) resuspension and survivability	Providence, Rhode Island	2