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International Stormwater BMP Database

2020 Summary Statistics

International Stormwater BMP Database: 2020 Summary Statistics

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Abstract and Benefits

Abstract:

The International Stormwater Best Management Practices (BMP) Database is a publicly accessible repository for BMP performance monitoring study, design, and cost information. The overall purpose of the project is to provide scientifically sound information to improve the design, selection and performance of BMPs. Continued population of the database and assessment of its data supports improved understanding of the factors influencing BMP performance and supports improvements in BMP design, selection and implementation. The performance, design, and cost data have also supported and will continue to support the development of science-based stormwater regulations, policies, and programs that seek to balance receiving water protection, technical feasibility, and cost.

This report provides a summary of BMP performance for reducing total suspended solids, nutrients, metals, and fecal indicator bacteria in stormwater for the most commonly monitored and reported BMP types available in the December 2019 release of the BMP Database, updating previous performance summary reports, which were last completed for the 2016 BMP Database release (Clary et al. 2017). BMPs included in the analysis include grass strips, bioretention, bioswales, extended detention basins, media filters (mostly sand filters), porous pavement, permeable friction course, retention ponds (wet ponds), wetland basins, wetland channels, and several manufactured treatment device categories. This 2020 analysis not only includes new performance studies, but also new analysis categories for manufactured treatment devices. Data summaries include basic summary statistics for BMP influent and effluent concentrations, graphical summaries of statistics and hypothesis test results for assessing whether the BMP had an effect on influent concentrations for various pollutant-BMP combinations. Additionally, information about typical pollutant sources, dominant pollutant removal mechanisms in BMPs and design considerations are provided.

Benefits:

- Provides consolidated summary statistics for the December 2019 version of the International Stormwater BMP Database.
- Provides hypothesis testing results to indicate which BMPs demonstrate statistically significant differences in influent and effluent concentrations.
- Helps researchers identify potential data gaps for BMPs and pollutant types that warrant additional research.
- Synthesizes national BMP performance research that can be used for comparative purposes for local BMP studies or to support local planning efforts.
- Provides information on pollutant sources, removal mechanisms in BMPs and factors that appear to be affecting removal.

Keywords: Best management practice, stormwater control measure, green infrastructure, performance, monitoring, nutrients, bacteria, metals, sediment, water quality.

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Acronyms and Abbreviations

ASTM	American Society for Testing and Materials
ASCE	American Society of Civil Engineers
BOD	Biological oxygen demand
BMP	Best management practice
cfu	Colony forming units
CI	Confidence interval
COD	Chemical oxygen demand
DO	Dissolved oxygen
EPA	U.S. Environmental Protection Agency
EMC	Event mean concentration
EWRI	Environmental and Water Resources Institute
FHWA	Federal Highway Administration
GI	Green infrastructure
HDS	Hydrodynamic separator
HRBF	High rate biofiltration
HRMF	High rate media filtration
IQR	Interquartile Range
LID	Low impact development
mg/L	milligrams per liter
MPN/100 mL	Most probable number per 100 milliliters
MS4	Municipal Separate Storm Sewer System
N	Nitrogen
NA	Not applicable
NCHRP	National Cooperative Highway Research Program
ND	Non-detect
NOx	Nitrate + nitrite and nitrate
NSQD	National Stormwater Quality Database
OGS	Oil-grit separator
ORP	Oxidation-reduction potential
P	Phosphorus
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
QMRA	Quantitative microbial risk assessment
ROS	Regression on statistics
SRP	Soluble reactive phosphorus
TOC	Total organic carbon
TDS	Total dissolved solids
TMDL	Total maximum daily load
TKN	Total Kjeldahl nitrogen
TPH	Total petroleum hydrocarbons
TSS	Total suspended solids

TVS	Total volatile solids
TVSS	Total volatile suspended solids
µg/L	Micrograms per liter
µm	Micrometer
USGS	U.S. Geological Survey
WRF	The Water Research Foundation

Executive Summary

The International Stormwater Best Management Practices (BMP) Database is a publicly accessible repository for BMP performance, design, and cost information. The overall purpose of the project is to provide scientifically sound information to improve the design, selection and performance of BMPs. Continued population of the database and assessment of its data supports improved understanding of the factors influencing BMP performance and supports improvements in BMP design, selection and implementation. As of December 2019, the BMP Database contains data sets collected over four decades from over 700 BMP studies through the U.S. and several other countries that are accessible on the project website (www.bmpdatabase.org).

This 2020 report summarizes influent and effluent concentrations for various pollutant-BMP combinations utilizing basic summary statistics, graphical summaries of statistics and hypothesis test results from comparing influent and effluent concentrations. The pollutant performance data sets selected for this report include total suspended solids, nutrients, fecal indicator bacteria and metals based on data in the December 2019 release of the BMP Database. BMPs included in the analysis include grass strips, bioretention, bioswales, extended detention basins, media filters (mostly sand filters), porous pavement, permeable friction course (overlays), retention ponds (wet ponds), wetland basins, wetland channels and several manufactured treatment device categories. Additionally, information about typical sources, dominant pollutant removal mechanisms and design considerations is provided.

Overall findings for pollutant categories addressed in this report include:

1. Solids: All of the BMP types evaluated demonstrated statistically significant reduction in total suspended solids (TSS). The lowest effluent concentrations observed for TSS include bioretention, media filters, high rate biofiltration devices, and retention basins. These BMPs enable sedimentation and filtration, which are effective treatment processes for sediment removal. Conversely, none of the BMP types evaluated showed statistically significant reductions in total dissolved solids (TDS).
2. Bacteria: The fecal indicator bacteria data set for U.S. Environmental Protection Agency (EPA) recommended fecal indicators remains limited. Nonetheless, several observations can be made from the available data. Most BMP types analyzed are not able to consistently reduce bacteria concentrations to primary contact recreation receiving water standards. However, some BMP types show the ability to significantly reduce currently recommended fecal indicator bacteria concentrations, including bioretention, wetland basins, retention ponds, media filters and dry extended detention basins. Bacteria load reductions may be more significant than concentration reductions due to volume reduction provided by BMPs that provide infiltration such as bioretention. Based on these findings and given the many diffuse sources of fecal indicator bacteria in watersheds, source identification and control should be the first steps in addressing fecal indicator bacteria impairments for receiving waters (Clary et al. 2014).
3. Nutrients-Phosphorus: Phosphorus in the particulate form can be removed from a variety of BMP types; however, removal of soluble forms is more challenging. Many BMPs show statistically significant reductions for phosphorus, but grass swales, grass strips, and bioretention show phosphorus export, which is likely due to the presence of phosphorus rich soils and planting media (e.g., containing compost) for many of the studies in the BMP Database. Detention basins effectively remove total phosphorus, but not dissolved phosphorus or orthophosphate. The best performing BMPs for total phosphorus reduction are media filters, high rate biofiltration, and high rate media filtration with total phosphorus median effluent concentrations of 0.05 to 0.09 mg/L. The best performing BMPs for orthophosphate in the

analysis data set are retention ponds and media filters. Retention ponds also show reductions for dissolved phosphorus. Most practices do not show statistically significant reductions for dissolved phosphorus and orthophosphate. Grass swales, grass strips and bioretention export dissolved phosphorus and orthophosphate in this data set. Bioretention had the most elevated phosphorus concentrations in effluent; therefore, careful attention to the phosphorus content of media in bioretention facilities is important.

4. Nutrients-Nitrogen: Many BMPs show statistically significant reductions in total nitrogen forms, with media filters producing the lowest median effluent concentrations of 0.9 and 0.6 mg/L for total nitrogen and TKN, respectively. Conversely, bioretention, media filters, and porous pavement show nitrate export, indicating that ammonification and nitrification of organic nitrogen is likely occurring. For the removal of nitrate, the best performing BMPs are retention ponds, wetland basins, and wetland channels.
5. Metals: As was the case for nutrients, total forms of metals are more readily removed than dissolved forms. For example, most of the BMPs evaluated showed statistically significant reduction of total copper, lead and zinc. Performance varies depending on the individual pollutant and unit treatment processes provided by the BMP. When evaluating metals performance, it is particularly important to be cognizant of influent concentrations – in cases where influent concentrations are already very low often indicated by non-detects in influent samples), then additional reductions of metals concentrations may not be feasible. See the summary tables provided in this report to assess expected performance for various BMP-metal combinations.

Research needs and data gaps identified as a result of this analysis include:

1. More BMP performance data sets are needed for fecal indicator bacteria for multiple BMP types, particularly for enterococcus and *E. coli*, which are the current EPA-recommended fecal indicator bacteria. Given that pathogens are the top cause of waterbody impairments nationally, this is a major research need.
2. Other urban stormwater analytes with limited data sets for analysis purposes include:
   - Heavy metals other than copper, lead, and zinc.
   - Oxygen demanding substances such as BOD, COD, and TOC.
   - Organic pollutants, such as TPH, PAHs, PCBs, phthalates, and dioxins.
3. More robust design information in BMP performance study submittals would be valuable for all BMP categories. This information is important for identifying the factors that lead to the best performance for various BMP types and would support more detailed evaluation within subgroups of BMP categories. For example, additional media filter and biofiltration studies with engineered media mixes (e.g., peat, biochars, zeolites, oxide-coated sands, etc.) other than sand and innovative designs (e.g., outlet control, internal water storage zone, etc.) could be useful in understanding which design variations are most effective.
4. Of the BMP categories evaluated, porous pavement and permeable friction course (overlay) studies, followed by wetland basins and engineered media filters (other than sand filters), are among the least represented in the database. Considering the high level of treatment that these BMP types appear to provide and the potential applicability of these in the ultra-urban settings and the highway environment, additional studies are needed. This is also true for manufactured devices that provide high rate biofiltration and high rate media filtration. Available data indicates that these devices are performing well for multiple water quality constituents and may be the only option for highly constrained locations in need of treatment.
5. Although some studies in the BMP Database include long-term performance data, many studies

are monitored for a few years or less, often relatively soon after installation. More long-term studies and/or studies that resume monitoring at previously monitored sites would be useful to better understand how BMP performance varies over time, ideally with maintenance practices, intervals and costs documented. This research need is particularly relevant for vegetated infiltration-oriented practices where root structure develops over time and may influence infiltration rates.

6. Although not a research need in terms of new monitoring, meta-analysis of existing studies in the BMP Database could be updated given significant growth in the BMP Database since Geosyntec and WWE (2013) completed *International Stormwater Best Management Practices (BMP) Database Advanced Analysis: Influence of Design Parameters on Achievable Effluent Concentrations*.

CHAPTER 1

Introduction

The International Stormwater BMP Database project is a long-term research effort that features a growing database of stormwater BMP performance monitoring study data sets, statistical analysis reports, monitoring guidance and other study-related publications. The overall purpose of the project is to provide scientifically sound information to help improve the design, selection and performance of BMPs as well as to inform stormwater management programs, policies, and regulations. Continued population of the database and assessment of its data will ultimately lead to a better understanding of factors influencing BMP performance and help to promote improvements in BMP design, selection and implementation.

The project began in 1996 under a cooperative agreement between the American Society of Civil Engineers (ASCE) and the U.S. Environmental Protection Agency (EPA). In 2004, the project transitioned to a more broadly supported group of partners now led by The Water Research Foundation (WRF), including the Federal Highway Administration (FHWA), and the Environmental and Water Resources Institute (EWRI) of ASCE. Organizations such as the National Cooperative Highway Research Program, the American Public Works Association and the Mile High Flood District (Denver, CO) have also helped to support the project.

Over the project's history, various performance summaries have been prepared. From 2012 through 2016, these summaries have been released as brief tabular and graphical summary reports with limited discussion and interpretation. However, in 2010-2011, a series of more detailed performance reports were prepared focusing on several pollutant categories: solids, bacteria, metals and nutrients. In addition to performance statistics, the 2010-2011 pollutant reports included background information on regulatory context, pollutant sources, pollutant removal mechanisms, and associated BMP design considerations for various pollutants based on the unit treatment processes occurring in the BMP and pollutant chemistry. This 2020 report integrates a condensed and updated version of the previous technical reports with the most current data in the BMPDB as of December 29, 2019.

A significant change in this technical report relative to previous analyses is inclusion of several types of manufactured treatment devices, as well as permeable friction course overlay pavements. Additionally, since completion of the previous BMP Database 2016 summary statistics report (Clary et al. 2017), more than 60 new studies including over 90 BMPs have been added to the database. This addition includes performance monitoring for 28 BMPs uploaded from the Southern California Coastal Water Resources Project database, 24 transportation-related BMPs, additional periods of record for long-term monitoring locations, and other studies.

This analysis continues to focus on concentration-based characterizations and the assessment of significant differences between influent and effluent concentrations. To estimate load reductions, concentration-based influent and effluent data can be combined with site-specific or watershed-specific estimates for volume reduction associated with infiltration-based practices or other practices providing runoff volume reduction. As recognized by EPA, utilizing this approach for load reductions is a much more robust method than percent-removal based analyses (Jones et al. 2008).

1.1 Performance Analysis Overview

Approximately every two years following upload of new data sets, the BMPDB team generates data analysis reports that include updates of summaries that characterize categories of BMPs and/or that involve advanced or targeted analyses. Updates of the BMP category-level statistical analysis reports focus on commonly monitored water quality analytes including of solids, bacteria, metals, and nutrients, as summarized in Table 1-1. The BMP categories included in the analysis are summarized in Table 1-2. This BMP category-level analysis includes summary statistics for various BMP category-analyte combinations, graphical representations of statistics and hypothesis testing comparing inflow versus outflow concentrations.

Table 1-1. Constituents Analyzed by Pollutant Category.

Solids	Bacteria	Nutrients	Metals
Total suspended solids (TSS) Total dissolved solids (TDS)	Fecal coliform *Escherichia coli* (*E. coli*) Enterococcus	Total phosphorus Orthophosphate Dissolved phosphorus Total nitrogen Total Kjeldahl nitrogen (TKN) Nitrate and nitrate plus nitrite (NOx) Ammonia as N	Arsenic (total and dissolved) Cadmium (total and dissolved) Chromium (total and dissolved) Copper (total and dissolved) Iron (total and dissolved) Lead (total and dissolved) Nickel (total and dissolved) Zinc (total and dissolved)

Table 1-2. BMP Categories Included in 2020 Performance Analysis.

BMP Category	Code	Description
Detention Basin	DB	Dry extended detention grass-lined and concrete lined basins that empty out after a storm.
Retention Pond	RP	Surface wet pond with a permanent pool of water, may include underground wet vaults.
Wetland Basin	WB	Similar to a retention pond (with a permanent pool of water), typically with more than 50 of its surface covered by emergent wetland vegetation.
Wetland Channel	WC	A continuously wet channel with wetland vegetation and slow velocities.
Grass Swale	BS	Shallow, vegetated channel, also called bioswale or vegetated swale.
Grass Strip	BI	Vegetated areas designed to accept laterally distributed sheet flow from adjacent impervious areas, also called buffer strips or vegetated buffers.
Bioretention	BR	Shallow, vegetated basins with a variety of planting/filtration media and often including underdrains. Also called rain gardens and biofiltration.
Media Filter	MF	Filter bed with granular media, typically sand.
High Rate Biofiltration	HRBF	Manufactured devices with high rate filtration media that support plants.
High Rate Media Filtration	HRMF	Manufactured devices with high rate filtration media consisting of a variety of inert and sorptive media types and configurations (e.g., cartridge filters, upflow filters, membrane filters, vertical bed filters).
Hydrodynamic Separation Devices	HDS	Manufactured devices providing gravitational settling using swirl concentrators, screens, and baffles.
Oil/Grit Separators and Baffle Boxes	OGS	Manufactured devices including oil/water separators and baffle chambers designed for removing floatables and coarse solids.
Permeable Friction Course (Overlay)	PF	Open-graded bituminous mixture placed over an impervious road base.
Porous Pavement	PP	Full-depth pervious concrete, porous asphalt, paving stones or bricks, reinforced turf rings, and other permeable surface designed to replace traditional pavement.

Note: Additional BMP types are included in the BMP Database. This table represents BMP types with sufficient data for inclusion in category-level, pollutant concentration focused statistical analysis.

1.2 Performance Analysis Methods

The performance analyses methods in this report are based upon the analysis of distributions of influent and effluent water quality sample concentration data for individual events by BMP category, thereby providing greater weight to those studies for which there are a larger number of storm events monitored and reported. In other words, the performance analysis presented in this technical summary is storm-weighted, rather than equaling weighting each BMP study's results.

To be included in this category-level summary, a minimum of three BMP study data sets must be included in the BMP category, with each BMP study having influent and effluent data for at least three storms. Additional data screening that was applied included the exclusion of base flow water quality samples from BMP studies, exclusion of grab samples for BMPs without permanent pools (i.e., only event mean concentrations [EMCs] are used except for retention ponds and wetland basins, which would tend to have more consistent outflow due to mixing). In addition, due to holding time restrictions, fecal indicator grab samples are included in this analysis. A variety of additional screening criteria have been applied for purposes of category-level analysis to make sure that the data sets and BMP designs are reasonably representative, as documented in the "Monitoring Station" table of the BMP Database. Note that poor pollutant reduction performance of a BMP is not a reason for data exclusion; conversely, there still may be a tendency for researchers to monitor and submit data from well designed and constructed BMPs that are well-performing more often than less well designed and constructed poor-performing BMPs.

1.2.1 Tabular Summaries

For each pollutant analyzed, tabular summaries of data counts for each BMP category, interquartile ranges (i.e., 25th and 75th percentiles), influent/effluent medians, and 95% confidence intervals about the medians are provided. The median and interquartile ranges were selected as descriptive statistics for BMP performance because they are non-parametric (do not require distributional assumptions for the underlying data sets) and are less affected by extreme values than means and standard deviations. Additionally, medians are less affected by assumptions regarding values below detection limits and varying detection limits for studies conducted by independent parties over many years.

Since confidence intervals about the median can still be affected by outliers if simple substitution is used, a robust regression-on-order statistics (ROS) method as described by Helsel and Cohn (1988) was utilized to provide probabilistic estimates of non-detects before computing descriptive statistics. When applying the ROS method, non-detect values are imputed based on their plotting positions relative to the probability distribution estimated from the detected data.

Despite use of this robust method, conclusions regarding BMP performance should carefully consider the influence of large percentages of non-detects. For example, pollutant removals may be found to be statistically insignificant for a BMP, but that BMP may still provide removals at higher influent concentrations. The number of influent and effluent non-detects should be reviewed before making conclusions, particularly for dissolved metals where non-detects are most prevalent. Pollutant-BMP combinations with high percentages of non-detects are identified as part of the tabular summaries.

Confidence intervals in the box plots and tables were generated using the bias corrected and accelerated (BCa) bootstrap method described by Efron and Tibishirani (1993). This method is a robust approach for computing confidence intervals that is resistant to outliers and does not require any distributional assumptions. Comparison of the confidence intervals about the influent and effluent medians can be used to roughly identify statistically significant differences between the central tendencies of the data. As part of this statistical analysis, non-parametric hypothesis tests, including the Mann-Whitney rank sum test and the Wilcoxon signed-rank test, are also completed to provide additional and more robust results for evaluating significant differences between medians (i.e., rejection of the null hypothesis that the medians are equal). The Mann-Whitney test applies to independent data sets, whereas the Wilcoxon test applies to paired influent and effluent data sets (Helsel and Hirsch 1992).

In some cases, the Mann-Whitney and Wilcoxon hypothesis test results produce conflicting conclusions regarding statistically significant differences. Such cases are more likely to occur where there are imbalances in the number of influent and effluent samples for a particular data set because the Mann-Whitney test utilizes the entire data set whereas the Wilcoxon test only utilizes data pairs. For BMPs with short residence times and limited storage, the Wilcoxon hypothesis test results may be more reliable for evaluating whether concentration reductions are statistically significant because the test operates on the individual paired differences of influent and effluent storm event concentrations. For BMPs with long residence times and/or permanent pools (e.g., wet ponds), the paired storm event hypothesis test results relying on the Wilcoxon test may be less reliable than the Mann-Whitney test because of variations in sampling program designs for collection of influent and effluent samples that may not enable accurate event-based pairing of monitoring data. For example, inflow for a storm event on a particular date may mix with water from a previous event that has been stored since the previous storm. Thus, in cases where the Mann-Whitney and Wilcoxon test results conflict for BMPs with larger permanent pools, the Mann-Whitney results may provide a better indicator of concentration reduction performance.

In the summary tables provided in Chapters 2 through 5, the final column (labeled "In vs. Out" provides a concise graphic that conveys the results of three statistical tests used to determine whether the distributions of the influent and effluent pollutant concentrations at a BMP are statistically significantly different. The three tests include:

1. Check for overlap between the 95% confidence intervals of the influent and effluent medians. The absence of overlap indicates the influent and effluent medians are considered statistically significantly different.
2. Mann-Whitney ranked test on the influent and effluent concentration without considering the observations as paired values. When the p-value of this statistics is less than 0.05, the influent and effluent concentrations are statistically significantly different.
3. Wilcoxon ranked-sum test on the influent and effluent concentration that considers only the paired observations. When the p-value of this statistics is less than 0.05, the influent and effluent concentrations are statistically significantly different.

Table 1-3 provides a key for the symbols used in the summary tables to represent test results.

Table 1-3. Symbols Representing Hypothesis Test Results in Summary Tables.

Symbol	Interpretation
▼	Influent and effluent concentrations are statistically significantly different, with effluent concentrations lower than influent concentrations.
◇	Influent and effluent concentrations are not statistically significantly different.
△	Influent and effluent concentrations are statistically significantly different, with effluent concentrations greater than influent concentrations.
NA	Not Available: Hypothesis test could not be performed due to limited data.

Be aware that for some BMP types, a statistically significant difference between influent and effluent concentrations may not be present, but the effluent concentrations achieved by the BMP are relatively low and may be comparable to the performance of other BMPs that have statistically significant differences between inflow and outflow. For example, data sets that have low influent concentrations and similarly low effluent concentration (i.e., clean water in = clean water out) may not show statistically significant differences. However, the BMP could have been effective at higher influent concentrations.

Lastly, this report focuses solely on influent and effluent concentrations and does not characterize influent and effluent loads. For BMPs that provide significant volume reduction, load reductions may still occur in the absence of concentration reductions or even in some cases with an increase in concentrations (e.g., phosphorus export from bioretention systems). Volume-related data can also be retrieved from the BMPDB for independent analysis and have been evaluated in detail in past analyses for some BMP categories. For example, see *International Stormwater Best Management Practices (BMP) Database Addendum 1 to Volume Reduction Technical Summary (January 2011) Expanded Analysis of Volume Reduction in Bioretention BMPs* (Geosyntec and Wright Water Engineers 2012a), accessible at www.bmpdatabase.org.

1.2.2 Graphical Summaries

Side-by-side box plots have been generated using the influent and effluent concentrations from the studies. For each BMP category, the influent box plots are provided on the left and the effluent box plots are provided on the right. A series of notched box plots are provided for each pollutant-BMP combination. The notch in the box plot represents the 95% confidence interval (CI) for the median, with the bottom and top of the box representing the 25th and 75th percentiles of the data set, respectively. A key to the box plots is provided in Figure 1-1.

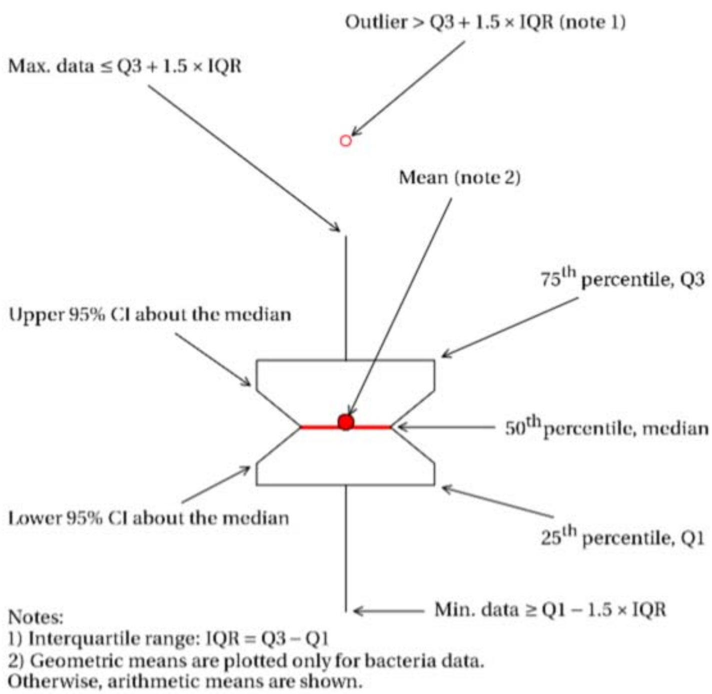

Figure 1-1. Box Plot Key.

1.3 BMP Types Excluded from Analysis or Underrepresented in the BMPDB

This summary report focuses on categories of BMPs with sufficient data appropriate for category-level statistical analysis focused on pollutant concentrations. The BMPDB itself, accessed using tools on the BMPDB website or in the downloadable version of Microsoft Access, has additional BMP types and data sets. Examples of some of these data sets and reasons for exclusion from this summary report include:

- Low Impact Development Sites (site-scale): Several site-scale LID sites are included in the BMPDB. Because LID studies include combinations of practices that are unique to a particular site, these practices are not included in this particular report. Performance of these sites are better evaluated individually and with integration of volume reduction benefits as part of the analysis. Many of the LID studies in the BMPDB monitor both the overall site and individual BMP components. (If individual BMP components are monitored, they are included in this report.)

- Composite (Treatment Train) Sites: Similar to LID studies, several treatment train studies are included in the BMPDB and are also best evaluated individually, given that the combination of practices in these treatment trains may vary significantly. For example, some treatment train studies are combinations of wetland channels followed by ponds, whereas others may be a sedimentation vault followed by a sand filter. Rather than analyzing these combinations as an overall category, they should be evaluated individually or in subcategories with similar unit treatment process combinations.
- Green Roofs: The BMPDB contains green roof studies, but they are excluded from this pollutant concentration-focused statistical analysis because their most significant water quality benefits are related to volume reduction. Because the "influent" is rainfall with relatively low pollutant concentrations, some green roofs have been shown to export some pollutants relative to rainfall water quality; therefore, analysis focused on pollutant concentrations alone can be misleading.
- Rainwater Harvesting: The BMPDB accepts rainwater harvesting studies; however, insufficient studies are available for analysis at the category level. In addition, the primary benefit would be runoff volume reduction, although the storage vessel would result in some pollutant settling.
- Disinfection: Several disinfection practices for the purposes of reducing pathogen and fecal indicator bacteria are included in the BMPDB, but are excluded from this analysis report due to limited data.
- Manufactured Treatment Devices Subcategories: Many types of manufactured treatment devices are included in the BMPDB. This report focuses on several of the most common subcategories. Other unique designs and subcategories are included in the BMPDB, but many have had an inadequate number of studies for inclusion in this report at this time as an analysis category.
- "Other" BMP Types: This category stores performance information for various unique BMP types that do not fit into the established BMPDB categories. These are not included in this report.

Two categories of important, but underrepresented, BMP design variations in the 2020 BMPDB include:

- Engineered Media for Bioretention and Media Filters: An area of current and growing research relates to optimizing filtration media in various stormwater controls such as bioretention (biofilters) and media filters to optimize removal of specific metals, bacteria and other challenging pollutants. Both design configurations and media amendments such as biochar, iron, water treatment residuals, granular activated carbon, zeolite, peat, coconut coir, and other materials are part of this research. A detailed analysis and discussion of this emerging research is not possible at this time due to the limited number of studies and is beyond the scope of this report. As more of these special studies are uploaded to the BMPDB, more detailed analysis and comparisons of these designs will be included in future BMPDB reports. For examples of pertinent research, see Pitt and Clark (2010), Clark and Pitt (2012), Erickson et al. (2012), Chandrasena (2014), Mohanty and Boehm (2015), O'Neil and Davis (2012a; 2012b), Mwabi et al. (2012), Prabhukumar (2013), Mohanty et al. (2018), Isaacson (2019), among many others.
- Subsurface Treatment Wetlands: Subsurface flow wetlands with detention are engineered, below-ground treatment wetlands that include many of the natural treatment processes of surface flow constructed wetlands as well as the filtration mechanisms of media filters. Water flows through a granular matrix, which typically supports the growth of emergent wetland vegetation on the surface. The matrix provides a significant surface area for the filtration of particulate-bound constituents and the growth of bacterial biofilms that metabolize and degrade pollutants. Due to the low treatment flow rates, an equalization basin is typically needed upgradient of the wetlands to

handle peak flows and provide a near constant discharge to the facility. Currently, no subsurface flow wetland performance studies are included in the BMP Database; however, published research is available that suggests that subsurface flow wetlands may be effective at reducing fecal indicator bacteria and reducing nitrogen through denitrification (Kadlec and Knight 1996, U.S. EPA 1993b, Puigagut et al. 2007, Sleytr 2007). Subsurface treatment wetlands are also a practice commonly recommended in many California fecal indicator bacteria total maximum daily load (TMDL) implementation plans (Geosyntec 2010). Implementation of a subsurface flow wetland is dependent on adequate baseflow, which may not be available in all settings, particularly in semi-arid and arid climates (WWE and Geosyntec 2011).

The analysis in this report is limited to urban structural stormwater control practices. In recent years, the BMP Database project has expanded to include a separate stream restoration practices database and an agricultural BMP database. Performance studies in those database modules are not included in this analysis. For more information, see www.bmpdatabase.org.

1.4 Limitations and Recommendations on Appropriate Uses of BMPDB Data

The BMPDB data set can be useful for characterizing the treatment performance for selected BMP categories. However, the number of studies and number of storm events monitored should be closely reviewed when assessing the reliability of the summary statistics provided. When possible, a closer investigation of the underlying data sets is encouraged. Additional screening of studies or particular monitoring periods may be warranted in some cases. For example, a researcher may choose to focus on a subset of the data with influent concentrations comparable to those expected for their site or region, particularly given the relatively low influent concentrations present in the BMPDB for certain BMP-analyte concentrations.

For certain data sets such as dissolved metals, the number of non-detects may introduce potential statistical bias into summary statistics. The BMPDB analysis uses the ROS substitution method to minimize this bias; however, other approaches may be used. Statistics that quantify the variability or uncertainty of the data set may be particularly affected by a high number of non-detects.

Submittal of performance data to the BMPDB by researchers is voluntary; therefore, novel BMP designs and technological advances may not be included in the database.

Although the reporting protocols for the BMP Database request information on operation and maintenance, this metadata is not always provided. Studies included in this analysis have not been screened into categories of well-maintained or poorly maintained practices. Additional metadata analysis could be considered as part of a future analysis effort. As a companion project to the BMP Database, a BMP Operations and Maintenance database has been developed, given that many communities track BMP maintenance, but may not conduct performance monitoring. See *Recommended Operation and Maintenance Activity and Cost Reporting Parameters for Stormwater Best Management Practices Database* (Clary et al. 2018, accessible from www.bmpdatabase.org) for more information.

Finally, researchers may choose to download the BMPDB and apply more restrictive or less restrictive screening criteria to the data sets in the BMPDB for purposes of their own analysis.

1.5 Pollutant Reduction Versus Pollutant Removal

The performance of stormwater BMPs is commonly discussed in terms of “pollutant removal” in engineering and scientific literature, as well as some discharge permits, and this convention is used throughout this report. The authors recognize that the term “pollutant reduction” is technically more accurate in most cases. For example, pollutants that are immobilized through sedimentation and filtration can be resuspended or remobilized under some circumstances. In other cases, pollutants may be transformed into other forms or sample fractions under various oxidation-reduction conditions. To avoid potential confusion with the chemical processes associated with oxidation-reduction and reduced forms of pollutants, the phrase “pollutant removal” is retained in this report.

CHAPTER 2

Solids

As of 2020, the U.S. Environmental Protection Agency (EPA) has identified over 138,000 miles of stream as threatened or impaired due to sediment-related causes. Over 5,960 streams and lakes are listed as impaired due to sediment (U.S. EPA 2020). Excessive sediment can adversely impact aquatic life and fisheries, source waters for drinking water supplies, and recreational uses (U.S. EPA 1999). Fine particulates also often carry other pollutants such as heavy metals (e.g., lead, copper, zinc), PCBs, PAHs, dioxins, phthalates, and other pollutants. Therefore, removal of suspended solids from runoff can also reduce sediment-bound pollutants.

Dissolved solids can also be a concern for many receiving waters located in cold weather climates where road salts are applied or in arid climates where evaporation is high. Reduction of dissolved solids concentrations in stormwater runoff is challenging.

This performance analysis focuses on two types of solids: total suspended solids (TSS) and total dissolved solids (TDS). Sources of solids, removal mechanisms, a BMP performance summary and a discussion of performance findings is provided in this chapter.

Basic Solids Terminology

Adapted from U.S. EPA 1999; EWRI 2010; Roesner, Pruden and Kidner 2007; USGS 2020.

Adsorption: Adsorption is the adhesion of atoms, ions or molecules from a liquid to a surface via a loose electrical bond.

Flocculation: The process by which suspended colloidal or very fine particles combine into larger masses.

Gross Solids: Litter, trash, leaves, and coarse sediment that travel either as floating debris or as bedload in urban runoff conveyance systems.

Organic Matter: Plant and animal residue at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population.

Sediment: Material in suspension in water or recently deposited from suspension. In the plural, the word is applied to all kinds of deposits in waterbodies.

Suspended Sediment Concentration (SSC): A measure of sediment suspended in the water column resulting from analytical methods that use the entire water sample (i.e., ASTM D3977-97(B)). This method is recommended by the USGS.

Total Dissolved Solids (TDS): A measure of solids in the water column that pass through a 0.45 to 2 µm membrane filter. EPA's operational definition of "dissolved" includes particles less than 0.45 µm.

Total Suspended Solids (TSS): A measure of solids suspended in the water column that is commonly used to refer to results from a variety of test methods for suspended sediment. The term is most correctly applied to analytic methods that use a subsampling technique for analysis (i.e., EPA 160.2, SM 2540D).

2.1 Sources

A wide range of solids types can be found in stormwater. Although this chapter focuses on TSS and TDS, it is first important to understand how solids are classified in the context of urban stormwater runoff.

2.1.1 Types of Solids

Solids in urban stormwater have been classified by size using various approaches. Figure 2-1 provides a solids classification approach illustrating the types of solids by size in runoff (adapted from Roesner, Pruden, and Kidner 2007). A dashed line at 0.45 µm has been included in the figure because TDS may be defined by particles passing through a membrane filter with a pore size of 0.45 µm to 2 µm, depending on the method used.

In the context of stormwater, the primary concern has traditionally been the fine solids fraction because these particles have relatively more surface area and tend to be more associated with other pollutants of concern that adsorb to these particles. Fine particles can also cause impairments to receiving waters through nuisance turbidity and siltation of aquatic habitat (e.g., filling in gravels that salmonids use for spawning). Whereas most particles with diameters greater than 75 µm and densities similar to sand are easily removed through sedimentation and filtration in stormwater BMPs, fine particles and dissolved solids are more challenging to remove.

Sediment concentrations in urban stormwater are commonly reported as “TSS”; however, this generic term may actually reflect results from analytical methods that measure different fractions of suspended sediment. Although the majority of the sediment data in the BMP Database is reported as “TSS”, suspended solids concentration (SSC) is also reported for some studies.

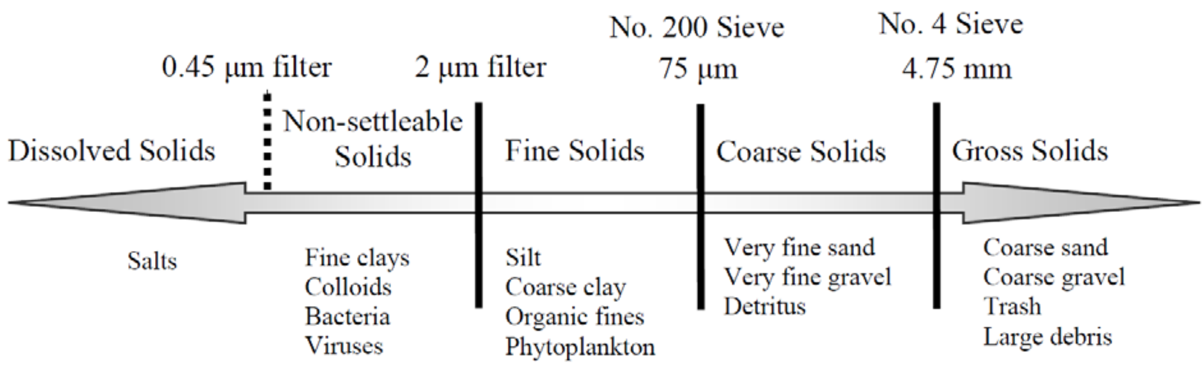

Figure 2-1. Solids Classification Scheme.

Geosyntec and WWE 2011, adapted from Roesner, Pruden, and Kidner 2007.

TDS is made up of inorganic salts, as well as a small amount of organic matter. Inorganic salts found in stormwater typically consist of cations such as calcium, magnesium, potassium and sodium, and anions such as carbonates, nitrates, bicarbonates, chlorides and sulfates. Available data for TDS are included in this analysis.

Although not included in this analysis, gross solids are the litter, trash, leaves, and coarse sediment that travel either as floating debris or as bedload in urban runoff conveyance systems. A variety of BMPs are designed to remove gross solids, including sediment basins, baffle boxes, hydrodynamic separators, oil/grit separators, modular treatment systems, and inlet traps, among others. The removal of gross solids is important. For example, concern about ocean plastics has resulted in communities implementing practices to control gross solids. Although the BMPDB can accommodate performance data related to gross solids, there is limited information currently included in the BMPDB and it is not currently analyzed.

Other solids measures included in the BMPDB include total solids, total volatile solids (TVS), total volatile suspended solids (TVSS) and others that may be reported with BMP monitoring studies. Total solids (also referred to as total residue) is the term used for material left in a container after evaporation and drying of a water sample. Total solids include both TSS (the portion of total solids retained by a filter) and TDS (the portion that passes through a filter). Note that the filter size may range from 0.45 µm to 2 µm, so the distinction between TSS and TDS may vary depending on the lab or field method.

Additionally, characteristics such as particle size distribution and associated settling velocity distributions are also important information for characterizing sediment in runoff and the potential for its removal by BMPs; however, this information is often not reported as part of urban stormwater monitoring. More detailed discussion of analytical issues related to sediment can be found in a variety of references (EWRI 2009; Geosyntec and WWE 2009; Clark and Siu 2008; Bent, Gray, Smith, and Glysson 2000).

2.1.2 TSS

Sediment is naturally present to varying degrees in receiving waters and runoff; however, both urban and agricultural human activities can increase sediment loads to levels that impact aquatic life and other beneficial uses of waterbodies. Sources of sediment in urban runoff include construction activities, denuded landscape areas, road sanding, decaying leaves or other organic matter (detritus), metallic dust from car brakes or engines, tire fragments, erosion of hillslopes, dust from atmospheric deposition (either directly deposited or carried by rain), and a variety of other human and natural sources. Accelerated stream channel erosion is also common in urban areas due to increased flow rates and concentration of flows, durations and volumes from urban runoff, with the extent of erosion varying based on site-specific factors. Biological growth, such as algae blooms and iron oxidizing biofilms, within stormwater infrastructure may also contribute to TSS concentrations and overall solids loadings to receiving waters. Algae can become a seasonal issue in wetlands and wet ponds receiving nutrient-rich inflows and can contribute to export of organic solids during these blooms. Biofilms can be an issue in areas with groundwater intrusion and can lead to clogged filters, orifices, and small valves.

Sediment is a key constituent of interest from a water quality perspective not only due to the physical impact that it can have on aquatic life and aesthetics, but also because sediment in urban runoff is often associated with other pollutants. For example, phosphorus, pesticides, non-polar organics, and metals such as copper, zinc, cadmium, chromium, lead, and nickel may adsorb onto the surface of sediment, especially to clay and organic particles in runoff (Chebbo and Bachoc 1992; Muthukaruppan, Chiew and Wong 2002; Roesner, Pruden, and Kidner 2007). As particles decrease in size, they have a higher ratio of surface area to mass, so smaller particles generally have a higher capacity for adsorbing heavy metals and nonpolar organics (Krein and Schorer 2000; Roesner, Pruden and Kidner 2007). However, large particles comprised of organic materials may also have high concentrations of associated pollutants in some cases. Ellis and Revitt (1982) found that particles smaller than 100 µm (15% of the total sampled mass) carried 70% of the metal pollution.

2.1.3 TDS

From a stormwater runoff perspective, the primary concern related to TDS is transport of road salt used for deicing in cold climates. Aside from deicing runoff, TDS concentrations for various land uses (Table 2-1) are typically well below regulatory benchmarks such as 500 mg/L TDS as a Secondary Drinking Water Standard.

TDS is a gross index for solids that are generally less than 0.45 to 2 µm and therefore can include much of the colloidal fraction of total solids concentration. TDS includes inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates) and typically some amount of dissolved organic matter. Because TDS includes both negative and positive ions, the source of TDS is not always readily apparent without additional water quality characterization data. Stormwater in contact with calcium and magnesium-rich soils could be high in TDS as could stormwater and snowmelt exposed to chloride-based road salt and synthetic deicing materials, such as calcium magnesium acetate (Strecker et al. 2005). In arid regions, evaporation rates are high and salts can build up in soils and stormwater green infrastructure. When rainfall does occur in these arid regions, TDS concentrations in surface water and groundwater can become elevated due to dissolution of these accumulated salts as stormwater passes through the soil matrix. Sansalone et al. (1997) found that dissolved solids typically exhibit a stronger first flush than suspended solids, regardless of rainfall intensity or flow. Sansalone et al. (1998) confirmed this observation, as dissolved solids first flush strength was higher than suspended solids, and total solids displayed a weaker first flush effect during low rather than high flow rate events.

NCHRP Research Report 918 (National Academies 2019) summarized land use water quality data for TDS by combining data from the Highway Runoff Database version 1.0.0a (Smith and Granato 2010), the National Stormwater Quality Database version 4.02 (posted on the BMP Database website), and influent concentrations from the BMPDB. The summary statistics are shown in Table 2-1. The range of TDS concentration across land uses are similar, with highway land uses slightly lower. This indicates that the source of TDS in stormwater is not directly associated with land use and may be more associated with site-specific soils and localized activities (e.g., road sanding and salting). In NCHRP Synthesis 449, the Transportation Research Board indicates that proactive mitigation strategies (i.e., source controls) are currently the most commonly used methods for reducing the footprint of chloride roadway deicers (National Academies of Sciences 2013).

Table 2-1. TDS Concentrations Based on Land Use in mg/L.

Land Use Category	Number of Sites/Samples (% non-detect)	Median Concentrations (25th to 75th Percentiles) mg/L
Highway	47/918 (4%)	58.0 (32.0-98.0)
Commercial	55/887 (1%)	75.0 (49.5-122)
Industrial	49/619 (7%)	101 (53.0-204)
Institutional	3/49 (0%)	88 (58.0-132)
Residential	115/1566 (<1%)	78.0 (50.0-132)
Open Space	24/336 (<1%)	77.9 (46.8-130)

2.2 Summary of Removal Mechanisms

Effective removal of solids from urban runoff by stormwater BMPs is determined by both the unit treatment processes present in the BMP and the characteristics of solids in the urban runoff. A discussion of these factors follows, along with recommendations for BMP design where solids removal is an objective.

2.2.1 Dominant Removal Mechanisms for TSS

Dominant removal mechanisms for suspended sediment include sedimentation and filtration. Both processes are enhanced by coagulation and flocculation.

Sedimentation is the process in which particulates settle to the bottom of a water column. Sedimentation is affected by gravitational force, buoyancy, and drag force. The settling velocity is dependent upon the density differences between the fluid and the particle, the viscosity of the fluid which is a function of temperature, as well as the diameter and shape of the particle temperature (Gibbs et al. 1971). All of these tend to be highly variable when stormwater particles are considered. This variability is critically important to the performance of sedimentation processes in stormwater BMPs. For a given sample of stormwater having a range of particles of equal density and shape, the particles of 50 µm diameter will settle 100 times as fast as those of 5 µm diameter, all other factors being equal. Since stormwater typically has suspended particles both smaller than 5 µm and larger than 50 µm, the particle size distribution is a key factor when selecting and designing stormwater BMPs.

Media filtration removes sediment by directing the influent through a bed of media, which may be composed of materials such as sand, peat, compost, zeolite, engineered media, activated carbon, or mixtures thereof. Filtration of stormwater involves a number of physical and chemical mechanisms, which, depending on the filter media, may include (Metcalf and Eddy 2013):

- Straining
- Sedimentation
- Impaction
- Interception
- Adhesion
- Flocculation
- Chemical Adsorption
- Physical Adsorption
- Biological Growth

Filters are designed to remove particulate matter either on the surface of the filter through surficial straining or within the filter through depth filtration. The buildup of particles either on the filter surface as a cake layer or within the filter media can result in a significant increase in head loss, drastically decreasing the potential flow rate of a filter system. In centralized water and wastewater plants, bed filters are cleaned through regular backwashing, but this is usually impractical in stormwater treatment systems. Instead, the surface of stormwater bed filters must be regularly raked to break up surface crusts or be well vegetated to maintain flow pathways along plant stems and roots. Note that these preferential flow pathways can result in short-circuiting of the media and reduced adsorption of other pollutants. If depth clogging occurs, the media must be replaced (or backflushed, if possible). To reduce the frequency of media replacement, sedimentation pre-treatment is generally recommended for all stormwater filtration systems.

Although coagulation and flocculation are not removal mechanisms themselves, they are processes that can improve the performance of filtration and sedimentation. Coagulation/flocculation processes in stormwater can be grouped as active and passive. Active coagulation/flocculation processes involve the controlled addition of a coagulation agent or electricity (i.e., electrocoagulation) followed by mixing (both to distribute the coagulation agent and promote fluid shear), and finally sedimentation and/or filtration. Such processes are routinely used in water and wastewater treatment systems and have become more common for stormwater treatment at construction sites and in some cases, industrial sites. However, for post-construction stormwater treatment, use of active coagulation/flocculation systems has been relatively limited due to the need for active management and monitoring of chemical/energy addition and associated equipment, as well as concerns about potential toxicity of some coagulating agents, which are not allowed in some states.

Passive coagulation/flocculation has been observed to occur in BMPs due to the presence of natural coagulating agents in BMP soils such as aluminum and iron salts and calcium. These agents may be naturally occurring or added as soil amendments. Additionally, in wet ponds and lakes, some researchers have observed that natural polymers produced by bacteria can also facilitate coagulation/flocculation. These processes are believed to occur quite slowly and are highly dependent on environmental factors and water chemistry; therefore, they are not considered to be dominant removal mechanisms in most stormwater BMPs (Dugan 1975; Minton 2005).

2.2.2 Dominant Removal Mechanisms for TDS

Treatment mechanisms for TDS are very limited and typically rely on some form of active treatment depending on the nature of the mineral salts and dissolved organic matter that comprise the mass of dissolved solids in solution. Treatment options primarily include evaporation, precipitation, or reverse osmosis. However, adsorption and coagulation/flocculation followed by sedimentation or filtration may be effective for some fractions of TDS.

2.2.3 Factors Affecting Removal Mechanisms

Some of the basic stormwater characteristics and environmental conditions influencing dominant removal mechanisms of solids include:

- **Temperature:** Temperature has a substantial impact on settling velocities of stormwater particles, with settling velocities decreasing as temperature decreases (Gibbs et al. 1971). The viscosity of the water more than doubles as the temperature declines from 80°F to near freezing. In Stokes' formulation, such a temperature change has the effect of reducing the settling velocity by half, making sedimentation a much less effective process in cold water situations.
- **Particle Size Distribution:** Particle size distribution refers to the relative percentage of particles present (by volume or weight), with respect to particle size, typically sorted by size. Particle size is an important factor affecting sedimentation processes in terms of particle settling velocities (Gibbs et al. 1971) and it also affects whether a particle can be effectively removed by filtration. Generally,

with densities being equal, larger particles are more easily removed than smaller particles. Particle size distributions may change during and between events (Kim and Sansalone 2008). These changes may result from differences in antecedent dry period, rainfall intensity, rainfall duration, vegetation density, watershed sources contributing runoff, and other factors. Such changes in particle size distributions likely explain some of the observed variations in TSS effluent concentrations from BMPs. For more information on particle size distribution research and the large ranges in the masses associated with measured grain sizes in runoff sediments from storm to storm and site to site, see Granato (2013), Kim and Sansalone (2008), Sansalone and Tribouillard (1999), Li et al. (2006), Smith and Granato (2010) Selbig and Bannerman (2011) and others.

- **Density:** Particle density has a substantial impact on particle settling velocity. The density frequently used to estimate particle settling velocity is 2.65 g/cm^3, which is equivalent to the density of quartz. In a literature review, Karamelegos et al. (2005) found that densities of particles in stormwater ranged from 1.1 to 2.86 g/cm^3, with the most common values in the 1.4 to 1.8 g/cm^3 range. Different particle size classes would be expected to have different densities due to variation in the percent of organic matter and changes in mineralogy or the anthropogenic materials (i.e., copper brake pad wear vs. tire-wear particles). The metal particulates in runoff will settle more rapidly than quartz particles of equivalent size and shape because the densities of commercial-grade metals are larger (Granato 2013). Similar to findings related to particle size distribution, it is expected that the densities also would vary from event to event based on pre-storm soil saturation levels, rainfall characteristics (e.g., intensity, depths, and duration), season, vegetative canopy, the contributing watershed areas and other environmental factors. The reported sediment density values in the literature, which vary considerably, indicate that the settling velocities of runoff sediments will also vary considerably (Granato 2013).
- **Charge:** As particle size decreases, the importance of electric charge on sediment particles increases. Clay particles, in particular, tend to have charged surfaces. These particles are aluminosilicates, and are therefore different in chemical structure than sand. Because clays are less than 2 µm in size and have this flat structure, the ratio of surface area to mass is very large; therefore, the effects of electrical charge dominate for these particles. If free cations such as dissolved metals are present in the water column, they will readily absorb to the clay particle surfaces until the electric charge is balanced. However, if free cations are not present, the net negative charge and small mass will cause the clay particles to repel each other in water and disperse, forming a colloid. These colloids typically must be destabilized by coagulation before they can be removed via sedimentation or filtration.

2.3 Performance Data Summary for TSS and TDS

Analysis for solids focused on total suspended solids (TSS) and total dissolved solids (TDS). Other solids can also be retrieved and analyzed through the BMPDB. Tables 2-2 and 2-3 provide influent/effluent summary statistics for TSS and TDS, respectively. Figures 2-2 and 2-3 provide graphical representations of these data.

Table 2-2. Influent/Effluent Summary Statistics for TSS (mg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	44; 575 (0.7%)	46; 611 (0.7%)	24.4 - 131	10.0 - 49.0	65.1 (57.0, 74.0)	22.0 (17.1, 22.5)	▼▼▼
Retention Pond	72; 1199 (1.1%)	74; 1191 (3.0%)	15.0 - 150	5.00 - 32.9	49.0 (41.0, 54.0)	12.0 (11.0, 13.0)	▼▼▼
Wetland Basin	31; 601 (0.3%)	30; 563 (3.0%)	14.0 - 89.0	4.69 - 32.0	35.5 (29.7, 40.0)	14.0 (11.5, 15.2)	▼▼▼
Wetland Channel	15; 269 (0.0%)	13; 219 (0.0%)	14.0 - 81.0	10.0 - 70.5	25.7 (20.5, 32.0)	24.0 (17.0, 28.0)	◇◇▼
Grass Swale	35; 582 (0.2%)	40; 656 (0.3%)	10.4 - 62.0	6.00 - 34.7	26.0 (22.0, 28.1)	13.7 (12.0, 14.9)	▼▼▼
Grass Strip	52; 920 (0.1%)	52; 711 (2.8%)	24.0 - 95.0	10.0 - 49.0	48.0 (43.0, 50.0)	23.0 (20.0, 24.0)	▼▼▼
Bioretention	43; 840 (0.0%)	41; 685 (5.3%)	16.0 - 119	4.00 - 20.0	44.0 (38.0, 48.0)	10.0 (8.00, 10.0)	▼▼▼
Media Filter	35; 533 (0.6%)	39; 563 (8.7%)	19.6 - 105	2.82 - 18.6	44.0 (37.0, 49.1)	7.20 (6.00, 8.00)	▼▼▼
HRBF	6; 104 (0.0%)	6; 104 (1.0%)	15.8 - 55.2	2.5 - 6.0	30.8 (21.0; 35.2)	3.80 (3.00; 4.15)	▼▼▼
HRMF	18; 392 (0.5%)	18; 392 (3.8%)	20.0 - 100	8.15 - 32.6	44.0 (37.0, 53.5)	18.0 (15.0, 19.0)	▼▼▼
HDS	27; 488 (0.4%)	27; 452 (1.1%)	26.6 - 162	15.9 - 87.0	63.9 (56.6, 73.0)	39.0 (33.0, 43.8)	▼▼▼
OGS	16; 261 (0.4%)	16; 216 (1.9%)	11.0 - 88.0	4.38 - 44.2	36.0 (27.8, 42.0)	15.5 (11.2, 19.1)	▼▼▼
PFC	NA	6; 135 (0.0%)	NA	6.00 - 16.5	NA	9.00 (8.00, 10.0)	NA
Porous Pavement	16; 483 (0.8%)	24; 402 (2.2%)	23.0 - 226	10.1 - 43.9	77.0 (63.0; 90.0)	22.0 (18.0; 23.5)	▼▼▼

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

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

Table 2-3. Influent/Effluent Summary Statistics for TDS (mg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range ($25^{th} – 75^{th}$ %)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	14; 156 (0.0%)	14; 140 (0.0%)	65.6 - 193	65.1 - 192	109 (85.9; 130)	110 (83.5; 120)	◇◇◇
Retention Pond	16; 169 (0.0%)	16; 156 (0.0%)	69.0 - 180	78.3 - 364	122 (100; 130)	178 (158; 206)	△△△
Wetland Basin	5; 65 (1.5%)	5; 38 (2.6%)	77.0 - 197	92.0 - 238	127 (84.7; 152)	149 (92.0; 168)	◇◇△
Wetland Channel	7; 103 (0.0%)	7; 100 (1.0%)	194 - 670	216 - 695	389 (284; 482)	391 (270; 486)	◇◇◇
Grass Swale	14; 161 (0.0%)	13; 130 (0.0%)	48.0 - 102	44.8 - 123	76.5 (64.0; 79.0)	80.0 (67.0; 84.0)	◇◇◇
Grass Strip	34; 617 (5.8%)	33; 433 (3.2%)	28.0 - 96.0	50.0 - 120	56.0 (50.0; 56.0)	82.0 (74.0; 84.0)	△△△
Bioretention	4; 139 (0.0%)	7; 77 (0.0%)	30.1 - 141	61.7 - 541	58.8 (46.2; 68.5)	210 (175; 298)	△△◇
Media Filter	15; 196 (4.1%)	16; 193 (2.1%)	24.0 - 80.0	44.0 - 134	45.7 (37.0; 52.0)	75.7 (58.0; 89.2)	△△△
HRMF	6; 171 (45.0%)	6; 171 (43.3%)	31.5 - 75.0	28.2 - 75.0	47.6 (41.3; 51.1)	46.0 (38.9; 50.9)	◇◇◇
HDS	5; 106 (3.8%)	5; 105 (1.9%)	74.0 - 1,560	64.0 - 2,830	183 (110; 224)	208 (94.0; 238)	◇◇△
Porous Pavement	NA	3; 43 (0.0%)	NA	968 - 4,740	NA	2,300 (1,110; 3,080)	NA

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

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

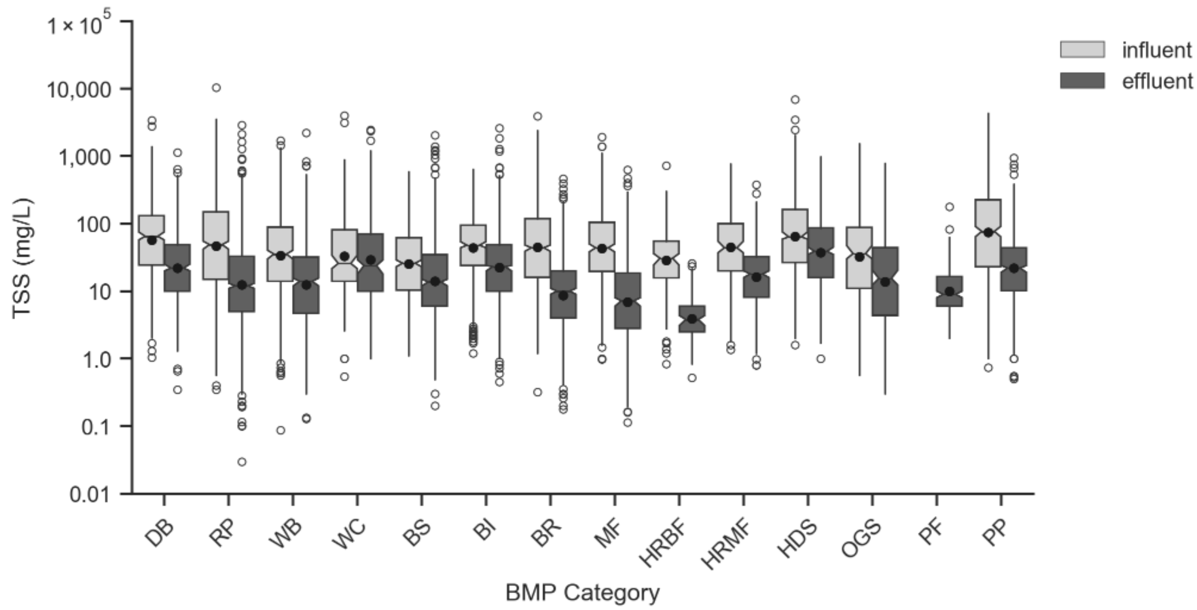

Figure 2-2. Box Plots of Influent/Effluent TSS (mg/L).

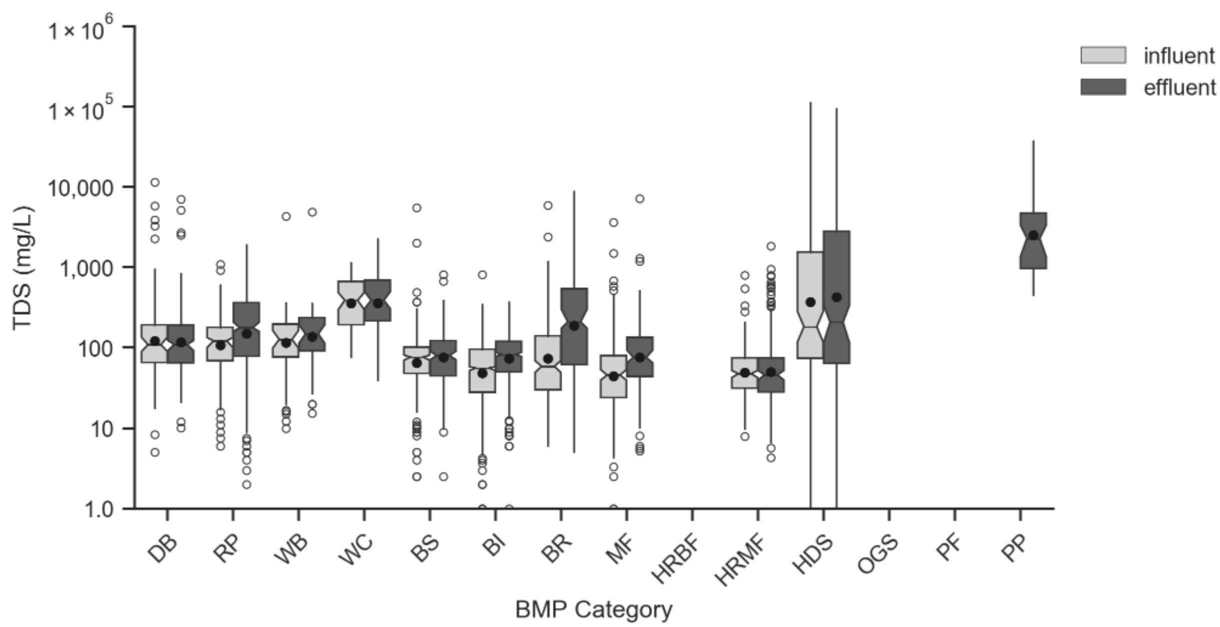

Figure 2-3. Box Plots of Influent/Effluent TDS (mg/L).

2.4 Summary of Findings for TSS and TDS

All of the BMPs included in the sediment analysis generally performed well with respect to TSS, both in terms of statistically significant pollutant removal and relatively low effluent concentrations. Conversely, no BMPs showed statistically significant removal of TDS, while filter strips, media filters and retention ponds showed increases in TDS effluent concentrations. Primary observations for TSS include:

- Median influent TSS concentrations generally range between 26 and 77 mg/L.
- All BMPs with sufficient data for analysis show statistically significant reductions.
- The best performing BMPs are bioretention, media filters, and high rate biofiltration with effluent TSS concentrations ranging from 4 to 10 mg/L.
- Retention ponds and wetland basins performed similarly with effluent TSS concentrations in the 12-14 mg/L range.
- Median influent concentrations for TSS varied considerably, with detention basins, porous pavement and hydrodynamic separators treating more elevated influent TSS relative to several other BMP categories. This observation is not a function of BMP type; it is simply an observation that some BMP categories had relatively clean influent, which may be related to land use or level of source control. This may affect interpretation of statistical tests. For example, out of the three statistical tests, only the Wilcoxon signed-rank test showed statistically significant reduction of TSS for wetland channels; however, the median inflow TSS was already relatively low at 26 mg/L.

Primary observations for TDS include:

- TDS data are more limited than TSS data for many BMP types.
- No BMP with sufficient data has statistically significant concentration reductions for TDS. Furthermore, retention ponds, wetland basins, grass strips, media filters, and hydrodynamic separators increase TDS.
- The HDS category had unusually high concentrations of TDS, which were also highly variable. Further review of the underlying studies in this category indicated the statistics are influenced by a USGS study at a city maintenance yard in Madison, WI. Waschbusch (1999) reports that the site may have unique conditions, particularly the presence of road sand and salt piles close to the system inlet. The Madison site's median inflow TDS was 3,858 mg/L, whereas median influent concentrations at the other three sites ranged from 44 to 118 mg/L.
- Without advanced treatment, volume reduction is likely the only effective method for reducing TDS loads to surface receiving waters, based on the BMP types currently analyzed in the BMPDB. Note that for mobile TDS fractions (i.e., road salt), volume reduction due to infiltration may cause groundwater or interflow issues; therefore, identification of potential source controls is particularly important for TDS.

As this analysis shows, stormwater managers have a broad range of options for reducing TSS concentrations in urban runoff. BMPs that provide sedimentation and filtration processes and are well designed, installed and maintained are expected to provide good removal of TSS. In general, these mechanisms are anticipated to be more effective if linked together in a treatment train (i.e., sedimentation followed by filtration) and as the hydraulic residence time increases for each. Hydraulic residence can be increased in wetlands and ponds by increasing flow paths through the use of berms, baffles, and dense vegetation, as well as multi-stage outlet structures, such as perforated risers. In media filters and bioretention, increasing bed thickness and evenly distributing flows would likely improve performance. Outlet control would also be expected to increase performance by minimizing short circuiting and increasing residence times. For infiltration-oriented BMPs, maintenance is critical to prevent clogging from sediment build-up. Designing BMPs to minimize scour and resuspension of deposited sediment is important, along with ensuring appropriate long-term maintenance to remove accumulated sediment.

As would be expected, TDS data available in the BMP Database to date (which are relatively limited) indicate that TDS removal in stormwater BMPs is challenging at best; therefore, BMPs that provide volume reduction benefits may be the best general strategy for reducing TDS. In this regard, it is noteworthy that neither bioretention nor porous pavement had adequate data sets for inclusion in performance analysis for TDS. Impacts to groundwater must be carefully considered for any location where infiltration of high TDS stormwater is proposed.

CHAPTER 3

Fecal Indicator Bacteria

As of 2020, EPA has identified over 187,000 miles of stream as threatened or impaired due to "pathogens", based on the presence of elevated fecal indicator bacteria. Pathogens are the top cause of stream impairments nationally, with 9,874 impairment listings for streams and lakes (U.S. EPA 2020).

Enterococcus, *E. coli* and fecal coliform are the three fecal indicator bacteria included in this analysis. EPA's currently recommended recreational water quality criteria include enterococcus or *E. coli* (U.S. EPA 2012). Although fecal coliform is no longer recommended by EPA as a fecal indicator in its recreational water use criteria, some states still include fecal coliform in regulations, as do many TMDLs.

3.1 Types of Fecal Indicator Bacteria and Background on Recreational Water Quality Criteria[1]

Both internationally and in the U.S., epidemiological and other health studies form the basis for Recreational Water Quality Criteria based on the risk to swimmers of contracting disease from exposure to water containing a specified number of microorganisms (IAWPRC 1991, Jin et al. 2004, U.S. EPA 2012). EPA initially released Recreational Water Quality Criteria in 1976, updated the criteria in 1986, and most recently updated the criteria in 2012. The Recreational Water Quality Criteria include numeric criteria for fecal indicator bacteria that are intended to be indicative of health risks associated with recreational use. The overall goal of the criteria is to provide public health protection from gastroenteritis (i.e., gastrointestinal illness) associated with exposure to fecal contamination during water-contact recreation. These criteria have evolved over time; therefore, there is variation among the criteria adopted by various states as water quality standards. EPA relies on fecal indicator bacteria, as opposed to pathogens, as the basis of water quality criteria because fecal indicator bacteria are easier to identify and enumerate in water quality samples than the broad range of pathogens in human and animal feces.

Basic Bacteria/Pathogens Terminology

Adapted from U.S. EPA 2001 in WWE and Geosyntec 2010.

Fecal Indicator Bacteria: Bacteria present in the intestines or feces of warm-blooded animals that are used to indicate the potential presence of other organisms such as pathogenic bacteria and viruses. Fecal indicator bacteria are more easily sampled/measured as opposed to monitoring for the many individual pathogens potentially present in receiving waters.

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

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

***Escherichia coli* ("*E. coli*") and enterococcus:** Subgroups of fecal coliform bacteria that are part of the normal intestinal flora in humans and animals; used as indicators of fecal contamination in the 2012 EPA Recreational Water Quality Criteria.

***E. coli* O157:H7:** A specific enteropathogenic strain of *E. coli* that can cause serious infection resulting in gastroenteritis. Presence of the *E. coli* subgroup does not necessarily mean that this pathogenic strain of *E. coli* is present.

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

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

[1] Portions of this background summary have been condensed from the 2014 EWRI publication *Pathogens in Urban Stormwater Systems* (Clary et al. 2014), which in turn included information from WWE and Geoysntec (2010).

EPA provides two equally acceptable options for recreational water quality criteria based on allowable illness rates, as shown in Table 3-1. (See U.S. EPA [2012] for a more detailed explanation on interpreting allowable illness rates.) Recommendations for secondary contact (e.g., fishing, some boating) are not included in the Recreational Water Quality Criteria; however, many states have secondary contact standards, typically set at five times the primary contact standard.

Table 3-1. Summary of EPA's Currently Recommended Recreational Water Quality Criteria.

Source: U.S. EPA 2012.

Fecal Indicator Bacteria	Recommendation 1 (Est. Illness Rate 36/1,000)		Recommendation 2 (Est. Illness Rate 32/1,000)	
	Geometric Mean (cfu/100 mL)	Statistical Threshold Value (cfu/100 mL)	Geometric Mean (cfu/100 mL)	Statistical Threshold Value (cfu/100 mL)
Enterococci (marine and freshwater)	35	130	30	110
E. coli (freshwater)	126	410	100	320

Note: Allowable exceedance frequency is 10% for the Statistical Threshold Value and 0% for the geometric mean. The recommended assessment period is 30 days. Criteria shown are for culture-based test methods.

Although EPA's criteria are based on fecal indicator bacteria, human pathogens in surface water include viruses, bacteria, protozoa, and parasitic worms. The primary concern with regard to pathogens in surface waters is incidental human ingestion of contaminated water during recreational contact with the water, resulting in illness. Enteric pathogens are the group of microorganisms that result in enteric (or gastrointestinal) diseases. Most microbes that inhabit the intestines are harmless, or even beneficial. Others are harmless in normal individuals but can produce disease in the very young, those with weakened immune systems, or in a new host that has no prior exposure to the microbe (U.S. EPA 2009).

Although many different types of pathogens may exist in surface water from both natural and human sources, the World Health Organization and the U.S. Centers for Disease Control have identified a short list of pathogens expected to be responsible for over 97% of non-foodborne illness. This list includes norovirus, adenovirus, rotavirus, *Cryptosporidium* spp., *Giardia lamblia*, *Campylobacter jejuni*, *Salmonella enterica* and *E. coli* O157:H7. Similar to the list above, the primary focus of recent quantitative microbial risk assessment (QMRA) research (Soller et al. 2010a; Ashbolt et al. 2010; Soller et al. 2016) in the context of recreational illness includes these "reference" pathogens: norovirus, *Cryptosporidium* spp., *Giardia lamblia*, *Campylobacter jejuni*, *Salmonella enterica* and *E. coli* O157:H7 (U.S. EPA 2010). These pathogens are considered representative of the transport and fate of other pathogens potentially of concern from the waterborne route of exposure (Ferguson et al. 2009) and have corresponding dose-response relationships in the peer-reviewed literature (Soller et al. 2010a). Research also continues regarding the risks associated with various sources of fecal contaminations (Soller et al. 2010b; Soller et al. 2014).

For urban stormwater managers, a significant question remains regarding the role of stormwater (and nonpoint sources) in recreational waterborne illnesses, since most of the epidemiological research to date has focused on sanitary-impacted locations or at locations where the role of stormwater was not specifically quantified. Wade et al. (2003) conducted an extensive review of the available studies to determine the relationship between recreational water quality, exposure and health effects and found that less than 5% of these studies provided adequate data on the pertinent variables related to the sources of the microorganisms. Since that time, a three-year wet weather surfer health study in California (Schiff et al. 2016) found a relationship between increased health risk and water quality conditions during wet weather, but that relationship predicted less risk than allowed by EPA guidelines (Table 3-1). Thus, scientific questions remain regarding the specific sources of pathogens causing elevated human health risk in recreational waters in non-sewage related studies.

3.2 Sources

Sources of pathogens and fecal indicator bacteria in MS4s and receiving waters vary widely, originating from both animal and human sources. Table 3-2 provides a summary of potential fecal indicator bacteria sources. Although some of these sources can be controlled to an appreciable extent (e.g., wastewater discharges, illicit connections), other sources are much more difficult to control. These diffuse and often mobile sources include wildlife such as raccoons, beavers, birds, etc., as well as environmental sources, such as the biofilms, organic debris and sediments which can provide a stable habitat for these organisms to reproduce.

Table 3-2. Potential Sources of Fecal Indicator Bacteria and Pathogens.

WWE and Geosyntec 2016, as adapted from Armand Ruby Consulting 2011.

General Category	Source/Activity
Municipal Sanitary Infrastructure (piped)	Sanitary sewer overflows (SSOs)
	Leaky sewer pipes (Exfiltration) (see Sercu et al. 2011)
	Illicit sanitary connections to MS4
	WWTPs (if inadequate treatment or upsets)
Other Human Sanitary Sources (some also attract urban wildlife)	Leaky or failing septic systems (may include excessive density of systems in one area or temporary overuse of the systems)
	Homeless encampments or other human outdoor sources
	Porta-Potties
	Dumpsters (e.g., diapers, pet waste, urban wildlife)
	Swimmers/bathers, boaters, trail users (e.g., hikers, runners)
	RVs (mobile) and other illegal dumping
	Trash cans
	Garbage trucks
Domestic Pets	Dogs, cats, etc.
Urban Wildlife (naturally occurring and human attracted)	Rodents/vectors (rats, raccoons, squirrels, opossums)
	Birds (gulls, geese, ducks, pigeons, swallows, etc.)
	Open space (coyotes, foxes, beavers, feral cats, etc.)
Other Urban Sources (including areas that attract vectors/wildlife)	Landfills
	Food processing facilities
	Outdoor dining
	Restaurant grease bins
	Bars/stairwells (washdown areas)
	Green waste, compost/mulch
	Animal-related facilities (e.g., pet boarding, zoos, off-leash parks)
Urban Non-stormwater Discharges (Potentially mobilizing surface-deposited fecal indicator bacteria)	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
Agricultural Sources (potentially including ranchettes within MS4 boundaries or areas in urban growth boundaries)	Livestock, manure storage
	Livestock, pasture
	Livestock, corrals
	Livestock, confined animal feeding operations (CAFO) (NPDES-regulated)
	Manure spreading, pastures/crops
	Municipal biosolids re-use
	Reclaimed water (if not properly managed)
	Irrigation tailwater
	Slaughterhouses (NPDES-regulated)
Natural Open Space/Forested Areas	Wildlife populations
	Grazing
	Natural area parks, off-leash areas
Other Naturalized Sources	Decaying plants/algae, sand, soil (naturalized fecal indicator bacteria)

3.3 Removal Mechanisms

Removal mechanisms for fecal indicator bacteria in stormwater control practices include both passive and active processes. Based on a literature review conducted for Water Environment Research Foundation (WERF) Stormwater Research Challenge (Strecker et al. 2009), the dominant passive removal mechanisms for fecal indicator bacteria include natural inactivation, predation, inert filtration and sedimentation, sorption and chemical inactivation (via contacting products). Key passive pollutant removal processes that may be present in various stormwater control types are described below (Strecker et al. 2009, Leisenring et al. 2013, WERF 2007, Clary et al. 2014, WWE and Geosyntec 2016). [2]

- **Natural Inactivation:** Natural inactivation is a general removal mechanism that refers to fecal indicator bacteria die-off or inactivation due to a wide range of environmental factors. Unless provided with suitable conditions for reproduction, the number of live cells will tend to decrease with time. Growth and decay rates are highly dependent on environmental factors, which are continually changing. The most important environmental factors affecting rate of inactivation are exposure to sunlight, water temperature, and exposure to air (drying or desiccation). Additionally, fecal indicator bacteria bound to particulates have been found to be inactivated at slower rates because particulates are hypothesized to provide both nutrients and shelter (WERF 2007).
- **Predation:** Predation of fecal indicator bacteria by other microorganisms is interrelated with natural inactivation and has been found to be a major removal mechanism. The most important predators of fecal indicator bacteria are believed to be protozoa and other eukaryotic organisms. Studies have found that predation may account for approximately 90% of overall mortality rates of fecal indicator bacteria (WERF 2007). Additional studies such as Zhang et al. (2011) have begun to explore changes in microbial ecology in bioretention cells that reduce fecal indicator bacteria levels, but more research is needed in this area.
- **Filtration and Sedimentation:** Inert filtration and sedimentation of solids are mechanisms that would be expected to remove fecal indicator bacteria bound to particulates from the water column. The effectiveness of particle removal at reducing fecal indicator bacteria concentrations is a function of the partitioning of fecal indicator bacteria between particulate-bound and free-floating forms, and the association of fecal indicator bacteria across the particle size distribution. The removal of fecal indicator bacteria from the water column through sedimentation or filtration does not necessarily constitute an ultimate removal mechanism because the survival of fecal indicator bacteria is expected to be greater when fecal indicator bacteria are bound to sediment, and resuspension of communities of fecal indicator bacteria sheltered by sediment could represent a significant later source of fecal indicator bacteria in some systems. Typical trapping efficiencies for sand filters and bioretention cells are estimated to be in the range of 60 to 80% for well-designed devices, with trapping efficiency decreasing as untreated runoff bypasses the devices and is discharged through the overflow structures during periods of high flows or when the filter is clogged (Barfield et al. 2010, Hayes et al. 2008).

  Additionally, Clark and Pitt (2012) note that most bacteria are in the lower limits of the size range for effective physical filtration using a sand medium. However, as the filter ages, removals will tend to increase, partly due to reduction in the effective pore size and due to the exopolymers that many bacteria excrete. These exopolymers provide surface reactive sites, even on a relatively inert sand media. Because of their negative surface charge, bacteria can be removed by attaching to these surface reactive sites. Organic media provide a location for captured bacteria to reside and grow (with potential for predation, as well). The challenge in filtration media selection is to encourage

[2] Removal mechanism text adapted from the *Colorado E. coli Toolbox* (WWE and Geosyntec 2016) and *Pathogens in Urban Stormwater Systems* (Clary et al. 2014), integrating a previous synthesis by Strecker et al. (2009) and the previous WWE and Geosyntec (2010) BMP Database summary report on fecal indicator bacteria.

capture and potential growth to create reactive sites, but without excessive growth that sloughs off the media and is flushed out of the media during successive storms.

- **Sorption:** Sorption involves the bonding of microorganisms to the surface of particles. This bonding is affected by parameters related to electrostatic charge, polarity and other factors. Sorption may be reversible as conditions change (WERF 2007). Partitioning of fecal indicator bacteria to particles is expected to depend on a variety of environmental factors, stormwater characteristics and hydrodynamics and is expected to change drastically with time and likely from site to site.
- **Chemical Inactivation:** Chemical inactivation of fecal indicator bacteria through contact with antimicrobial products is an approach used in some proprietary BMPs. A common agent in these types of treatment devices is an organosilane derivative (C-18 organosilane quaternary), which is reported to inactivate most fecal indicator bacteria without being consumed or dissipated and without producing toxic byproducts (Nolan et al. 2004). It is presumed that effectiveness of stormwater controls relying on a fixed microbial agent would depend on the degree of contact and contact time between stormwater and the microbial agent, dilution, and the amount of fecal indicator bacteria bound to particulates. It is not clear whether C-18 organosilane degrades over time and needs to be recharged/replaced. If so, the time since installation or last maintenance would be expected to influence the effectiveness of such proprietary devices. Silt films on the microbial agent could reduce the effective area and would be expected to decrease their performance.

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

3.4 Factors Affecting Removal

Fecal indicator bacteria and pathogens may persist in the environment for extended periods of time (outside of a warm-blooded host) in sediments, biofilms (Ferguson 2006), and organic litter in streams, lakes, industrial ponds, and stormwater facilities (e.g., Byappanahalli et al. 2003, Byappanahalli et al. 2006, Davies et al. 1995, Whitman et al. 2003, Schilling et al. 2008, Kolb and Roberts 2009, Skinner et al. 2010, Coghlan 1996, Costerton et al. 1995, Donlan and Costerton 2002, Donlan 2002). Flow-related factors such as mixing, sediment deposition and resuspension affect bacteria persistence in the water column. Figure 3-1 illustrates some of the factors that affect the survival, fate and transport of microorganisms in an open waterbody. These factors are discussed further below.

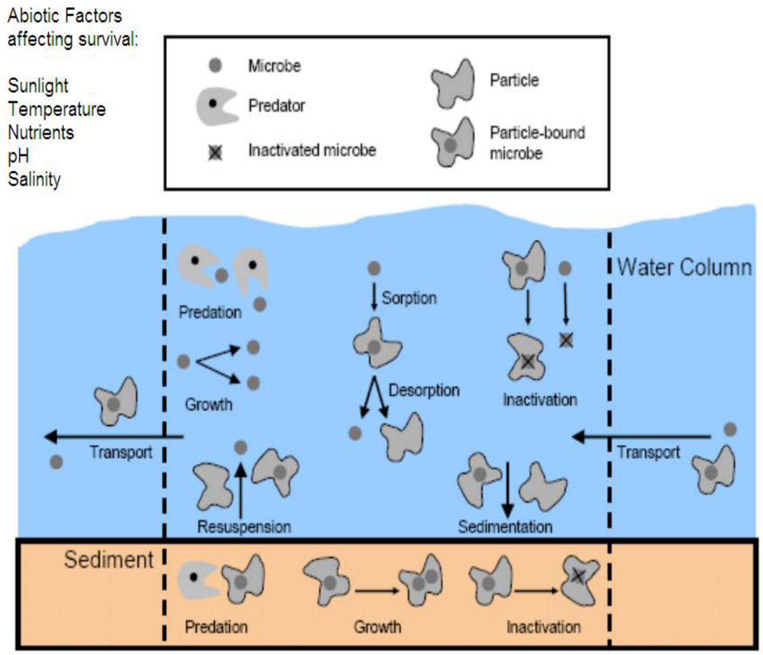

Figure 3-1. Potential Factors that Impact Fate of Microorganisms in Waterbodies and Associated Sediment.
Source: Olivieri et al., in WERF 2007, abiotic notes provided by S.E. Clark.

The primary characteristics and conditions expected to influence fecal indicator bacteria persistence in the environment (and affect treatability in stormwater BMPs) include:

- **Sunlight (solar irradiation):** Sunlight accelerates the inactivation of fecal indicator bacteria transported in water. Studies have shown that sunlight is consistently associated with a decrease in fecal indicator bacteria (WERF 2007). The degree of exposure affects the degree and rate of fecal indicator bacteria inactivation by sunlight. If the fluid is highly turbid, sunlight does not penetrate as well and is therefore less significant in removal. Similarly, if the fluid does not mix well, deeper layers will be affected less because light does not penetrate water perfectly. Clumping or association with particulate material can also cause shading that reduces exposure to sunlight. Turbidity is significant enough as a determinant of removal by sunlight that turbidity may be a potential surrogate for determining the effectiveness of sunlight treatment of fecal indicator bacteria and pathogens (Tang et al. 2011).
- **Temperature:** Temperature is commonly identified as a key factor regulating both bacteria growth and die-off rates (WERF 2007, Struck et al. 2006). Research has shown that warmer water temperatures result in faster inactivation of bacteria because warmer temperatures cause faster metabolism and earlier natural inactivation, as well as increased activity (i.e., appetite) of predatory microorganisms. Colder temperatures tend to “preserve” the vitality of bacteria by slowing metabolic processes (Wang and Doyle 1998). In natural water systems, however, temperature-related die-off rate research and seasonal observations of fecal indicator bacteria in environmental receiving waters having somewhat contradictory findings, with higher bacteria concentrations in natural waters having been correlated with higher water temperatures in the summer and fall. Kadlec and Wallace (2008) noted that bacterial regrowth is fostered by high concentrations of organic matter and by elevated temperatures. Hathaway et al. (2010) also noted that, in North Carolina and other parts of the country, fecal indicator bacteria concentrations in surface waters are higher during warmer seasons (Borst and Selvakumar 2003, McCarthy 2008, Young and Thackston 1999, Line et al. 2008, Schoonover and Lockaby 2006). Similarly, bacteria have been found to be significantly lower in snowmelt when compared with warm-weather rainfall-runoff (Clark et al.

2010). Pitt and McLean (1986) found that fecal coliforms, fecal streptococci, and *Pseudomonas aeruginosa* populations were significantly lower (by about tenfold) in snowmelt than in warm weather runoff in Toronto. Hathaway et al. (2010) concluded that temperature likely acts as a surrogate for seasonal variations and interactions among multiple factors such as moisture and temperature.

- **Turbidity and Particle Association/Partitioning**: Turbidity and the associated colloids in water affect the amount of sunlight passing through water, which can reduce the effectiveness of UV radiation in inactivating fecal indicator bacteria. The solids in water can provide a surface for microbial attachment, which may protect the bacteria from harsh environmental conditions and predators, and also act as carriers of attached bacteria to the sediment. Estimates of partitioning and particle association for microorganisms vary greatly between studies, with the fraction that is particle associated increasing as the suspended solids concentration/turbidity increases. Since bacteria are generally negatively charged, particulates with positive charges on all or part of their surface tend to attract and retain microorganisms; however, bacteria-particulate bonds may be rather weak (Borst and Selvakumar 2003). With regard to bacteria association with specific particle sizes, only a limited number of studies exist and their results are not consistent enough to predict particle size associations. As an example, Jeng et al. (2005) found that between 63% and 88% of fecal coliform bacteria in stormwater exist as free-floating in the water column and not associated with suspended sediment.
- **Nutrient Availability:** Nutrients in water may affect survival of bacteria. Researchers hypothesize that one reason particulate-bound bacteria survive when compared to free-floating bacteria is due in part to nutrients on particle surfaces. However, the results of recent studies vary regarding the expected role that nutrients play in bacteria survival. For example, Line et al. (2008) showed no correlation between fecal coliform concentrations and nitrate-nitrogen or ammonia-nitrogen in three watersheds in North Carolina. Conversely, McCarthy (2008) showed positive correlations between ammonia-nitrogen and *E. coli* for three out of four watersheds monitored in Melbourne, Australia. In California, Surbeck et al. (2010) found that fecal indicator bacteria concentrations were strongly positively correlated with dissolved organic carbon (DOC) concentration in runoff, and microcosm studies showed that the survival of *E. coli* and enterococci in runoff were strongly dependent on the concentration of both DOC and phosphorus.
- **pH:** Low and high pH are believed to decrease the survival of bacteria. While little research has been conducted on the effect of pH on survivability of stormwater pathogens, one study noted that bacteria thrived near neutral pH (Solic and Krstulovic 1992, from WERF 2007).
- **Salinity:** Salinity can affect the survival of bacteria. Additionally, certain fecal indicator bacteria such as *E. coli* lyse (break apart or dissolve) in saltwater, which is why *E. coli* is not a recommended fecal indicator for marine water.
- **Microbial Community (predators, competitors):** Fecal indicator bacteria and pathogens differ from chemical constituents in that they are living organisms that are affected by microbial interactions such as predation and competition (Clary et al. 2014).

It should be noted that these factors are generally interdependent. For example, flow affects turbidity via sediment transport, and turbidity affects the efficiency of sunlight penetration, which in turn affects die-off; thus, the effects of sunlight, flow and turbidity can be interrelated.

3.5 Fecal Indicator Bacteria Performance Data Summary and Findings

The BMP performance data summary for fecal indicator bacteria focuses on EPA's currently recommended fecal indicator bacteria of *E. coli* and enterococcus and the previously recommended fecal coliform. These data are summarized in Tables 3-3 through 3-5 and Figures 3-2 through 3-4. (In the figures, note that the circle on the box plots represents the geometric mean rather than the average for these figures.) The BMPDB currently contains only very limited pathogen data. Additionally, although several active disinfection studies are included in the BMPDB, these BMP types are not included in this analysis. Also note that some of these data sets are from grab samples due to researchers' efforts to comply with short sample holding times for bacteria. There is also more data on fecal coliform than the other indicators due to its longer history of use as a standard.

Table 3-3. Influent/Effluent Summary Statistics for *E. coli* (MPN/100 mL).

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

Table 3-4. Influent/Effluent Summary Statistics for Enterococcus (MPN/100 mL).

BMP Category	Study & Sample Count(% ND)		Interquartile Range (25^{th} – 75^{th} %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Retention Pond	4; 49 (0.0%)	4; 49 (12.2%)	245 - 24,100	20.0 - 10,500	3,270 (344; 6,940)	870 (62.0; 3,110)	◇▼▼
Wetland Basin	5; 68 (1.5%)	5; 61 (6.6%)	248 - 11,700	80.0 - 2,100	1,750 (738; 3,970)	410 (108; 594)	▼▼▼
Bioretention	3; 48 (0.0%)	3; 49 (8.2%)	178 - 2,440	32.0 - 2,190	586 (225; 922)	218 (58.0; 437)	◇▼▼
HDS	4; 40 (2.5%)	4; 43 (0.0%)	664 - 9,980	1,500 - 8,980	3,180 (1,290; 5,940)	3,650 (1,700; 5,480)	◇◇◇

Footnotes for Tables 3-4 and 3-5:

*Confidence interval about the median; computed using the BCa bootstrap method described by Efron and Tibishirani (1993).

** Each symbol represents an influent/effluent comparison test. Left position compares overlap of 95% confidence intervals around influent/effluent medians. Middle position compares Mann-Whitney rank-sum hypothesis test P-value to a significance value of 0.05. Right position compares Wilcoxon signed-rank hypothesis test P-value to a significance value of 0.05.

NA not available or less than three studies for BMP/constituent

% ND percentage of non-detects

◇ influent/effluent comparison test indicates no significant difference in concentrations

▼ influent/effluent comparison test indicates significant reduction in concentrations

△ influent/effluent comparison test indicates significant *increase* in concentrations

Table 3-5. Influent/Effluent Summary Statistics for Fecal Coliform (cfu/100 mL).

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

*Confidence interval about the median; computed using the BCa bootstrap method described by Efron and Tibishirani (1993).

** Each symbol represents an influent/effluent comparison test. Left position compares overlap of 95% confidence intervals around influent/effluent medians. Middle position compares Mann-Whitney rank-sum hypothesis test P-value to a significance value of 0.05. Right position compares Wilcoxon signed-rank hypothesis test P-value to a significance value of 0.05.

% ND percentage of non-detects

NA not available or less than three studies for BMP/constituent

◇ influent/effluent comparison test indicates no significant difference in concentrations

▼ influent/effluent comparison test indicates significant reduction in concentrations

△ influent/effluent comparison test indicates significant *increase* in concentrations

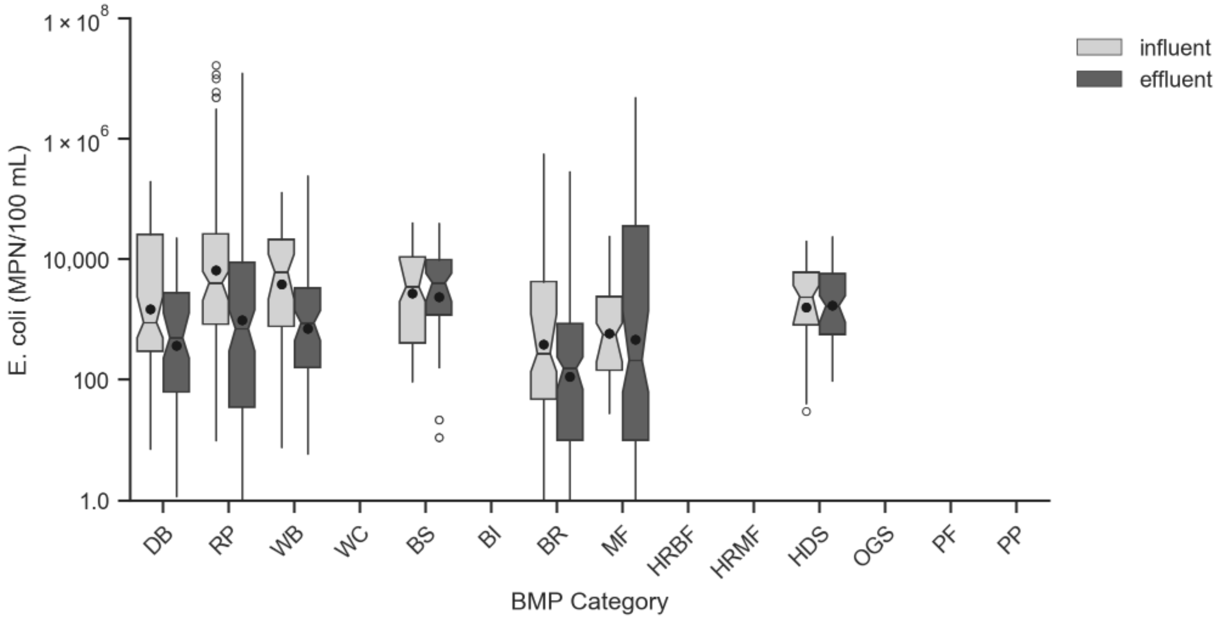

Figure 3-2. Box Plots of Influent/Effluent *E. coli* (MPN/100 mL).

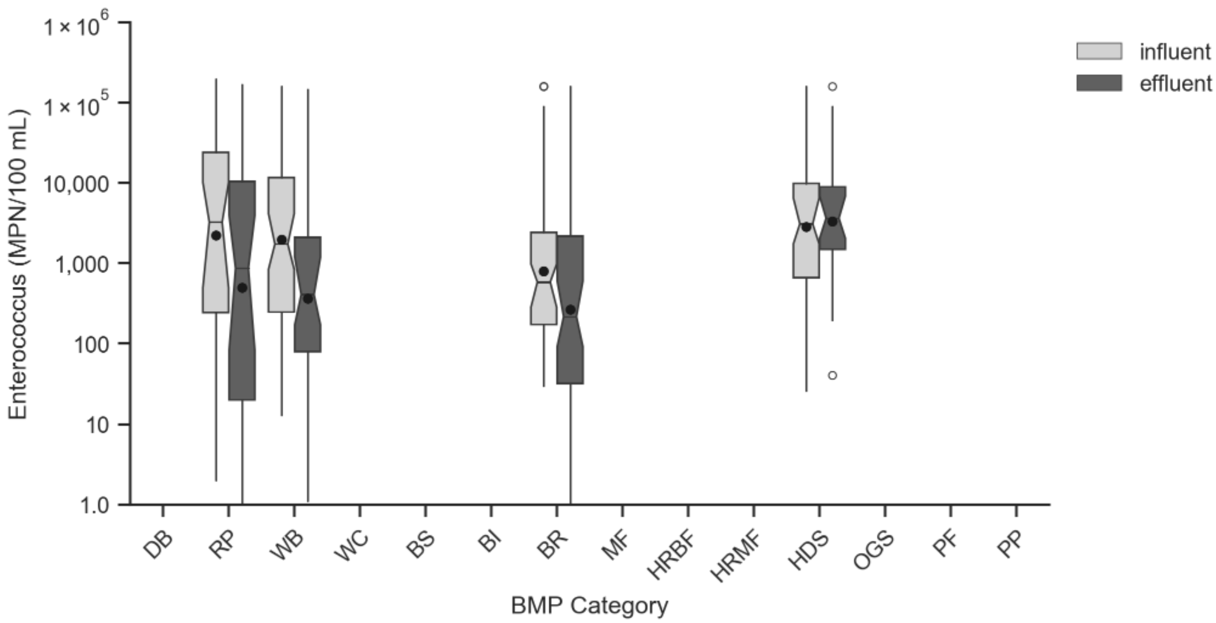

Figure 3-3. Box Plots of Influent/Effluent Enterococcus (MPN/100 mL).

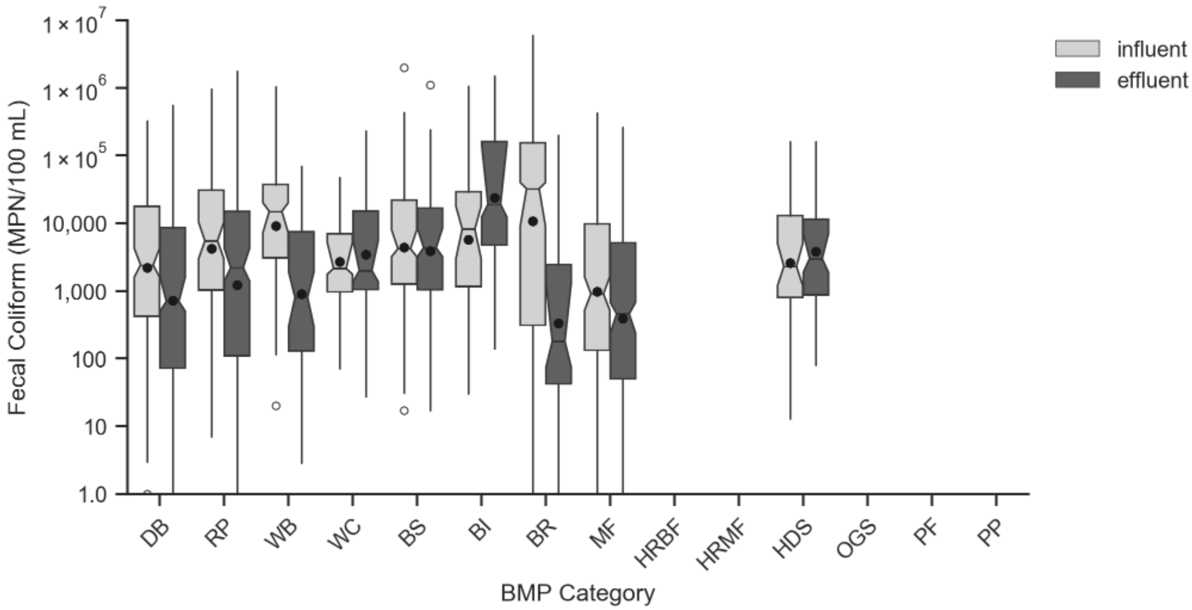

Figure 3-4. Box Plots of Influent/Effluent Fecal Coliform (cfu/100 mL).

3.6 Performance Findings and Discussion

Conclusions that can be drawn regarding stormwater control device performance for fecal indicator bacteria based on this analysis are generally consistent with previous analyses completed for the BMP Database. Key findings and observations based on the data set analyzed include:

- Regardless of fecal indicator bacteria type, the available data set shows that concentrations in urban stormwater runoff typically exceed primary contact recreation standards, often by one or more orders of magnitude.
- Regardless of stormwater control type or fecal indicator bacteria type, both inflow and outflow concentrations are highly variable, typically spanning an order of magnitude or more for the interquartile range (IQR). The high IQR arises from the variability within and between studies, which indicates sources of variation are both locational and temporal.
- Specific findings by fecal indicator bacteria type include:
    - *E. coli*: Sufficient data for analysis are only available for detention basins, retention ponds, wetland basins, grass swales, bioretention, media filters, and hydrodynamic separators. Detention basins, retention ponds, wetland basins, bioretention, and media filters show statistically significant reductions for *E. coli*. Bioretention and media filters achieve the lowest effluent concentrations, but these BMPs also had the lowest influent concentrations.
    - Enterococcus: Of the three fecal indicator bacteria evaluated, the enterococcus data set is the most limited in terms of both BMP categories and sample sizes. Sufficient data for analysis were only available for detention basins, retention ponds, wetland basins, bioretention, and hydrodynamic separators. Wetland basins, retention basins and bioretention showed statistically significant reductions in concentrations.
    - Fecal coliform: More data are available for fecal coliform for several BMP types. Detention basins, retention ponds, wetland basins, bioretention, and media filters show statistically significant reductions in fecal coliform concentrations. Grass strips and hydrodynamic separators indicate statistically significant increases in fecal coliform concentrations.

Bioretention has the largest concentration reductions and achieves the lowest effluent concentration as compared to any other BMP.

- Currently available data suggest that it is unlikely that conventional structural stormwater controls using passive treatment can consistently reduce fecal indicator bacteria concentrations in runoff to receiving water primary contact recreation standards. Bioretention and media filters are the only stormwater control categories evaluated with effluent concentrations approaching primary contact stream standards for *E. coli*.
- Considering all three fecal indicator bacteria types, practices showing statistically significant reductions for one or more types fecal indicator bacteria include bioretention, media filters, retention (wet) ponds, wetland basins and detention ponds. Unit processes such as sorption and filtration are present in bioretention and media filters, whereas wet ponds may provide long holding times that enable sedimentation, solar irradiation and habitat conducive to natural predation. Detention basins rely primarily on sedimentation; therefore, careful design (limiting entrainment velocities) and regular maintenance are likely needed to prevent scouring and resuspension of sediment deposited in detention basins that may be a potential on-going source of fecal indicator bacteria loading in the effluent. Review of individual detention basin studies shows that some detention basins export fecal indicator bacteria, whereas others reduce fecal indicator bacteria concentrations.
- Grass strips and swales do not appear to reduce fecal indicator bacteria concentrations in their effluent. Instead, increases in effluent concentrations for fecal coliform were found for grass strips and some grass swales studies. These stormwater control types may be exporting fecal indicator bacteria, either from entrainment of previously deposited fecal indicator bacteria, naturalized fecal indicator bacteria in the soil, or from new sources (e.g., animal excrement). (Note: reductions in fecal indicator bacteria loading due to infiltration and evapotranspiration are not evaluated in this analysis.)
- The only category of manufactured treatment devices included in this analysis is hydrodynamic separators, which do not demonstrate reduction of fecal indicator bacteria. There is insufficient data to evaluate other subcategories of manufactured treatment devices for fecal indicator bacteria for the studies currently included in the BMPDB.
- Currently, insufficient permeable pavement studies for fecal indicator bacteria have been submitted to the BMP Database for analysis. To the extent that permeable pavement sites reduce runoff volumes from a site, they would be expected to help reduce discharged pollutant loads under wet weather conditions and to reduce the frequency of standards exceedance days, similar to bioretention. Roads and other pavement typically would not be expected to have major sources of bacteria except potentially overpasses or bridges where birds or bats frequently roost or roadways near animal feed lots where track-out may be occurring. Other exceptions may exist, depending on the nature of the drainage system associated with the paved area.

Based on the performance data available to date in the BMP Database, general recommendations include:

- Those working to address pathogen impairments on streams should focus first and foremost on source controls (i.e., finding and repairing/replacing leaking sewers and/or septic systems, reducing direct human sources, etc.). Source control requires clear identification of the primary sources of fecal indicator bacteria relative to site-specific conditions. Focusing on controllable sources of bacteria, particularly those of human origin, is believed to be the most important first step in protecting human health (Orange County MS4 Permittees 2020; Clary et al. 2009) although source control alone may not be sufficient to meet ambient water quality standards.

- In terms of reducing overall bacteria loads to receiving waters, site designs and individual BMPs that reduce runoff volumes should reduce bacteria loading from urban runoff.

Several BMP types that communities may consider using to reduce fecal indicator bacteria loading are not currently well represented in the BMP Database. These include subsurface flow wetlands with upstream detention for flow equalization, permeable pavement, engineered media for biofilters (Li et al. 2012; Li et al 2014a; Li et al 2014b; Mohanty et al. 2013; Mohanty et al. 2014; Zhang et al. 2011) and emerging manufactured device products that include engineered media filtration or disinfection. These are discussed in Section 1.3 of this report.

CHAPTER 4

Nutrients

As of 2020, EPA has identified over 118,000 miles of stream as threatened or impaired due to nutrients, representing the third leading cause of stream impairments nationally. Over 7,090 lakes and streams are listed as impaired and over 6,600 waterbodies are listed as impaired due to organic enrichment and oxygen depletion, which is often associated with nutrient loading (U.S. EPA 2020). Nitrogen and phosphorus are targeted as part of major national water quality efforts in the Chesapeake Bay, the Gulf of Mexico and the Great Lakes. Adoption of numeric nutrient criteria vary throughout the states, with EPA encouraging the development of water quality standards for nutrients. EPA guidance recommends that water quality standards address causal (both nitrogen and phosphorus inputs) and response (chlorophyll-a and clarity) variables for all waters because of the interrelationships between these parameters (U.S. EPA 2000).

Nutrients included in this analysis include total phosphorus, orthophosphate, dissolved phosphorus, total nitrogen, total Kjeldahl nitrogen (TKN), NO_x (nitrate and nitrate+nitrite), and ammonia.

Basic Nutrients Terminology

Adapted from U.S. EPA 1999.

Nutrients: Primary elements necessary for the growth of living organisms.

Total Phosphorus: The total amount of phosphorus, including both organic and inorganic forms.

Particulate Phosphorus: That portion of total phosphorus that does not pass through a 0.45-micron membrane filter.

Dissolved Phosphorus: That portion of total phosphorus that passes through a 0.45-micron membrane filter.

Organophosphates: Phosphorus in a form that is bound to an organic compound.

Soluble Reactive Phosphorus: Phosphorus in a form that is most readily available to plants, including various forms of orthophosphate (e.g., $H_2PO_4^{1-}$, HPO_4^{2-}, and PO_4^{3-}).

Orthophosphate: The biologically available form of inorganic phosphorus in water is orthophosphate (PO_4^{3-}).

Total Nitrogen: The total amount of nitrogen in a sample, including organic nitrogen, nitrate, nitrite, and ammonia.

Total Kjeldahl Nitrogen: The total of organic and ammonia nitrogen in a sample determined by the Kjeldahl method.

Nitrate and Nitrite: Oxidized inorganic nitrogen species. Nitrate is the form of nitrogen preferred by aquatic plants.

Ammonia: Inorganic form of nitrogen; product of hydrolysis of organic nitrogen and denitrification. Ammonia is preferentially used by phytoplankton over nitrate for uptake of inorganic nitrogen.

4.1 Nutrient Sources

Like many other water quality constituents, nutrients occur naturally in the environment and are necessary for the health of aquatic systems. If available in insufficient amounts, the growth of primary producers may be limited, which impacts the health of life on other trophic levels. Excessive nutrients, however, can result in the accelerated growth of macrophytes and phytoplankton and potentially harmful algal blooms which lead to declines in oxygen, aquatic species imbalances, public health threats, and general declines in aquatic resource value. Investigations have shown that the key causative factors are excessive concentrations of the primary nutrients, phosphorus and/or nitrogen depending on the receiving water.

While nutrients occur naturally in the environment, human activities are a common cause of excessive nutrient loading to waterbodies. Human activities associated with nutrient over-enrichment in waterbodies include agricultural and urban/residential fertilization, treated sewage effluent, detergents, septic systems, combined sewer overflows, sediment mobilization, and animal waste. Human activities can also affect natural processes such as atmospheric deposition (e.g., fuel combustion resulting in NOx emissions), internal nutrient recycling from sediment, and stream channel erosion which can mobilize soils and organic matter containing nutrients.

Nutrient loading to receiving waters as a result of the above activities varies for each primary nutrient because of the unique chemical characteristics of each. Phosphorus, because of its tendency to sorb to soil particles and organic matter, is primarily transported in surface runoff with eroded sediments. Inorganic phosphate and organophosphate components of total phosphorus are typically derived from soil, plant, and animal materials associated with undisturbed and agricultural land uses – primarily due to the use of fertilizers and manures, and to a lesser extent the use of phosphorus-containing pesticides on agricultural lands. In urban and suburban rainfall-runoff, phosphorus sources include fertilizer use, detergents, flame-retardants in many applications (including in engine lubricants), corrosion inhibitors, plasticizers and soil erosion. In areas with high phosphorus content in soils, transport of sediment due to construction or other land disturbance activities can also represent a significant source. Phosphorus can also be associated with fine-grained particulate matter found in the atmosphere which can enter natural waters through both dry fallout and rainfall.

Nitrogen, on the other hand, does not sorb as strongly to soil particles and is transported in surface runoff in both particulate and dissolved phases. Dissolved inorganic nitrogen can be transported to surface waters through the unsaturated zone and groundwater. Because nitrogen species may occur as a gaseous phase in the environment, it is transported to surface water via atmospheric deposition as well.

4.2 Nutrient Forms

4.2.1 Phosphorus

Phosphorus occurs in natural waters almost solely as phosphates. In laboratory analysis, total phosphorus is usually first separated into dissolved and particulate portions. The dissolved portion is then typically divided into soluble reactive phosphorus (SRP) and soluble unreactive phosphorus. Soluble reactive phosphorus is primarily composed of inorganic orthophosphates and is readily available for plants, algae, and microorganisms. Soluble unreactive phosphorus is primarily composed of polyphosphates and various organic compounds. Particulate phosphorus is primarily composed of bacteria, algae, detritus, zooplankton, and inorganic particulates such as silt and clay. Organic particulate phosphorus in water can be broken down and eventually converted to orthophosphates by bacteria (Tchobanoglous and Schroeder 1985). Figure 4-1 illustrates the analytical procedure for differentiating between the various forms of phosphorus commonly analyzed using EPA analytical methods. Multiple reporting forms for phosphorus are included in the BMPDB; this summary report focuses on the most commonly reported forms.

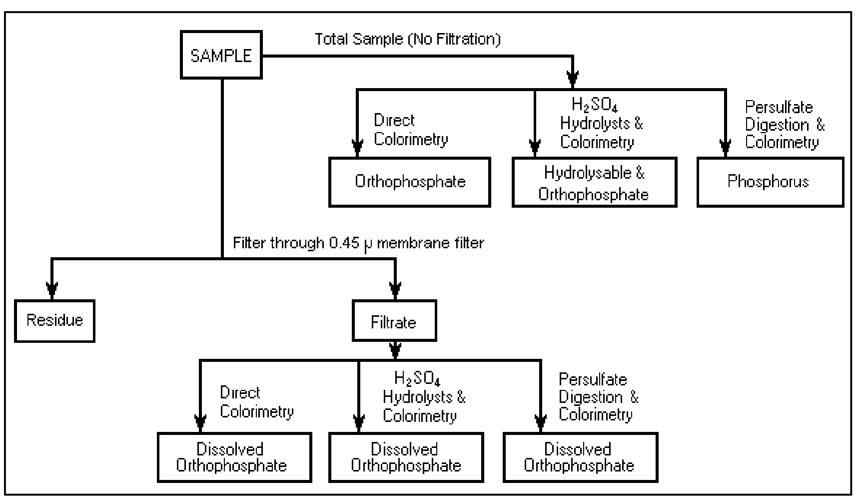

Figure 4-1. Analytical Procedure for the Differentiation of Phosphorus Forms.
Source: U.S. EPA 1993a.

Because phosphorus is typically the limiting nutrient in most freshwater systems, stormwater discharge of phosphorus, especially SRP, has the potential to cause significant water quality impairment to receiving waters. While phosphorus is an essential nutrient for all life forms, increased amounts of bioavailable phosphorus in surface waters can stimulate excessive algae growth and result in associated water quality problems such as decreased water clarity, disagreeable odors, habitat loss, toxicity, and low dissolved oxygen resulting in fish kills (WERF 2005).

Most dissolved phosphorus is readily bioavailable. Among particulate-bound forms of phosphorus, some are more readily converted to bioavailable forms than others. Generally, as complexity (molecular weight) of forms increases, phosphorus species become less readily bioavailable (WERF 2005).

4.2.2 Nitrogen

Nitrogen is present in runoff and natural waters in several forms, depending on the source and the environmental conditions. Common forms include organic nitrogen, which can be either dissolved or particulate, and the inorganic ions ammonium, nitrite, and nitrate. The nitrogen cycle is a series of biologically catalyzed reactions by which one form of nitrogen is transformed into another, as illustrated in Figure 4-2. Nitrite is a short-lived intermediate state, whereas nitrate tends to be more mobile and persistent (WERF 2005).

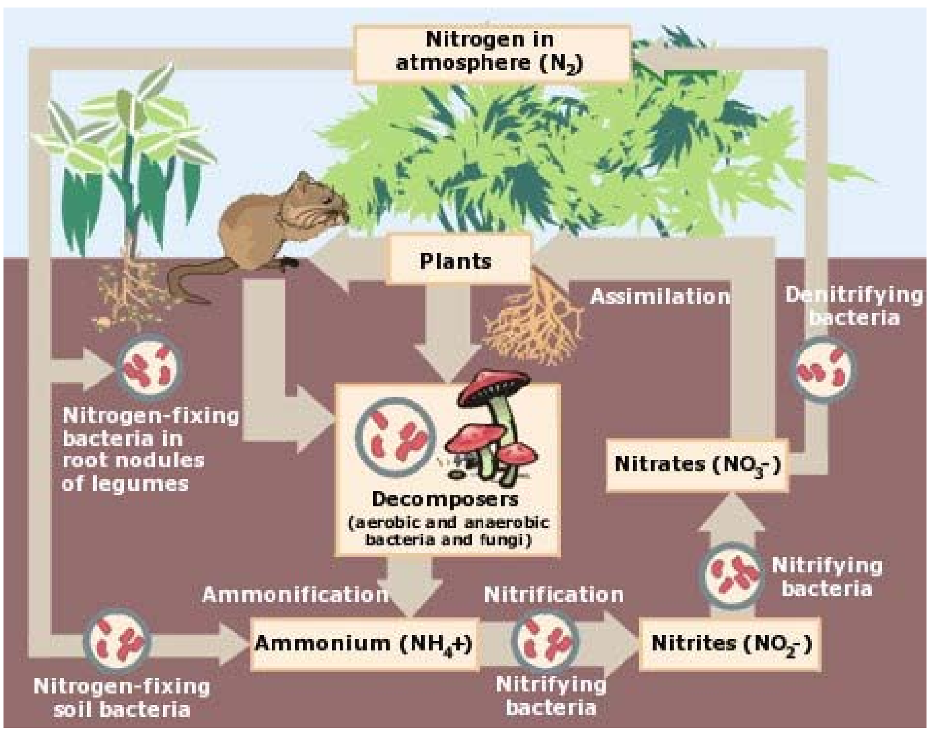

Figure 4-2. Simplified Illustration of the Nitrogen Cycle.

Source: https://www.epa.gov/sites/production/files/2015-11/nitrogen_cycle.png.

Nitrogen concentrations are typically reported using the following indices:

Total ammonia nitrogen	$TAN = (NH_3 + NH_4^+)_{aq}$
Total inorganic nitrogen	$TIN = (NH_3 + NH_4^+ + NO_2^{-1} + NO_3^{-1})_{aq}$
Total Kjeldahl nitrogen	$TKN = \text{Organic N} + NH_3 + NH_4^+$
Organic nitrogen	$ON = TKN - (NH_3 + NH_4^+)$
Total nitrogen	$TN = TKN + NO_2^{-1} + NO_3^{-1}$

The two primary concerns with nitrogen in stormwater are eutrophication of receiving waters and toxicity. Nitrate is readily available for biological uptake and, when present with sufficient amounts of phosphorus, which is often the case for estuaries and coastal environments, can cause eutrophication. Ammonia is of concern due to its fairly rapid transformation to nitrate, but also because unionized ammonia (NH_3) can be toxic to some aquatic species at fairly low concentrations. Nitrate is a concern for drinking water.

4.3 Phosphorus Removal Mechanisms and Factors Affecting Removal

Treatability for phosphorus is a function of partitioning (dissolved vs. particulate). If dissolved, treatability is a function of concentration and speciation. If particulate-bound, treatability is a function of the association of phosphorus to particles across the particle size and density distribution. Phosphorus can readily undergo surface complexation reactions, be adsorbed or precipitated. Media or soils containing iron, aluminum, calcium, or hydrated Portland cement can be very effective at removing phosphorus species from solution through surface complexation or precipitation. However, complexation or partitioning to engineered media or particulate matter can be reversible; and particulate-bound phosphorus can be a chronic threat, especially in a cyclic redox environment (WERF 2005). In other words, phosphorus release from sediment or organic matter is a major concern with respect to long-term phosphorus removal. Thus, routine maintenance of BMPs to remove sequestered forms of phosphorus before they become bioavailable again is a critical factor in effective phosphorus removal. Depending on the BMP type, the maintenance activity may include removing accumulated sediment and debris, scraping off the top few inches of media, replacing adsorptive media, or harvesting vegetation. Overall, BMPs must be designed with multiple treatment mechanisms, avoid the use of phosphorus containing materials (e.g., compost), and be actively maintained to achieve consistent removal and meet low numeric targets for phosphorus. Table 4-1 provides a summary of the primary transformation and removal mechanisms of major phosphorus species along with the factors that may affect those mechanisms.

Table 4-1. Summary of Phosphorus Transformations, Removal Mechanisms, and Important Factors.

Species	Transformation and Removal Mechanisms	Important Factors
Particulate Phosphorus	Physical separation (inert filtration and sedimentation)	Partitioning of phosphorus between particulate and soluble forms. Oxidation-reduction potential, pH, and bacterial communities that may transform phosphorus into soluble forms thereby releasing previously captured phosphorus.
Orthophosphates	Adsorption/precipitation	Contact with reactive media/soils, pH, temperature.
	Plant and microbial uptake	Vegetation and root density, presence of nitrogen and other essential nutrients, bacterial communities. Periodic harvesting of vegetation.

Some of the key factors affecting dominant removal mechanisms for phosphorus include:

- **Particulate Association:** Particle size and density are important factors in determining particle settling velocity (or time required for particles to settle) and filtration effectiveness. Therefore, particle size distribution and densities of suspended solids in untreated stormwater are major factors that affect the overall fraction of particles that may be removed in a stormwater treatment system. The fraction of phosphorus that can be removed through sedimentation and filtration – two of the most common unit processes harnessed in stormwater treatment BMPs – is dependent on two additional factors:

- The fraction of total phosphorus bound to particulates, and
- The fraction of particulate-bound phosphorus associated with each particle size bin.

  A study of stormwater treatability found that, on average, approximately 70% of total phosphorus and phosphate were removed from stormwater through removal of particles with diameter greater than 20 µm (WERF 2003). Unfiltered (i.e., starting) concentrations for these tests were 0.38 and 0.8 mg/L, respectively. Removing particulates down to 5 µm increased removal efficiency to approximately 80% and removing particles greater than 0.45 µm increased the removal efficiency to approximately 90% for both. Other studies on phosphorus fractionation (i.e., mass associated with various particle size ranges) in soils and sediment suggest that concentrations are typically greatest on fine particles (clays and silts); however, the particle size distribution also determines where most of the phosphorus mass resides. For example, if most of the suspended particles are sands, then most of the particulate-bound phosphorus mass in stormwater will be associated with sand (Dong et al. 2003; Vaze and Chiew 2004). More easily filterable larger solids such as leaves and other organic matter may also contribute significant fractions of phosphorus in stormwater (Washbush et al. 1999). For example, Selbig (2016) found that 56% of the annual total phosphorus yield in stormwater from two residential catchments in Madison, Wisconsin was due to leaf litter; with an aggressive leaf removal program, this yield could be reduced to 16% of the total annual phosphorus load.

- **pH:** Both pH and oxidation-reduction potential (ORP) have important and complex interrelated effects on partitioning and sorption. Solubility of phosphorus species in rainfall-runoff ranges from >80% at a pH of 6 to <1% at a pH of 8 (WERF 2005). As a result, phosphorus tends to adsorb onto particles at high pH. Additionally, at higher pH, metals tend to adsorb onto particulates, which creates more sorption sites for phosphorus (Holford and Patrick 1979). However, with increasing pH, the electrostatic potential at the surface of particles decreases and generally reduces the sorption capacity of particles (Barrow 1984). Phosphorus complexation with metals is also strongly influenced by pH. Phosphorus complexes with aluminum and iron in acidic conditions and with calcium in alkaline conditions (Minton 2005). These interactions and other factors suggest a complex, non-monotonic relationship between pH and sorption capacity.
- **Oxidation Reduction Potential (ORP):** ORP is especially important in interactions between phosphorus and iron in soils. Phosphorus may be removed from solution in oxidizing conditions (i.e., high ORP) as iron oxidizes from Fe^{+2} to Fe^{+3}, causing phosphorus to precipitate. However, this reaction is reversible, with phosphorus being released under reducing (i.e., low ORP) conditions. In fact, studies have shown that anaerobic conditions in BMPs can result in lower removal effectiveness for phosphorus (Minton 2005).
- **Cation Exchange Capacity**: Related to the above, the removal of dissolved phosphorus through sorption, precipitation, and complexation is dependent on the sorption capacity of media/soil. Two media/soil properties thought to be important factors in sorption are cation exchange capacity (CEC) and amount of phosphorus already present in the soil. Organic material with high CEC (such as hemic peat) has been shown to provide good phosphorus removal. Conversely, highly decomposed peat (sapric) and compost can be a source of phosphorus. As a result, some BMP design manuals have specified the use of partially decomposed fibric or hemic peat (e.g., NYSDEC 2010) and little to no compost. In addition, a variety of mineral substances such as zeolites, iron and aluminum oxide-coated sand, and similar filtration media have been found to promote the sorption of phosphorus (WERF 2005). Amendments that have been shown to be effective in increasing chemical sorption of dissolved P include iron filings (Erickson et al. 2012; Groenenberg et al. 2013), steel wool (Erickson et al. 2007), drinking water treatment residuals (O'Neill and Davis 2012a and 2012b; Hinman and

Wulkan 2012; Lucas and Greenway 2011), and various proprietary sorptive media (as summarized by Minnesota Pollution Control Agency 2020).

- **P-Index:** Leaching of phosphorus from media and soils can be counterproductive to BMP performance. Hunt et al. (2006) recommends using soils with a low "P-index" (an index describing the amount of phosphorus in soil/media) to improve phosphorus removal in bioretention cells and prevent leaching.
- **Temperature:** Changes in temperature can influence sedimentation by impacting water viscosity and settling velocities for sediments, which in turn would affect removal rates for particulate bound phosphorus. For example, decreases in temperature increase the viscosity of water, which in turn decrease rates of sedimentation. Although temperature has a substantial impact on microbial and plant activity, these processes are generally considered to be minor overall removal mechanisms for phosphorus. During winter months, some have found that phosphorus export may occur as a result of decaying of biological matter (NYSDEC 2010); however, additional study of this phenomenon is needed.

4.4 Nitrogen Removal Mechanisms and Factors Affecting Removal

The transport of nitrogen compounds in surface waters and stormwater runoff, and the transformation and removal of nitrogen in stormwater treatment BMPs is very complex. The dominant forms of nitrogen that occur in stormwater and the treatment processes available depend on the nitrogen cycle (Figure 4-2). The capture and removal of nitrogenous solids (e.g., sediment, leaf litter, etc.) and denitrification of nitrate are perhaps the most important treatment processes for nitrogen removal in BMPs. Denitrification is the anaerobic reduction of nitrate by heterotrophic bacteria, leading to the production of N_2 gas, which is then be released to the atmosphere. Therefore, denitrification completely removes nitrogen, whereas sedimentation and biotic assimilation may only provide temporary reductions unless captured solids are removed and/or vegetation is harvested. Table 4-2 provides a brief summary of dominant transformation and removal mechanisms and the factors understood to be important in each of these mechanisms. This discussion is intended to provide only a basic framework for discussing BMP performance.

Table 4-2. Summary of Transformations, Removal Mechanisms, and Important Factors.

Species	Transformation and Removal Mechanisms	Important Factors
Nitrogenous Organic Solids	Physical separation (removal)	Partitioning of nitrogen between particulate and soluble forms.
	Ammonification (transform via microbial decomposition to NH_4)	Temperature, pH, bacterial community.
Nitrate (NO_3)	Plant uptake (removal)	Vegetation density, presence of phosphorus. Periodic harvesting of vegetation.
	Denitrification (removal via biological reduction to N_2 gas and volatilization)	Bacterial community, oxidation-reduction potential/dissolved oxygen.
Ammonia (NH_4^+, NH_3)	Volatilization (removal)	Temperature, pH, circulation and air flow.
	Nitrification (transform via biological oxidation to NO_3 via NO_2)	Temperature, pH, bacterial community.

Key factors influencing nitrogen removal include temperature, pH, bacteria community and dissolved oxygen, as discussed further below.

- **Temperature:** The effectiveness of removal processes for the two most dominant forms of nitrogen (nitrogenous organic solids and nitrate) found in stormwater have been shown to be temperature dependent (Kadlec and Knight 1996). In general, higher temperatures have been shown to improve microbially mediated processes such as ammonification, volatilization, nitrification and denitrification.
- **pH:** Nitrogen removal processes are also highly dependent on pH, with optimal rates of removal processes occurring when the pH is near neutral or slightly higher than neutral.
- **Bacterial Community:** Ammonification, nitrification and denitrification processes rely on bacteria mediation; therefore, the presence and abundance of specific bacterial communities affects the rates of nitrogen removal from these processes.
- **Dissolved Oxygen (DO):** DO is an important environmental factor for nitrification and denitrification processes. For nitrification to occur, DO must be present. Low DO levels can limit nitrification rates because oxidation processes of nitrification can consume significant amounts of DO. To maintain nitrification processes, there must be a renewable and continual source of DO at rates equivalent to or higher than the consumption rate of optimal oxidation processes. Denitrification, in contrast, only occurs under anaerobic conditions, when little to no DO is present. The process of denitrification requires that nitrate act as an alternative terminal electron acceptor. When DO is present, it acts as the preferential terminal electron acceptor instead of nitrate, thereby inhibiting the denitrification process.
- **Organic Carbon:** Organic carbon must be available as a food source for the bacterial communities to thrive.

4.5 Nutrient Performance Data Summary

Nutrients included in this analysis include total phosphorus, orthophosphate, dissolved phosphorus, total nitrogen, TKN, NO_x (including both nitrate and nitrate+nitrite), and ammonia. Phosphorus and nitrogen are discussed separately below.

4.5.1 Phosphorus

Tables 4-3 through 4-5 and Figures 4-3 through 4-5 summarize available performance data for BMPs in the BMPDB for total phosphorus, orthophosphate, and dissolved phosphorus.

Table 4-3. Influent/Effluent Summary Statistics for Total Phosphorus as P (mg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	43; 542 (1.5%)	44; 577 (1.7%)	0.138 - 0.428	0.107 - 0.320	0.250 (0.216; 0.262)	0.186 (0.170; 0.200)	▼▼▼
Retention Pond	71; 1161 (0.9%)	75; 1138 (2.0%)	0.0996 - 0.542	0.0500 - 0.263	0.246 (0.220; 0.268)	0.120 (0.104; 0.129)	▼▼▼
Wetland Basin	27; 690 (0.3%)	27; 647 (1.4%)	0.106 - 0.319	0.0660 - 0.222	0.170 (0.151; 0.177)	0.122 (0.108; 0.133)	▼▼▼
Wetland Channel	15; 256 (0.4%)	13; 214 (0.0%)	0.129 - 0.372	0.120 - 0.338	0.201 (0.179; 0.230)	0.184 (0.160; 0.207)	◇◇▼
Grass Swale	34; 574 (0.3%)	39; 671 (0.3%)	0.0700 - 0.270	0.104 - 0.300	0.129 (0.118; 0.140)	0.180 (0.165; 0.190)	△△△
Grass Strip	50; 893 (8.2%)	50; 666 (3.2%)	0.0800 - 0.300	0.120 - 0.460	0.185 (0.160; 0.190)	0.230 (0.206; 0.240)	△△△
Bioretention	47; 850 (4.8%)	44; 667 (3.1%)	0.0800 - 0.460	0.0900 - 0.553	0.190 (0.170; 0.210)	0.240 (0.190; 0.270)	◇△△
Media Filter	32; 494 (1.4%)	35; 525 (5.1%)	0.0900 - 0.285	0.0490 - 0.147	0.165 (0.150; 0.180)	0.0900 (0.0800; 0.0973)	▼▼▼
HRBF	6; 100 (0.0%)	6; 100 (8.0%)	0.0640 - 0.157	0.0377 - 0.0848	0.0990 (0.0854; 0.112)	0.0500 (0.0409; 0.0600)	▼▼▼
HRMF	19; 349 (1.7%)	19; 351 (3.1%)	0.0680 - 0.500	0.0496 - 0.277	0.120 (0.100; 0.130)	0.0800 (0.0703; 0.0900)	▼▼▼
HDS	23; 338 (0.3%)	23; 303 (1.7%)	0.117 - 0.474	0.102 - 0.370	0.230 (0.198; 0.268)	0.176 (0.150; 0.197)	◇▼▼
OGS	10; 170 (4.7%)	10; 138 (10.9%)	0.0815 - 0.691	0.0367 - 0.530	0.316 (0.206; 0.428)	0.115 (0.0700; 0.213)	◇▼▼
PFC	NA	6; 124 (0.0%)	NA	0.0380 - 0.100	NA	0.0625 (0.0500; 0.0745)	NA
Porous Pavement	13; 447 (0.9%)	21; 365 (1.4%)	0.110 - 0.360	0.0700 - 0.194	0.170 (0.150; 0.180)	0.100 (0.0980; 0.112)	▼▼▼

*Confidence interval about the median computed using the BCa bootstrap method described by Efron and Tibishirani (1993).

** Each symbol represents an influent/effluent comparison test. Left position compares overlap of 95% confidence intervals around influent/effluent medians. Middle position compares Mann-Whitney rank-sum hypothesis test P-value to a significance value of 0.05. Right position compares Wilcoxon signed-rank hypothesis test P-value to a significance value of 0.05.

% ND percentage of non-detects

NA not available or less than three studies for BMP/constituent

◇ influent/effluent comparison test indicates no significant difference in concentrations

▼ influent/effluent comparison test indicates significant reduction in concentrations

△ influent/effluent comparison test indicates significant *increase* in concentrations

Table 4-4. Influent/Effluent Summary Statistics for Orthophosphate as P (mg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25^{th} – 75^{th} %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	10; 98 (18.4%)	11; 116 (31.0%)	0.0339 - 0.253	0.0271 - 0.175	0.0868 (0.0588; 0.130)	0.0646 (0.0440; 0.0875)	◇◇◇
Retention Pond	42; 734 (10.8%)	43; 687 (18.6%)	0.0288 - 0.243	0.00999 - 0.127	0.0856 (0.0700; 0.0945)	0.0340 (0.0275; 0.0390)	▼▼▼
Wetland Basin	13; 482 (9.1%)	14; 454 (9.3%)	0.0199 - 0.0832	0.0130 - 0.0798	0.0371 (0.0330; 0.0402)	0.0370 (0.0310; 0.0403)	◇◇▼
Wetland Channel	9; 150 (4.0%)	7; 122 (5.7%)	0.0168 - 0.147	0.0382 - 0.113	0.0594 (0.0400; 0.0750)	0.0665 (0.0583; 0.0760)	◇◇◇
Grass Swale	11; 300 (5.7%)	15; 418 (1.2%)	0.01000 - 0.0630	0.0333 - 0.155	0.0250 (0.0210; 0.0300)	0.0970 (0.0850; 0.105)	△△△
Grass Strip	40; 731 (22.7%)	40; 553 (12.3%)	0.0140 - 0.120	0.0310 - 0.330	0.0440 (0.0340; 0.0500)	0.105 (0.0900; 0.120)	△△△
Bioretention	25; 400 (21.2%)	24; 350 (3.7%)	0.00875 - 0.103	0.0720 - 0.450	0.0300 (0.0190; 0.0400)	0.270 (0.203; 0.295)	△△△
Media Filter	11; 179 (12.3%)	10; 168 (24.4%)	0.0250 - 0.0900	0.0156 - 0.0600	0.0500 (0.0320; 0.0510)	0.0300 (0.0198; 0.0310)	▼▼▼
HRMF	8; 120 (16.7%)	8; 120 (17.5%)	0.00855 - 0.0397	0.00828 - 0.0312	0.0167 (0.0137; 0.0206)	0.0150 (0.0112; 0.0181)	◇◇◇
HDS	6; 90 (11.1%)	6; 83 (13.3%)	0.0275 - 0.392	0.0200 - 0.389	0.140 (0.0520; 0.254)	0.0800 (0.0340; 0.110)	◇◇◇
OGS	3; 65 (40.0%)	3; 60 (41.7%)	0.107 - 0.509	0.0653 - 0.492	0.262 (0.146; 0.376)	0.236 (0.0903; 0.363)	◇◇◇
Porous Pavement	12; 256 (14.1%)	14; 209 (5.7%)	0.0222 - 0.0800	0.0260 - 0.100	0.0500 (0.0420; 0.0570)	0.0560 (0.0400; 0.0650)	◇◇△

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

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

Table 4-5. Influent/Effluent Summary Statistics for Dissolved Phosphorus as P (mg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25^{th} – 75^{th} %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	14; 195 (5.1%)	14; 182 (6.0%)	0.0417 - 0.150	0.0149 - 0.140	0.0800 (0.0690; 0.0924)	0.0700 (0.0470; 0.0800)	◇◇◇
Retention Pond	20; 396 (2.5%)	23; 435 (7.8%)	0.0700 - 0.212	0.0300 - 0.144	0.129 (0.114; 0.145)	0.0642 (0.0550; 0.0700)	▼▼▼
Wetland Basin	9; 338 (0.3%)	8; 311 (0.6%)	0.0320 - 0.101	0.0250 - 0.0815	0.0550 (0.0468; 0.0595)	0.0460 (0.0400; 0.0490)	◇▼◇
Wetland Channel	6; 121 (3.3%)	5; 89 (2.2%)	0.0600 - 0.192	0.0600 - 0.140	0.116 (0.0796; 0.134)	0.0900 (0.0700; 0.100)	◇◇◇
Grass Swale	12; 170 (4.1%)	11; 146 (2.1%)	0.0300 - 0.0800	0.0500 - 0.120	0.0480 (0.0400; 0.0500)	0.0700 (0.0600; 0.0700)	△△△
Grass Strip	5; 40 (0.0%)	6; 45 (0.0%)	0.0600 - 0.143	0.150 - 0.920	0.0800 (0.0600; 0.0800)	0.260 (0.140; 0.300)	△△△
Bioretention	6; 132 (9.1%)	5; 105 (2.9%)	0.0900 - 0.230	0.230 - 0.507	0.134 (0.113; 0.149)	0.350 (0.310; 0.370)	△△△
Media Filter	13; 128 (2.3%)	15; 155 (1.3%)	0.0200 - 0.100	0.0160 - 0.0907	0.0521 (0.0310; 0.0633)	0.0468 (0.0300; 0.0520)	◇◇▼
HRMF	9; 194 (14.4%)	9; 194 (14.9%)	0.0200 - 0.228	0.0200 - 0.190	0.0500 (0.0390; 0.0535)	0.0400 (0.0300; 0.0500)	◇◇▼
HDS	7; 125 (0.8%)	7; 119 (0.8%)	0.0370 - 0.160	0.0300 - 0.135	0.0740 (0.0558; 0.0990)	0.0570 (0.0393; 0.0710)	◇◇▼
Porous Pavement	4; 264 (6.8%)	4; 126 (3.2%)	0.0300 - 0.0800	0.0400 - 0.110	0.0500 (0.0425; 0.0575)	0.0600 (0.0486; 0.0600)	◇△△

*Confidence interval about the media computed using the BCa bootstrap method described by Efron and Tibishirani (1993).

** Each symbol represents an influent/effluent comparison test. Left position compares overlap of 95% confidence intervals around influent/effluent medians. Middle position compares Mann-Whitney rank-sum hypothesis test P-value to a significance value of 0.05. Right position compares Wilcoxon signed-rank hypothesis test P-value to a significance value of 0.05.

% ND percentage of non-detects

NA not available or less than three studies for BMP/constituent

◇ influent/effluent comparison test indicates no significant difference in concentrations

▼ influent/effluent comparison test indicates significant reduction in concentrations

△ influent/effluent comparison test indicates significant *increase* in concentrations

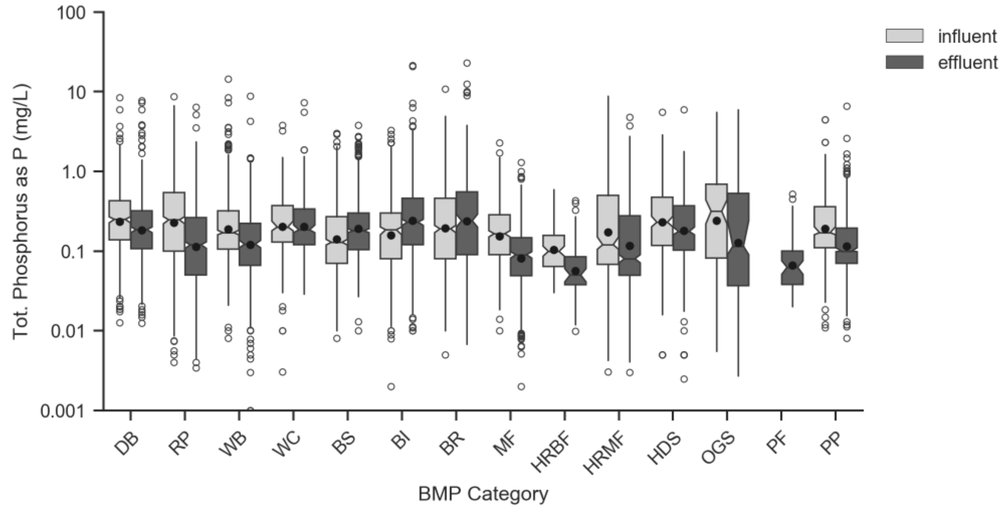

Figure 4-3. Box Plots of Influent/Effluent Total Phosphorus as P (mg/L).

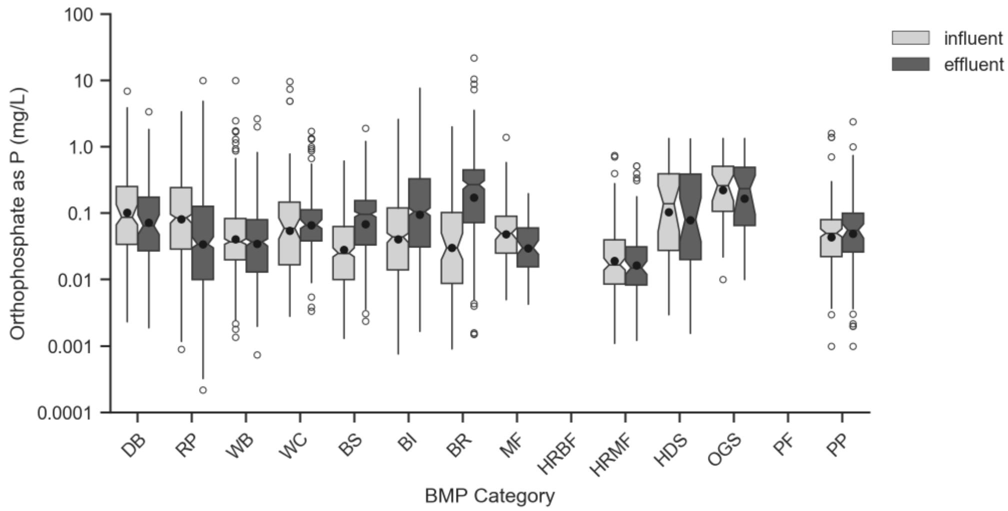

Figure 4-4. Box Plots of Influent/Effluent Orthophosphate as P (mg/L).

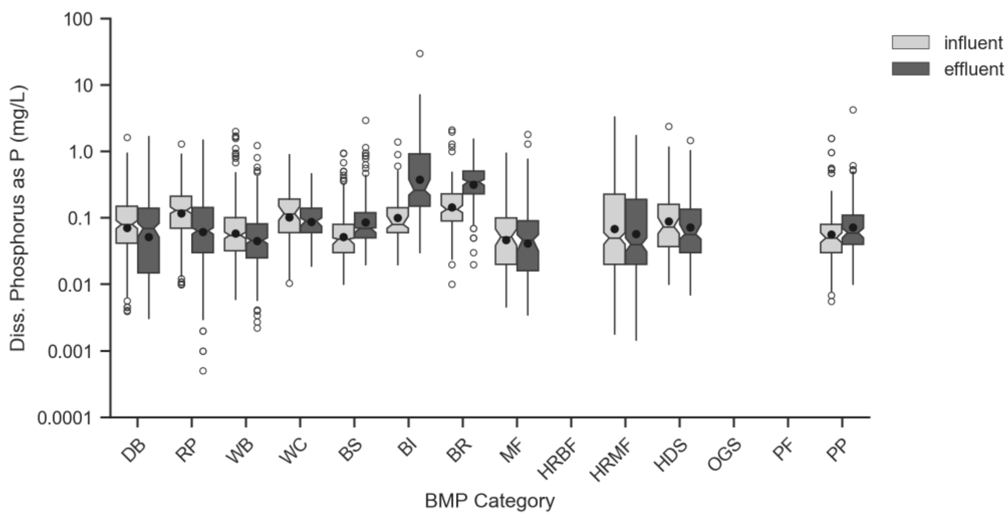

Figure 4-5. Box Plots of Influent/Effluent Dissolved Phosphorus as P (mg/L).

4.5.2 Nitrogen

Tables 4-6 through 4-9 and Figures 4-6 through 4-9 summarize available performance data for BMPs in the BMPDB for total nitrogen, TKN and NO_x (inclusive of nitrate and nitrate/nitrite).

Table 4-6. Influent/Effluent Summary Statistics for Total Nitrogen (mg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	17; 218 (0.0%)	17; 203 (0.0%)	0.856 - 2.01	0.785 - 2.22	1.24 (1.13; 1.36)	1.22 (1.05; 1.33)	◇◇▼
Retention Pond	35; 618 (0.0%)	37; 602 (0.0%)	1.05 - 2.66	0.830 - 1.70	1.63 (1.49; 1.75)	1.20 (1.13; 1.25)	▼▼▼
Wetland Basin	14; 471 (0.0%)	14; 477 (0.0%)	0.970 - 1.96	0.946 - 1.77	1.43 (1.34; 1.48)	1.37 (1.26; 1.40)	◇◇◇
Wetland Channel	8; 127 (0.0%)	7; 95 (0.0%)	1.24 - 2.40	0.950 - 1.93	1.76 (1.56; 1.90)	1.45 (1.05; 1.58)	▼▼▼
Grass Swale	14; 354 (0.0%)	18; 470 (0.0%)	0.450 - 1.31	0.420 - 1.10	0.710 (0.640; 0.790)	0.630 (0.570; 0.650)	◇▼◇
Grass Strip	10; 173 (0.0%)	11; 149 (0.0%)	0.868 - 2.20	0.829 - 1.82	1.47 (1.28; 1.61)	1.27 (1.13; 1.39)	◇◇▼
Bioretention	27; 386 (0.3%)	25; 318 (0.0%)	0.778 - 2.35	0.562 - 1.99	1.26 (1.15; 1.36)	0.96 (0.815; 1.06)	▼▼▼
Media Filter	14; 228 (0.0%)	14; 231 (0.0%)	0.693 - 1.76	0.588 - 1.44	1.06 (0.94; 1.18)	0.89 (0.81; 0.97)	◇▼▼
HRMF	3; 81 (0.0%)	3; 81 (0.0%)	0.890 - 3.00	0.700 - 2.00	1.88 (1.20; 2.27)	1.00 (0.900; 1.20)	◇▼▼
HDS	5; 119 (0.0%)	5; 104 (0.0%)	1.26 - 3.60	1.14 - 3.54	2.25 (1.66; 2.65)	2.21 (1.60; 2.57)	◇◇◇
OGS	5; 100 (0.0%)	5; 58 (0.0%)	1.99 - 4.30	2.16 - 3.51	2.81 (2.48; 3.12)	2.74 (2.49; 3.17)	◇◇▼
PFC	NA	3; 66 (0.0%)	NA	1.03 - 2.49	NA	1.55 (1.45; 1.83)	NA
Porous Pavement	NA	8; 84 (0.0%)	NA	1.66 - 3.11	NA	2.38 (1.98; 2.75)	NA

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

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

Table 4-7. Influent/Effluent Summary Statistics for Total Kjeldahl Nitrogen (mg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	25; 358 (2.0%)	26; 367 (3.5%)	0.768 - 2.17	0.697 - 2.09	1.33 (1.15; 1.40)	1.20 (1.00; 1.30)	◇◇▼
Retention Pond	47; 654 (1.8%)	52; 704 (2.4%)	0.820 - 2.30	0.714 - 1.51	1.35 (1.23; 1.40)	1.03 (0.982; 1.08)	▼▼▼
Wetland Basin	15; 188 (6.4%)	17; 274 (4.7%)	0.593 - 1.39	0.671 - 1.27	1.01 (0.880; 1.08)	0.928 (0.853; 0.971)	◇◇◇
Wetland Channel	11; 197 (1.5%)	11; 199 (1.0%)	1.10 - 2.00	0.900 - 1.92	1.60 (1.40; 1.70)	1.40 (1.30; 1.50)	◇◇◇
Grass Swale	21; 384 (0.0%)	25; 489 (0.2%)	0.370 - 1.49	0.310 - 1.10	0.759 (0.662; 0.860)	0.583 (0.510; 0.663)	▼▼◇
Grass Strip	47; 874 (0.0%)	45; 633 (0.0%)	0.822 - 2.30	0.787 - 2.00	1.40 (1.20; 1.40)	1.20 (1.10; 1.22)	▼▼◇
Bioretention	31; 612 (1.8%)	30; 525 (1.5%)	0.670 - 2.50	0.540 - 2.10	1.20 (1.10; 1.30)	1.20 (0.957; 1.20)	◇△△
Media Filter	27; 428 (4.2%)	27; 448 (5.1%)	0.541 - 1.70	0.337 - 0.994	0.936 (0.841; 1.00)	0.551 (0.481; 0.600)	▼▼▼
HRMF	7; 98 (12.2%)	7; 98 (25.5%)	0.632 - 1.70	0.362 - 1.40	1.11 (0.827; 1.20)	0.626 (0.530; 0.710)	▼▼▼
HDS	10; 207 (0.0%)	10; 173 (0.6%)	0.770 - 2.79	0.700 - 2.87	1.59 (1.40; 1.80)	1.44 (1.20; 1.70)	◇◇◇
OGS	7; 139 (2.2%)	7; 100 (5.0%)	1.09 - 2.85	1.10 - 2.45	1.76 (1.43; 2.02)	1.53 (1.40; 1.82)	◇◇◇
PFC	NA	6; 134 (0.0%)	NA	0.470 - 1.30	NA	0.804 (0.661; 0.931)	NA
Porous Pavement	11; 449 (0.4%)	21; 353 (4.5%)	1.20 - 3.00	0.544 - 1.40	2.00 (1.70; 2.10)	0.900 (0.701; 0.900)	▼▼▼

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

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

Table 4-8. Influent/Effluent Summary Statistics for NO_x as N (mg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	30; 409 (1.7%)	30; 412 (3.9%)	0.260 - 0.840	0.180 - 0.718	0.500 (0.430; 0.525)	0.372 (0.326; 0.413)	▼▼▼
Retention Pond	60; 958 (3.5%)	62; 932 (7.1%)	0.160 - 0.771	0.0343 - 0.451	0.400 (0.369; 0.421)	0.163 (0.140; 0.190)	▼▼▼
Wetland Basin	22; 561 (0.9%)	22; 523 (7.5%)	0.146 - 0.655	0.0400 - 0.550	0.370 (0.322; 0.390)	0.234 (0.170; 0.312)	▼▼▼
Wetland Channel	14; 237 (0.0%)	12; 192 (0.0%)	0.210 - 1.25	0.100 - 1.19	0.450 (0.340; 0.520)	0.273 (0.200; 0.380)	◇▼▼
Grass Swale	28; 518 (4.1%)	32; 618 (0.5%)	0.130 - 0.498	0.110 - 0.434	0.270 (0.240; 0.290)	0.219 (0.194; 0.230)	▼▼▼
Grass Strip	49; 889 (1.1%)	48; 673 (3.3%)	0.270 - 1.10	0.182 - 0.860	0.510 (0.440; 0.540)	0.390 (0.348; 0.430)	▼▼▼
Bioretention	40; 789 (2.5%)	38; 609 (3.4%)	0.204 - 0.618	0.170 - 1.26	0.360 (0.326; 0.380)	0.441 (0.380; 0.507)	△△△
Media Filter	30; 466 (2.6%)	31; 483 (3.3%)	0.192 - 0.589	0.200 - 0.810	0.320 (0.290; 0.339)	0.450 (0.397; 0.480)	△△△
HRMF	8; 158 (13.9%)	8; 157 (14.6%)	0.0722 - 0.633	0.0800 - 0.700	0.245 (0.165; 0.343)	0.270 (0.160; 0.370)	◇◇◇
HDS	15; 258 (1.2%)	15; 224 (2.2%)	0.225 - 0.800	0.195 - 0.635	0.425 (0.353; 0.500)	0.350 (0.290; 0.409)	◇▼▼
OGS	8; 141 (0.7%)	8; 103 (1.9%)	0.281 - 0.972	0.245 - 0.896	0.440 (0.390; 0.470)	0.390 (0.330; 0.467)	◇◇◇
PFC	NA	6; 133 (0.0%)	NA	0.250 - 0.640	NA	0.370 (0.330; 0.410)	NA
Porous Pavement	12; 454 (0.9%)	21; 357 (1.7%)	0.297 - 0.850	0.640 - 1.83	0.530 (0.436; 0.555)	1.09 (0.910; 1.20)	△△△

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

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

Table 4-9. Influent/Effluent Summary Statistics for Ammonia as N (mg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	16; 201 (10.4%)	16; 188 (18.6%)	0.0604 - 0.280	0.0425 - 0.190	0.117 (0.0843; 0.131)	0.0928 (0.0768; 0.111)	◇▼▼
Retention Pond	42; 654 (6.7%)	45; 644 (7.8%)	0.0425 - 0.229	0.0317 - 0.200	0.110 (0.0975; 0.123)	0.0785 (0.0670; 0.0901)	▼▼▼
Wetland Basin	16; 475 (2.9%)	16; 476 (2.9%)	0.0338 - 0.160	0.0220 - 0.136	0.0770 (0.0684; 0.0851)	0.0600 (0.0473; 0.0608)	▼▼▼
Wetland Channel	6; 106 (10.4%)	6; 92 (10.9%)	0.0867 - 0.379	0.138 - 0.448	0.170 (0.112; 0.195)	0.262 (0.207; 0.320)	△△◇
Grass Swale	15; 352 (5.7%)	19; 467 (10.9%)	0.0488 - 0.227	0.0200 - 0.107	0.104 (0.0900; 0.126)	0.0470 (0.0400; 0.0520)	▼▼▼
Grass Strip	36; 537 (4.1%)	36; 390 (10.5%)	0.220 - 0.730	0.120 - 0.530	0.350 (0.330; 0.420)	0.255 (0.220; 0.280)	▼▼▼
Bioretention	21; 374 (4.3%)	22; 330 (25.5%)	0.120 - 0.630	0.0209 - 0.130	0.300 (0.220; 0.320)	0.0500 (0.0500; 0.0600)	▼▼▼
Media Filter	16; 254 (9.1%)	17; 269 (20.8%)	0.0866 - 0.431	0.0312 - 0.160	0.186 (0.147; 0.215)	0.0742 (0.0568; 0.0828)	▼▼▼
HRMF	4; 52 (36.5%)	4; 52 (38.5%)	0.0330 - 0.139	0.0336 - 0.136	0.0660 (0.0459; 0.0800)	0.0543 (0.0431; 0.0784)	◇◇◇
HDS	9; 219 (5.9%)	9; 184 (12.0%)	0.0863 - 1.30	0.0435 - 1.37	0.390 (0.241; 0.460)	0.377 (0.191; 0.695)	◇◇◇
OGS	7; 121 (9.9%)	7; 80 (23.8%)	0.472 - 2.22	0.407 - 2.01	1.16 (0.855; 1.40)	0.847 (0.499; 1.18)	◇◇▼
Porous Pavement	4; 74 (5.4%)	8; 86 (36.0%)	0.343 - 0.790	0.0277 - 0.190	0.490 (0.400; 0.570)	0.0600 (0.0400; 0.0800)	▼▼▼

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

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

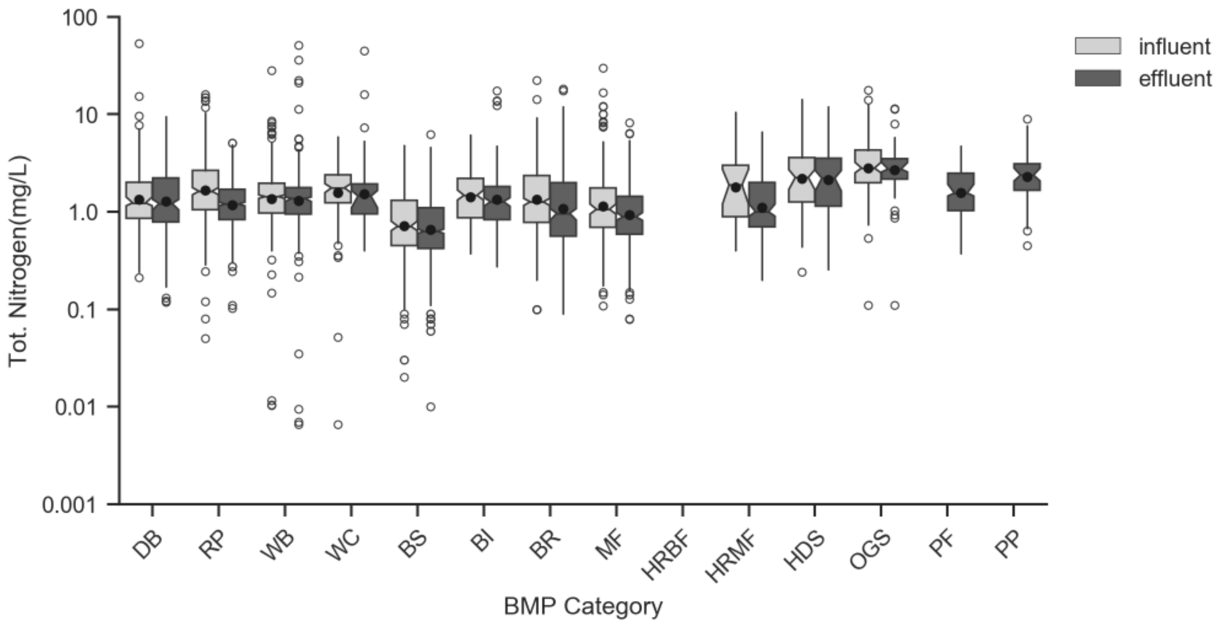

Figure 4-6. Box Plots of Influent/Effluent Total Nitrogen (mg/L).

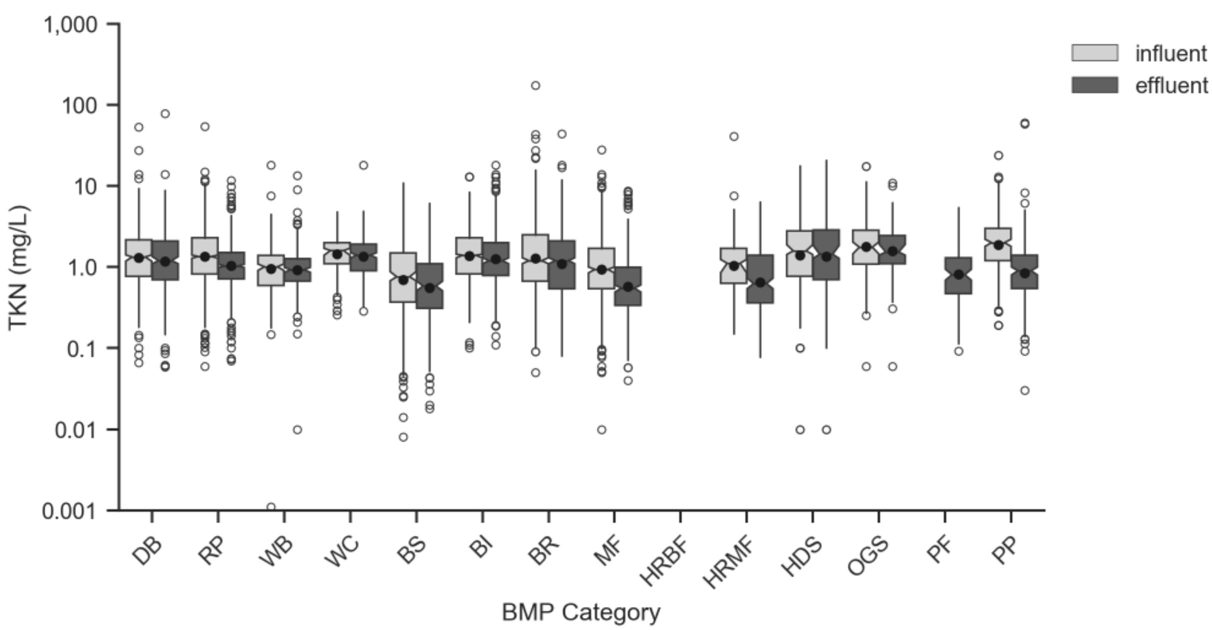

Figure 4-7. Box Plots of Influent/Effluent TKN (mg/L).

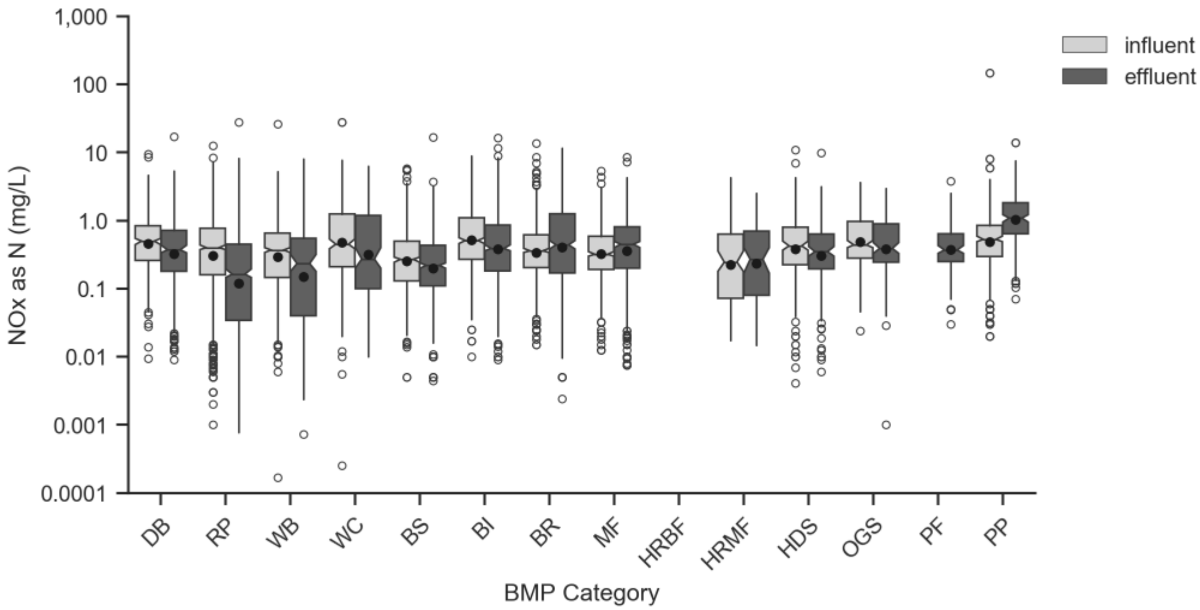

Figure 4-8. Box Plots of Influent/Effluent NOx as N (mg/L).

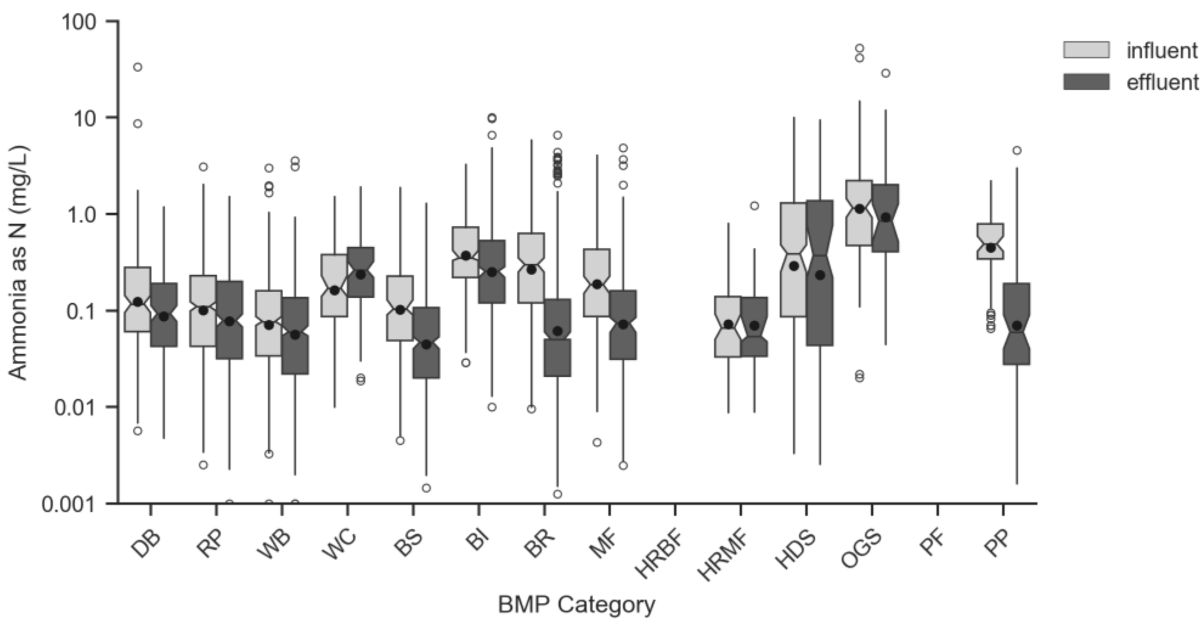

Figure 4-9. Box Plots of Influent/Effluent Ammonia as N (mg/L).

4.6 Performance Findings and Discussion

The analysis of BMP performance data for nutrients aligns relatively well with observed urban runoff concentration characteristics and theoretical background of unit treatment processes and transport mechanisms for phosphorus and nitrogen. Performance summaries of phosphorus and nitrogen are provided separately below.

4.6.1 Phosphorus

Effective phosphorus control is essential for protecting receiving waters from nutrient enrichment impacts because phosphorus is often the limiting nutrient in freshwater bodies. Findings for phosphorus include:

- Median influent total phosphorus concentrations generally range between 0.1 and 0.3 mg/L.
- Many BMPs show statistically significant reductions for total phosphorus, but grass swales, grass strips, and bioretention show phosphorus export. Bioretention had the highest phosphorus median effluent concentrations for all three forms of phosphorus analyzed, ranging from 0.24 to 0.35 mg/L, which exceeds water quality standards established by some states for total phosphorus. Although not evaluated in this analysis, it is possible that more recent bioretention designs with greater attention to the phosphorus content (e.g., P index, compost percentage) of media may have better results; conversely, some communities are also applying pressure for higher compost content to support better vegetative growth.
- Detention basins effectively remove total phosphorus, but not dissolved phosphorus or orthophosphate.
- The best performing BMPs for total phosphorus reduction are media filters, high rate biofiltration, and high rate media filtration with total phosphorus median effluent concentrations of 0.05 to 0.09 mg/L.
- The best performing BMPs for dissolved phosphorus and orthophosphate in the analysis data set are retention ponds, wetland basins, and media filters. High rate media filters and hydrodynamic separators also show reductions for dissolved phosphorus. Most practices do not show statistically significant reductions for dissolved phosphorus and orthophosphate.

In summary, because phosphorus in stormwater runoff is generally highly particulate-bound, BMPs with unit processes for removing particulates (i.e., sedimentation and filtration) will generally provide good removal for total phosphorus. In particular, BMPs with permanent pools appear to be effective at reducing the major forms of phosphorus. Leaching of phosphorus from soils/planting media and resuspension of captured particulate phosphorus may be a cause of phosphorus increases observed in vegetated BMPs such as bioretention, swales, and filter strips. Vegetated BMPs should be designed with adequate inlet protection, dense vegetation, and drop structures or check dams to minimize resuspension of particulates. The use of virgin compost or chemical fertilizers should be avoided and planting media within BMPs should be tested for phosphorus content prior to installation if phosphorus is a constituent of concern.

Filters capable of capturing fine particulates and containing adsorptive media may be very effective for phosphorus removal. Future analyses of the BMP Database could include comparison of various media amendments as more studies with media amendments are included in the database.

Infiltration can be an effective mechanism for reducing phosphorus loads, particularly since phosphorus presents very little risk to groundwater, even in the dissolved state, due to its affinity to adsorb to minerals and organics. Volume-related load reductions were not included in this analysis. However, in areas with naturally high phosphorus concentrations in soils or groundwater, infiltrating additional runoff might result in additional groundwater loadings to receiving waters.

4.6.2 Nitrogen

Findings for nitrogen include:

- Median influent concentrations are generally range between 1.1 and 2.9 mg/L for total nitrogen and between 0.2 and 0.5 mg/L for nitrate.
- Many BMPs show statistically significant reductions in total nitrogen forms with media filters producing the lowest median effluent concentrations of 0.9 and 0.5 mg/L for total nitrogen and TKN, respectively.
- Bioretention, media filters, and porous pavement show nitrate export indicating that ammonification and nitrification of organic nitrogen is likely occurring.
- For the removal of nitrate, the best performing BMPs are retention ponds, wetland basins, and wetland channels.
- For the removal of ammonia, detention basins, retention ponds, wetland basins, grass swales, grass strips, bioretention media filters and porous pavement all demonstrate reductions. Oil and grit separators in this data set had particularly high influent ammonia concentrations relative to other BMP types.

In summary, BMPs with permanent pools (i.e., retention ponds and wetlands) appear to be able to reduce nitrate concentrations but may ineffective, or potentially increase, organic nitrogen. The opposite appears to be true for biofilters and media filters. Based on the theory of unit processes and knowledge of the nitrogen cycle, it is hypothesized that retention ponds and wetlands sequester nitrate in wetland sediments and vegetation during the growing season and then release nitrogenous solids during vegetation die-off periods. As indicated by the relatively high TKN removal and low NO_x removal for media filters, inert filtration appears capable of capturing nitrogenous solids, but the conditions are not as conducive for significant denitrification or nitrogen uptake as compared to bioretention or BMPs with permanent pools (retention ponds and wetland basins). Therefore, a BMP designed for permanently reducing nitrogen may include a permanent wet pool followed by a vegetated swale or media filter. Alternatively, a bioretention cell with pore storage above and below the underdrain may provide aerobic and anaerobic zones for nitrification/denitrification processes (Davis et al. 2006). Harvesting of vegetation and removal of captured sediment may also be key maintenance practices for reliable removal of nitrogen.

Because the various forms of nitrogen are removed through different processes, the most important consideration for BMP design is the dominant form of nitrogen that the system is designed to treat, based on loading sources and downstream impairments. Nitrogen in stormwater runoff is predominantly organic nitrogen (e.g., leaves and other organic debris) and nitrate. For removal of organic nitrogen (which is predominantly particulate matter), BMPs that facilitate pre-screening of debris, settling and filtration, as well as biological activity under aerobic conditions, will be the most effective. Conversely, for removal of nitrate (which is soluble), treatment processes conducive to biological activity under anaerobic conditions (e.g., surface or subsurface flow wetlands, bioretention cells with internal water storage [Hunt et al. 2012]) will be most effective. Wetlands are ideal for nitrogen removal due to the variable depth zones that provide a diversity of oxidation-reduction potential conditions, and the shallow depths and long residence times that allow for microbial transformation processes to occur. Filtration processes are not expected to be effective for nitrate (Davis et al. 2006) except in special circumstances such as with engineered bioretention designed to incorporate a continuously submerged anoxic zone (Kim et al. 2003). Ammonia, which occurs at relatively low levels in typical urban runoff, would be effectively removed in wetlands and other long residence time treatment BMPs through volatilization and microbially mediated oxidation/nitrification processes.

Finally, due to the complexities of the nitrogen cycle, it is also important to recognize that “removal” of one form of nitrogen may result in an increase in another form later in the cycle. For example, organic nitrogen that settles from the water column can decay and later release nitrate unless maintenance activities periodically remove the settled material.

CHAPTER 5

Metals

EPA has identified metals (excluding mercury) as causing over 94,000 miles of stream impairments in the U.S. and over 7,060 stream and lake impairments (U.S. EPA 2020). Metals are among the most common stormwater pollutants and can be present at potentially harmful concentrations in urban runoff (Shaver et al. 2007). Metals in urban stormwater originate primarily from automobile-related activities and the exposure of building materials to rain (WERF 2003). Elevated concentrations of some naturally abundant metals such as iron and aluminum may be associated with erosion of soils. Atmospheric deposition of metals may also be an issue, particularly in the case of mercury, as a result of air emissions from coal-fired power plants, waste incinerators, certain manufacturing facilities, and other sources (U.S. EPA 2005).

This summary provides statistical analysis for selected metals data contained in the International Stormwater BMP Database. Over 30 different metals are reported in studies in the BMP Database. The analysis data set for this technical summary was limited to the eight most frequently reported metals:

- Arsenic
- Cadmium
- Chromium
- Copper
- Iron
- Lead
- Nickel
- Zinc

EPA's recommended water quality criteria for various metals are intended to protect aquatic life and human health, including exposure pathways through water and fish ingestion. Many of these criteria are based on hardness with both acute and chronic numeric limits. However, EPA's aquatic life freshwater criteria for copper is currently based on the Biotic Ligand Model, which uses many other water quality constituents to more accurately estimate copper bioavailability and resulting potential toxicity (U.S. EPA 2007). Few states have adopted the BLM-based criteria on a statewide basis, but several allow its use on a site-specific basis.

5.1 Sources

Metals concentrations above natural background levels in urban stormwater are often associated with automobile-related sources such as roads and parking lots and from building materials (e.g., galvanized roofs,

Basic Metals Terminology

Adapted from Weiner 2008; USGS 2020.

Dissolved Metals: (more correctly referred to as "filtered" metals). Refers to metals present in a water quality sample that has been filtered through a 0.45 µm to 2 µm filter, acidified to a pH of 2, then analyzed in a laboratory. A "true" dissolved sample requires field-filtering; however, in practice, dissolved metals samples are often filtered and acidified in a laboratory.

Total Metals: Refers to metals present in a non-filtered sample after the sample is "digested" in an acidic solution until essentially all of the metals are extracted into soluble forms for analysis.

Colloid: Particles intermediate in size between those found in solution and suspension that can remain evenly distributed without settling out.

Ion: An atom or group of atoms that carries a positive or negative electric charge as a result of having lost or gained one or more electrons.

Ligand: A molecule or ion that binds to a metal cation to form a complex. When metals bind with ligands, they are typically less toxic to aquatic life.

Sorption: Process of constituents becoming bound to particles by attractive chemical and electrostatic forces.

Ion Exchange: The reversible interchange of ions between a solid and a liquid. As water passes through a porous media, ions in the water can become attached to oppositely charged sites on media surfaces or be incorporated into the lattice structure through molecular sieving.

Redox Potential: A measure of the availability of electrons for exchange between chemical species, also known as oxidation-reduction potential. Redox conditions influence the solubility of certain metals.

Bioaccumulation: Biological sequestering of a substance at a higher concentration than that at which it occurs in the surrounding water. Metals in biologic tissue can be biomagnified at higher trophic levels.

gutters, downspouts, and fencing) exposed to rain. Treated wood is also a common source of metals in residential and commercial areas. Industrial areas may be "hot spots" for certain metals, depending on the industrial process and materials management practices. Other sources may include landfill leachate, soil erosion, household chemicals, and pesticides (Shaver et al. 2007). Table 5-1 summarizes key sources of selected metals in urban runoff.

Table 5-1. Common Sources of Metals in Urban Runoff.
Source: Shaver et al. 2007; Burton and Pitt 2001.

Metal	Source
Copper	Building materials, paints, wood preservatives, algaecides, brake pads
Zinc	Galvanized metals, paints and wood preservatives, roofing and gutters, tires, moss control products, batteries
Lead	Gasoline *(particularly prior to leaded gasoline phase-out),* paint, batteries
Chromium	Electroplating, paints and preservatives, cement
Cadmium	Electroplating, paints and preservatives
Iron	Soil erosion, equipment and vehicle body wear
Nickel	Diesel fuel and gasoline (exhaust), lubricating oil, metal plating, bushing wear, brake lining wear, asphalt paving
Arsenic	Treated wood, pesticides, paint, erosion of geologic materials

Many urban stormwater studies have been conducted that further refine the understanding of metals source areas. Summaries of many of these studies have been compiled by Pitt et al. (2004 a&b) and Shaver et al. (2007), which may be referenced for more detailed information on source area loading. Pavement used by vehicles (roads, parking lots, loading docks, etc.) is usually identified as the most important source for metals above natural background levels (Pitt et al. 2004b); however, significant regional differences may exist, depending on rainfall patterns (Shaver et al. 2007, citing Driver and Tasker 1990). Urban runoff in the form of snowmelt has also been shown to be a significant source of metals (Shaver et al. 2007, citing Oberts 1994). Naturally occurring soil and geologic conditions may also affect metals concentrations in runoff directly and indirectly. Additional comments on several metals include:

- Zinc: Several researchers have found zinc to be a key metal of interest in urban street runoff (Shaver et al. 2007; Rose et al. 2001; and May et al. 1997). Additionally, urbanized areas, especially industrial areas, may still have galvanized metal roofs that can be a significant source of zinc in urban runoff (Clark et al. 2008; Shaver et al. 2007). Other galvanized metal surfaces common in the urban environment include ductwork, heating/ventilation/air-conditioning (HVAC) equipment, ventilation fans, turbines, pipes, roof gutters/downspouts, fencing, and guardrails.
- Lead: Historically, leaded gasoline was an important source of lead in urban runoff. Substantially lower lead concentrations in urban runoff have resulted in the last few decades (Shaver et al. 2007) following the gradual phase-out of leaded gasoline in the U.S. that began in the 1970s, with sale of leaded gasoline banned by 1996 (U.S. EPA 1995). Leaded paint on buildings and structures has also diminished over time, but remains in some areas, including soils where improper leaded paint removal has occurred (WERF 2003).
- Iron: Iron is abundant in the earth's crust and are often associated with naturally occurring soil and geologic conditions. High concentrations of these metals may be exacerbated where mining or erosion is occurring in a watershed or within a stream channel.
- Mercury: Although mercury is not a focus of this technical summary, atmospheric fallout (primarily from fossil fuel power plants) is a key source of mercury (U.S. EPA 2005). More mercury BMP performance data collected at sufficiently low detection limits are needed.

Metals in stormwater may occur in particulate, dissolved or colloidal forms, depending on other water quality parameters such as pH, redox potential and the presence of other dissolved species such as sulfide or carbonate. Dissolved ("aqueous") forms generally include cations (e.g., Ag^+), complexes (e.g., $Zn(OH)_4^{2+}$), and organometallics (e.g., $Al(C_2H_5)_3$). Particulate forms include: mineral sediments (e.g., clays, carbonates, silicates); precipitated oxides, hydroxides, sulfides, carbonate, silicates, etc.; and cations and complexes that are sorbed to mineral sediments and organic matter (Weiner 2008). Metal species undergo continuous changes between dissolved, precipitated and sediment-sorbed forms. The rates of adsorption, desorption and precipitation processes depend on the water chemistry and sediment composition (Weiner 2008).

Many metals in urban runoff are predominantly associated with particulates; however, they may also occur in dissolved or colloidal forms. Particulate-bound metals are generally viewed as less toxic ecologically; however, the fine particulates associated with stormwater have been shown to cause substantial toxicity in various controlled experiments (WERF 2003). Shaver et al. (2007) reported that most metal contamination found in urban runoff is associated with fine particulate (mostly organic matter), such as is found deposited on rooftops, roads, parking lots, and other depositional areas within the urban environment (citing research by Ferguson and Ryan 1984; Good 1993; Pitt et al. 1995; Stone and Marsalek 1996; Crunkilton et al. 1996; Sutherland and Tolosa 2000). However, Shaver et al. (2007) also note that a significant fraction of copper, cadmium, and zinc can be found in urban runoff in the dissolved form (citing research by Pitt et al. 1995; Crunkilton et al. 1996; Sansalone and Buchberger 1997).

Partitioning data for metals associated with different particle sizes in stormwater are important for estimating the level of control that may be associated with different BMP designs. Concentrations of metals such as chromium, zinc, iron and lead can be substantially reduced by removing stormwater particulates, as shown in Table 5-2. Copper and cadmium can also be removed to a lesser degree by removing particulates. This information is important to understand because it informs both the BMP selection process as well as expectations of potential performance. For example, WERF (2003) reports that most well-designed wet detention ponds can remove particulates down to about 1 to 5 µm, depending on rain conditions and drainage area. Smaller ponds may only be able to remove particulates down to 20 µm, but ponds cannot remove the filterable fraction (<0.45 µm) relying solely on physical processes. Long hydraulic retention times (on the order of days to weeks) are generally needed for biochemical processes such as microbially mediated transformations and plant uptake.

Table 5-2. Percent Reduction in Various Metals After Removal of Various Particulate Sizes in Stormwater Samples.
Source: WERF 2003.

	Particle Size (µm)			
Metal	**>20**	**>5**	**>1**	**>0.45**
Cadmium	20%	22%	22%	22%
Copper	26%	34%	34%	37%
Lead	41%	62%	76%	82%
Iron	52%	63%	95%	97%
Zinc	64%	70%	70%	72%
Chromium	69%	81%	82%	84%

It is also important to understand whether filtered fractions tend to be in ionic or colloidal form. Although site-specific metals associations may vary, ionic and colloidal association results from WERF-sponsored treatability tests are summarized in Table 5-3. Cadmium tended to be present in colloidal form, whereas other metals evaluated were predominantly in ionic form. Other research by Morquecho (2005) showed somewhat different associations, with most of the zinc, cadmium and lead bound to colloids or organic matter, with only copper occurring in mostly ionic form. Ionic forms may be more feasible to remove through ion exchange/sorption, whereas colloids may be more difficult to remove in the absence of coagulant addition. However, in a study of dissolved copper in highway runoff, Nason (2012) found that >99.9% of dissolved copper from four highway stormwater runoff sites in Oregon was complexed by organic ligands (i.e., colloidal) and therefore was not as biologically available.

Table 5-3. Ionic and Colloidal Associations with Filtered (<0.45 µm) Pollutants in Stormwater Treatability Tests.

Source: WERF 2003.

Metals	% Ionic	% Colloidal
Cadmium	10	90
Copper	77	23
Lead	78	22
Chromium	95	6
Iron	97	3
Zinc	99	1

Related to the likelihood of particle association of various metals, it is also important to understand the likelihood of the metals disassociating from the particulates under ranges of pH conditions potentially present in stormwater BMPs. WERF (2003) conducted experiments to evaluate the likelihood of metals disassociating from particulates under pH conditions ranging from 4 to 11. Results showed that the metals remained strongly bound to the particulates during long exposures to the extreme pH conditions likely to occur in stormwater sediments, where particle-bound metals accumulate. Zinc was an exception to this finding, with significant desorption occurring at a pH of 4. Other conclusions included that metals will also likely remain strongly bound to the particulates in stormwater control device sumps or detention pond sediments where particulate-bound metals are captured. Similarly, tests of filter media under aerobic and anaerobic conditions showed that the metals tested were not mobilized under anaerobic conditions. However, it was also noted that under specific conditions, co-precipitation of metals by iron- and sulfate-reducing bacteria could occur in stormwater BMPs.

Most water quality criteria for metals are in the dissolved form due to concerns related to aquatic toxicity. As a result, urban stormwater monitoring objectives may include characterization of dissolved metals concentrations. This can either be determined by sample analysis, or in some cases through models. While sampling and analysis for total forms of metals is relatively straightforward, there are some challenges associated with dissolved metals sampling and analysis. For more in-depth discussion on this topic, see *Urban Stormwater BMP Performance Monitoring Manual* (Geosyntec and WWE 2009) and the BMP Database Technical Summary: Metals (WWE and Geosyntec 2011).

5.2 Removal Mechanisms

Metals removal is a function of partitioning (particulate vs. dissolved). If dissolved (i.e., aqueous or filtered), treatability is a function of concentration and speciation, and if particulate-bound, treatability is a function of association of metals to various particle sizes. Generally, particulate-bound metals can be removed by sedimentation, filtration and coagulation-flocculation (WERF 2005). Most stormwater treatment systems are passive; therefore, sedimentation and filtration are considered dominant mechanisms.

Dissolved metals can be removed from water mainly by sorption and precipitation processes. Sorption processes include adsorption, surface complexation and ion exchange. Metals complexed in aqueous solution and uncharged aqueous complexes (i.e., $CuCO_3$) are very difficult to remove unless precipitated or advanced unit operations such as reverse osmosis are applied (WERF 2005).

Some metals can form volatile metal-organic compounds in the natural environment by microbial reactions. For these, volatilization can be an important removal mechanism. Bioaccumulation in plants ("phytoremediation") can be a useful removal mechanism. Biotransformation of metals, in which redox reactions involving bacteria can cause some metals to precipitate, has also been shown to be a removal mechanism (Weiner 2008). However, both uptake and microbially mediated transformation processes can be slow compared to the time scale of rainfall-runoff events. As such, these are generally considered minor processes for stormwater treatment.

Dominant removal mechanisms include:

- **Sedimentation:** Sedimentation of particulates is a dominant removal mechanism for particulate-bound metals. The effectiveness of sedimentation as a metals removal mechanism is a function of the association of the metal to particles of different sizes and densities in the overall distribution. See Section 2.2, for additional discussion of sedimentation processes.
- **Filtration – Inert Filtration and Sorption:** Inert filtration includes physical filtration processes, but does not encompass chemical and biological processes of complexation, precipitation, biological uptake, and others that may occur in filter media. Sorption is a general term encompassing the processes of absorption and adsorption. Of these, adsorption – the binding of aqueous species to surfaces – is the most important mechanism in the removal of metals in stormwater BMPs. Adsorption itself is a general term that encompasses the processes commonly referred to as physical adsorption, ion exchange, surface complexation, and some types of precipitation. Sorption processes are extremely complex and are influenced by a variety of factors including pH, dissolved organic matter, carbonate concentrations, co-constituents competing for adsorption sites (e.g. magnesium, calcium, phosphorus, etc.), presence of other sorbed metal hydrates, and other factors. Discussion of adsorption models is beyond the scope of the discussion; see research by Schnoor (1996), Davis et al. (2001), Sansalone and Ying (2008), and Karathanasis (1999) for more information.

Minor removal mechanisms in stormwater control measures include chemical precipitation, microbially mediated processes, and plant uptake of metals. Highlights of these processes include:

- **Chemical Precipitation:** Active precipitation typically requires modification of pH and/or addition of a precipitating agent such as calcium carbonate. These are not considered to be common practices for urban stormwater management. However, some port facilities have successfully used crushed oyster shells to provide pH buffering and precipitation of dissolved metals (Taylor Associates 2008; Landau Associates 2013). Precipitation may also occur passively due to natural changes in water chemistry or at a micro-scale as a part of the adsorption process. For example, precipitation may occur in the pores of media such as zeolite and granular activated carbon, which are better known as sorbents (WERF 2003). Likewise, sorption of metals onto inactive bacteria cells can be mistaken for bacteria-mediated precipitation (discussed below).
- **Microbially Mediated Metals Removal:** Microbially mediated metals removal includes elements of sorption and precipitation. Processes that may be important in stormwater treatment facilities include microbially mediated precipitation, oxidation-reduction, bioaccumulation, and biosorption. Extra-cellular precipitation occurs when microorganisms produce metabolic products that are excreted and result in the immobilization of metals. Bioaccumulation refers to the active accumulation of metals by living microorganisms as part of metabolism and passive binding of metals to negatively charged functional groups on the surface of microorganisms. Oxidation and reduction of metals by bacteria can remove soluble metals from solution; however, little has been

studied about the effect of this process on metals, particularly within stormwater BMPs (WERF 2003).

- **Plant Uptake ("Phytoremediation"):** Plant uptake of dissolved metals is understood to be a function of plant type, density and contact time with water. Plant uptake of dissolved metals is believed to be minor compared to sorption. However, swale experiments summarized in WERF (2003) found that soluble metals (Cu, Cr, Pb, Zn, and Cd) were taken up by all three of the species of grass studied (Centipede, Kentucky Bluegrass, and Zoysia) after only 24 hours of contact time. Sun and Davis (2007) found plant uptake in lab-scale bioretention studies to be nearly ten times lower than sorption, but noted that greater biomass per filter volume would likely increase this ratio. Studies (Ye et al. 2001; Ye et al. 1997) have found that wetland plants tend to accumulate more copper in their roots when iron and manganese plaque is present on roots. Sun and Davis (2007) found that the majority of metal accumulation occurs in roots. Foliage can be removed from stormwater treatment facilities as part of routine maintenance; however, roots would require removal of the entire plant. These findings suggest that plants perhaps primarily provide a metals sequestering function, as opposed to completely removing metals from the system. Thus, the potential exists for sorbed metals to be released back into solution as roots decay.

5.3 Conditions Influencing Dominant Removal Mechanisms

This section is intended to generally identify the key characteristics and conditions that may influence the dominant removal mechanisms listed above. Because discussion of these conditions quickly becomes very complex, the discussion is limited to generalizations. These factors generally include partitioning and particulate association and speciation of the metal. As discussed in Section 5.1, speciation of metals is a function of water chemistry, including factors such as pH, redox conditions, presence of organic matter and other factors (Weiner 2008). Highlights include:

- **Partitioning and Particulate Association:** Particle size and density are important factors in particle settling velocity as well as important factors affecting whether a particle will be removed by filtration. Therefore, particle size distribution and densities of influent stormwater are major factors in the overall portion of particles a BMP would be expected to remove. The fraction of metals that can be removed through sedimentation and filtration is dependent on 1) the fraction of metals bound to particulates, and 2) the fraction of particulate-bound metals associated with each particle size and density range (i.e., bin).
- **pH:** The pH of stormwater is integrally related to speciation, partitioning and sorption processes. The pH in a stormwater treatment system is usually determined by the prevailing environmental conditions, and normally is in the range of 6 to 9 (Weiner 2008). Perhaps the most important effect of pH is its influence on the speciation of dissolved metals between the free ionic form and stable complexes. Partitioning of most metals generally favors the particulate fraction under high pH and favors the dissolved fraction under low pH (WERF 2005).
- **Organic Content:** The presence of biodegradable organic materials plays an important role in metals treatment (Weiner 2008). For example, the presence of humic substances promotes sorption of copper to particulates (Minton 2005). However, the complexes that form between copper and organic material is a function of the available active sorption sites on the organic matter. Studies have shown that filter media containing peat and organic material, such as compost, provide high sorption of certain metals. Inorganic filter media with a high cation exchange capacity (e.g., zeolite) have also been shown to perform well in removing certain metals, indicating that organics are not required to remove metals via filtration (WERF 2003). However, zeolites may need longer contact times for effective removal. Also, organic materials have multiple active sorption sites and can participate in many different types of biochemical reactions other than sorption that can assist with metals species transformation and immobilization.

- **Redox Conditions:** Redox potential is regulated by the dissolved oxygen level. Dissolved oxygen in stormwater is depleted mainly by biodegradation processes that decompose organic matter (Weiner 2008). Metals can be characterized as redox-sensitive or redox-insensitive, according to how strongly their solubility is influenced by changes in redox potential, within a range normally achievable under environmental or water treatment conditions. Redox-sensitive metalloids (arsenic and selenium) tend to behave the opposite of redox-sensitive metals. Redox-sensitive and insensitive metals can generally be characterized as:
    - Common Redox-Sensitive Metals: Chromium, Copper, Iron, Manganese, Mercury, Molybdenum, Thallium, Uranium, Vanadium.
    - Common Redox-Insensitive Metals: Aluminum, Barium, Cadmium, Lead, Nickel, Zinc.
    - Common Redox-Sensitive Metalloids: Arsenic, Selenium.

  Oxidizing conditions are optimal for precipitation of redox-sensitive metals as hydroxides and carbonates (when pH is high enough). However, redox-insensitive metals and redox-sensitive metalloids tend to be present as soluble species under oxidizing conditions.

  Reducing conditions and non-acid pH values are optimal for precipitation of redox-insensitive metals and redox-sensitive metalloids. In addition, because reducing conditions slow biodegradation processes markedly, organic sediments and debris accumulate, immobilizing dissolved metals by surface adsorption, as evidenced by the efficiency of wetlands in this respect.

5.4 Metals Performance Data Summary

Sections 5.4.1 to 5.4.8 present the tables and figures for BMP performance for the total and dissolved forms of arsenic, cadmium, chromium, copper, iron, lead, nickel and zinc. A discussion of the performance for BMPs for metals is included in Section 5.5.

5.4.1 Arsenic

Table 5-4. Influent/Effluent Summary Statistics for Total Arsenic (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	8; 86 (36.0%)	8; 82 (31.7%)	1.43 - 2.81	1.30 - 2.25	1.91 (1.74; 2.22)	1.80 (1.50; 1.84)	◇◇▼
Retention Pond	4; 33 (3.0%)	4; 30 (3.3%)	0.670 - 1.80	0.525 - 1.27	1.00 (0.970; 1.50)	0.870 (0.590; 1.00)	◇◇▼
Grass Swale	10; 93 (1.1%)	9; 78 (0.0%)	0.700 - 1.90	0.700 - 1.32	1.11 (0.900; 1.50)	1.00 (0.900; 1.10)	◇◇▼
Grass Strip	34; 605 (24.3%)	33; 428 (24.1%)	0.560 - 2.20	0.583 - 2.70	1.20 (1.20; 1.30)	1.60 (1.20; 1.70)	◇△△
Bioretention	5; 146 (43.2%)	5; 136 (30.9%)	0.908 - 1.90	0.989 - 2.43	1.31 (1.20; 1.47)	1.60 (1.25; 1.71)	◇◇△
Media Filter	11; 114 (7.0%)	11; 110 (20.0%)	0.500 - 1.80	0.500 - 1.30	0.900 (0.589; 0.980)	0.765 (0.600; 0.980)	◇◇◇
Porous Pavement	6; 298 (74.5%)	7; 174 (70.7%)	0.766 - 1.77	0.535 - 2.78	1.19 (1.09; 1.27)	1.19 (0.912; 1.44)	◇◇▼

Table 5-5. Influent/Effluent Summary Statistics for Dissolved Arsenic (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	7; 54 (1.9%)	7; 52 (0.0%)	0.570 - 1.30	0.623 - 1.42	1.10 (0.790; 1.20)	1.05 (0.800; 1.21)	◇◇◇
Grass Swale	9; 51 (0.0%)	8; 37 (0.0%)	0.500 - 2.50	0.500 - 0.850	0.680 (0.500; 0.730)	0.600 (0.500; 0.660)	◇◇◇
Grass Strip	34; 617 (35.7%)	33; 433 (30.5%)	0.300 - 1.30	0.466 - 2.10	0.780 (0.690; 0.800)	1.10 (0.781; 1.20)	◇△△
Media Filter	11; 114 (14.0%)	11; 110 (22.7%)	0.280 - 1.08	0.378 - 1.00	0.500 (0.500; 0.560)	0.600 (0.500; 0.635)	◇◇◇

Notes for both tables:
*Confidence intervals about the median computed using the BCa bootstrap method described by Efron and Tibishirani (1993).
** Each symbol represents an influent/effluent comparison test. Left position compares overlap of 95% confidence intervals around influent/effluent medians. Middle position compares Mann-Whitney rank-sum hypothesis test P-value to a significance value of 0.05. Right position compares Wilcoxon signed-rank hypothesis test P-value to a significance value of 0.05.
% ND percentage of non-detects
NA not available or less than three studies for BMP/constituent
◇ influent/effluent comparison test indicates no significant difference in concentrations
▼ influent/effluent comparison test indicates significant reduction in concentrations
△ influent/effluent comparison test indicates significant *increase* in concentrations
Shaded rows indicate data sets with high percentages of non-detects in the inflow.

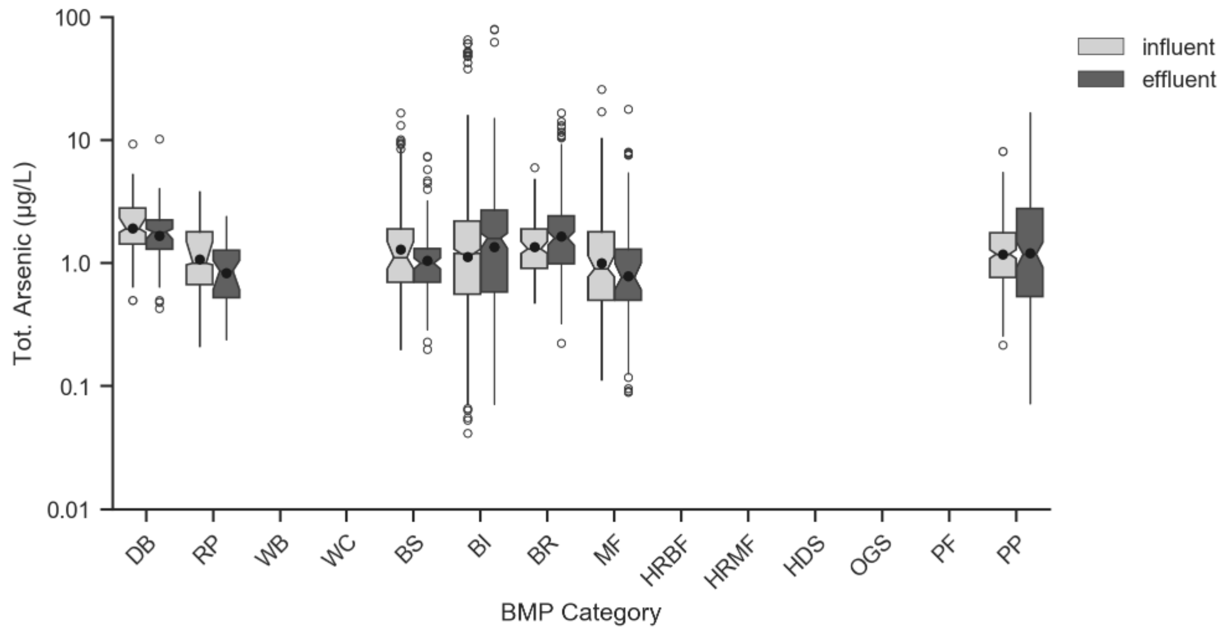

Figure 5-1. Box Plots of Influent/Effluent Total Arsenic (µg/L).

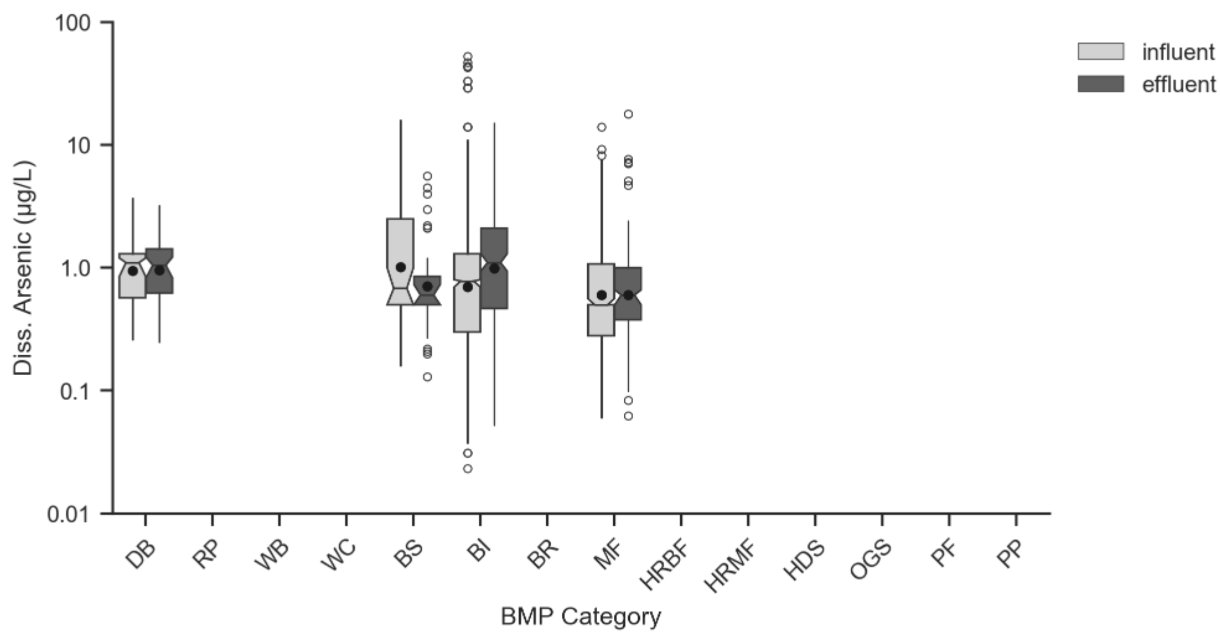

Figure 5-2. Box Plots of Influent/Effluent Dissolved Arsenic (µg/L).

5.4.2 Cadmium

Table 5-6. Influent/Effluent Summary Statistics for Total Cadmium (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	18; 234 (60.7%)	17; 219 (68.0%)	0.158 - 0.825	0.139 - 0.566	0.367 (0.294; 0.429)	0.280 (0.217; 0.320)	◇▼▼
Retention Pond	33; 518 (38.2%)	35; 545 (54.5%)	0.159 - 1.00	0.0696 - 0.477	0.400 (0.301; 0.445)	0.200 (0.154; 0.200)	▼▼▼
Wetland Basin	11; 180 (44.4%)	11; 169 (63.9%)	0.101 - 0.700	0.1000 - 0.360	0.271 (0.201; 0.312)	0.170 (0.114; 0.200)	▼▼◇
Wetland Channel	7; 55 (23.6%)	7; 52 (44.2%)	0.201 - 0.500	0.197 - 0.500	0.500 (0.226; 0.500)	0.500 (0.278; 0.500)	◇◇◇
Grass Swale	17; 188 (35.6%)	16; 164 (37.8%)	0.213 - 0.530	0.160 - 0.270	0.355 (0.284; 0.410)	0.200 (0.197; 0.200)	▼▼▼
Grass Strip	35; 620 (13.9%)	34; 437 (37.3%)	0.200 - 0.810	0.0904 - 0.400	0.480 (0.400; 0.500)	0.200 (0.200; 0.220)	▼▼▼
Bioretention	13; 232 (48.3%)	14; 216 (58.3%)	0.0605 - 0.300	0.0387 - 0.190	0.130 (0.0996; 0.152)	0.0825 (0.0647; 0.100)	◇▼▼
Media Filter	21; 264 (47.0%)	23; 286 (64.7%)	0.101 - 0.500	0.0292 - 0.200	0.247 (0.200; 0.300)	0.0772 (0.0642; 0.100)	▼▼▼
HRMF	4; 36 (63.9%)	4; 36 (63.9%)	0.0699 - 1.00	0.173 - 0.755	0.288 (0.0731; 0.885)	0.394 (0.200; 0.600)	◇◇△
HDS	9; 137 (19.0%)	9; 132 (24.2%)	0.158 - 0.470	0.109 - 0.400	0.286 (0.210; 0.319)	0.207 (0.146; 0.249)	◇▼▼
OGS	9; 118 (31.4%)	9; 89 (15.7%)	0.209 - 0.840	0.149 - 1.01	0.374 (0.347; 0.456)	0.250 (0.212; 0.330)	▼◇▼
Porous Pavement	4; 294 (63.9%)	8; 180 (76.1%)	0.141 - 0.600	0.100 - 0.254	0.277 (0.237; 0.312)	0.158 (0.141; 0.181)	▼▼▼

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

% ND percentage of non-detects
NA not available or less than three studies for BMP/constituent
◇ influent/effluent comparison test indicates no significant difference in concentrations
▼ influent/effluent comparison test indicates significant reduction in concentrations
△ influent/effluent comparison test indicates significant *increase* in concentrations
Shaded rows indicate data sets with high percentages of non-detects in the inflow.

Table 5-7. Influent/Effluent Summary Statistics for Dissolved Cadmium (μg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25^{th} – 75^{th} %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	11; 171 (72.5%)	11; 176 (76.7%)	0.0540 - 0.284	0.0411 - 0.200	0.117 (0.0927; 0.158)	0.0942 (0.0742; 0.114)	◇◇◇
Retention Pond	7; 84 (70.2%)	5; 92 (81.5%)	0.0940 - 0.271	0.125 - 0.200	0.163 (0.119; 0.200)	0.125 (0.125; 0.125)	◇◇◇
Wetland Basin	7; 55 (85.5%)	6; 40 (87.5%)	0.300 - 0.500	0.125 - 0.500	0.300 (0.300; 0.500)	0.300 (0.300; 0.500)	◇◇◇
Grass Swale	13; 88 (33.0%)	12; 74 (52.7%)	0.110 - 0.400	0.0775 - 0.200	0.200 (0.200; 0.300)	0.116 (0.0927; 0.153)	▼▼▼
Grass Strip	34; 614 (48.4%)	32; 431 (65.2%)	0.0580 - 0.255	0.0300 - 0.200	0.114 (0.100; 0.130)	0.0700 (0.0584; 0.0793)	▼▼▼
Bioretention	9; 251 (73.3%)	8; 184 (51.1%)	0.0115 - 0.0778	0.0290 - 0.151	0.0311 (0.0232; 0.0390)	0.0668 (0.0444; 0.0885)	△△△
Media Filter	12; 116 (24.1%)	13; 132 (55.3%)	0.100 - 0.200	0.0985 - 0.200	0.200 (0.115; 0.200)	0.128 (0.115; 0.146)	◇▼▼
HDS	7; 84 (21.4%)	7; 84 (17.9%)	0.0574 - 0.325	0.0378 - 0.300	0.137 (0.0821; 0.200)	0.0933 (0.0600; 0.190)	◇◇▼
OGS	5; 51 (23.5%)	5; 59 (16.9%)	0.0398 - 0.449	0.0400 - 0.282	0.155 (0.0500; 0.240)	0.101 (0.0500; 0.172)	◇◇▼
Porous Pavement	4; 304 (63.2%)	7; 148 (65.5%)	0.0956 - 0.164	0.0852 - 0.187	0.111 (0.101; 0.120)	0.109 (0.100; 0.122)	◇◇◇

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

% ND percentage of non-detects
NA not available or less than three studies for BMP/constituent
◇ influent/effluent comparison test indicates no significant difference in concentrations
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Shaded rows indicate data sets with high percentages of non-detects in the inflow.

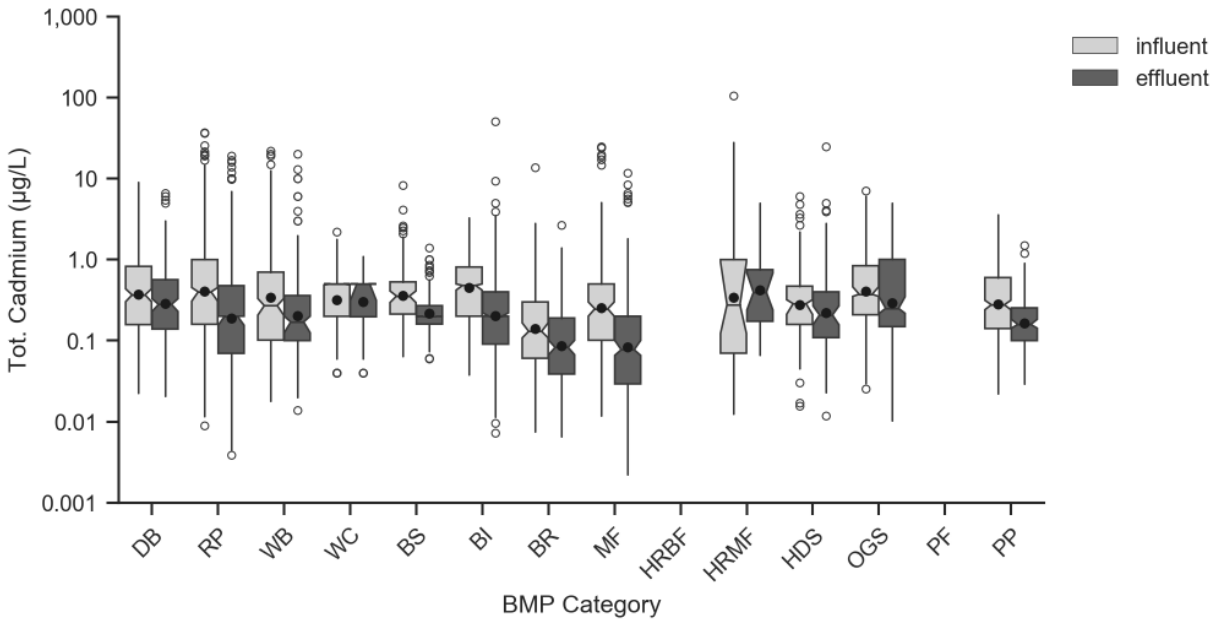

Figure 5-3. Box Plots of Influent/Effluent Total Cadmium (µg/L).

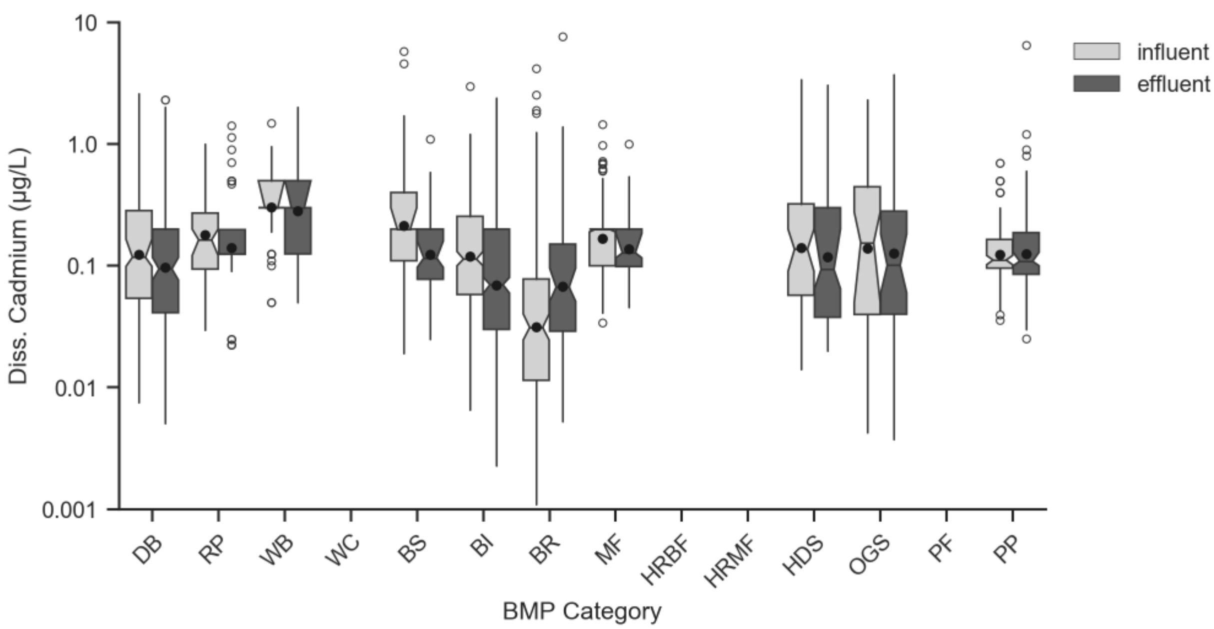

Figure 5-4. Box Plots of Influent/Effluent Dissolved Cadmium (µg/L).

5.4.3 Chromium

Table 5-8. Influent/Effluent Summary Statistics for Total Chromium (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	10; 102 (28.4%)	8; 79 (38.0%)	2.77 - 6.70	1.64 - 4.25	4.12 (3.38; 4.90)	3.10 (2.00; 3.40)	◇▼▼
Retention Pond	19; 252 (27.4%)	18; 231 (22.9%)	2.00 - 8.00	1.00 - 5.03	4.00 (3.00; 4.00)	2.00 (1.56; 2.46)	▼▼▼
Wetland Channel	6; 113 (21.2%)	6; 100 (25.0%)	1.50 - 10.5	1.18 - 12.0	4.00 (3.00; 5.00)	4.97 (3.00; 5.00)	◇◇△
Grass Swale	9; 89 (3.4%)	8; 73 (6.8%)	1.30 - 5.50	1.10 - 2.50	2.50 (2.10; 3.10)	1.80 (1.50; 2.10)	◇▼▼
Grass Strip	36; 639 (8.1%)	35; 441 (10.9%)	3.10 - 8.90	1.70 - 7.60	5.90 (5.50; 6.00)	4.20 (3.40; 4.60)	▼▼▼
Bioretention	7; 167 (34.1%)	7; 152 (66.4%)	2.21 - 7.60	0.284 - 1.87	4.00 (3.20; 4.63)	0.738 (0.510; 0.883)	▼▼▼
Media Filter	12; 125 (9.6%)	13; 127 (11.0%)	1.20 - 3.27	1.00 - 2.15	1.70 (1.50; 2.20)	1.00 (1.00; 1.20)	▼▼▼
HRMF	4; 34 (29.4%)	4; 34 (29.4%)	3.77 - 11.8	3.05 - 5.00	7.00 (4.26; 7.30)	4.40 (3.15; 5.00)	◇▼▼
HDS	3; 38 (15.8%)	3; 38 (18.4%)	2.28 - 4.44	2.30 - 4.40	3.10 (2.60; 3.58)	3.10 (2.50; 3.60)	◇◇◇
Porous Pavement	6; 324 (50.6%)	9; 198 (49.0%)	2.07 - 7.20	2.08 - 8.10	3.75 (3.37; 4.25)	4.00 (3.14; 4.89)	◇◇◇

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

% ND percentage of non-detects
NA not available or less than three studies for BMP/constituent
◇ influent/effluent comparison test indicates no significant difference in concentrations
▼ influent/effluent comparison test indicates significant reduction in concentrations
△ influent/effluent comparison test indicates significant increase in concentration
Shaded rows indicate data sets with high percentages of non-detects in the inflow.

Table 5-9. Influent/Effluent Summary Statistics for Dissolved Chromium (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25^{th} – 75^{th} %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	7; 70 (38.6%)	7; 63 (38.1%)	0.631 - 2.97	0.536 - 2.00	1.25 (0.893; 1.53)	1.00 (0.759; 1.40)	◇◇▼
Retention Pond	6; 48 (14.6%)	4; 81 (42.0%)	1.00 - 2.00	0.871 - 1.00	1.02 (1.00; 1.45)	1.00 (1.00; 1.00)	◇▼▼
Grass Swale	7; 43 (9.3%)	6; 29 (20.7%)	1.00 - 3.45	1.00 - 3.20	1.50 (1.10; 2.60)	1.20 (1.00; 2.70)	◇◇◇
Grass Strip	34; 617 (14.4%)	33; 434 (17.3%)	1.18 - 4.60	1.00 - 4.40	2.70 (2.20; 2.80)	2.30 (2.00; 2.70)	◇◇◇
Bioretention	4; 193 (58.0%)	3; 114 (75.4%)	0.293 - 1.30	0.287 - 0.700	0.606 (0.466; 0.726)	0.463 (0.371; 0.538)	◇▼▼
Media Filter	12; 124 (17.7%)	12; 109 (16.5%)	0.500 - 1.00	0.576 - 1.00	1.00 (0.686; 1.00)	1.00 (1.00; 1.00)	◇◇△
HDS	3; 29 (0.0%)	3; 29 (0.0%)	1.40 - 2.30	1.50 - 2.10	1.80 (1.30; 1.80)	1.80 (1.50; 2.00)	◇◇◇
Porous Pavement	6; 322 (86.3%)	5; 146 (8.9%)	0.500 - 0.500	1.80 - 3.90	0.500 (0.500; 0.500)	2.80 (2.30; 2.95)	△△△

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

% ND percentage of non-detects
NA not available or less than three studies for BMP/constituent
◇ influent/effluent comparison test indicates no significant difference in concentrations
▼ influent/effluent comparison test indicates significant reduction in concentrations
△ influent/effluent comparison test indicates significant increase in concentration
Shaded rows indicate data sets with high percentages of non-detects in the inflow.

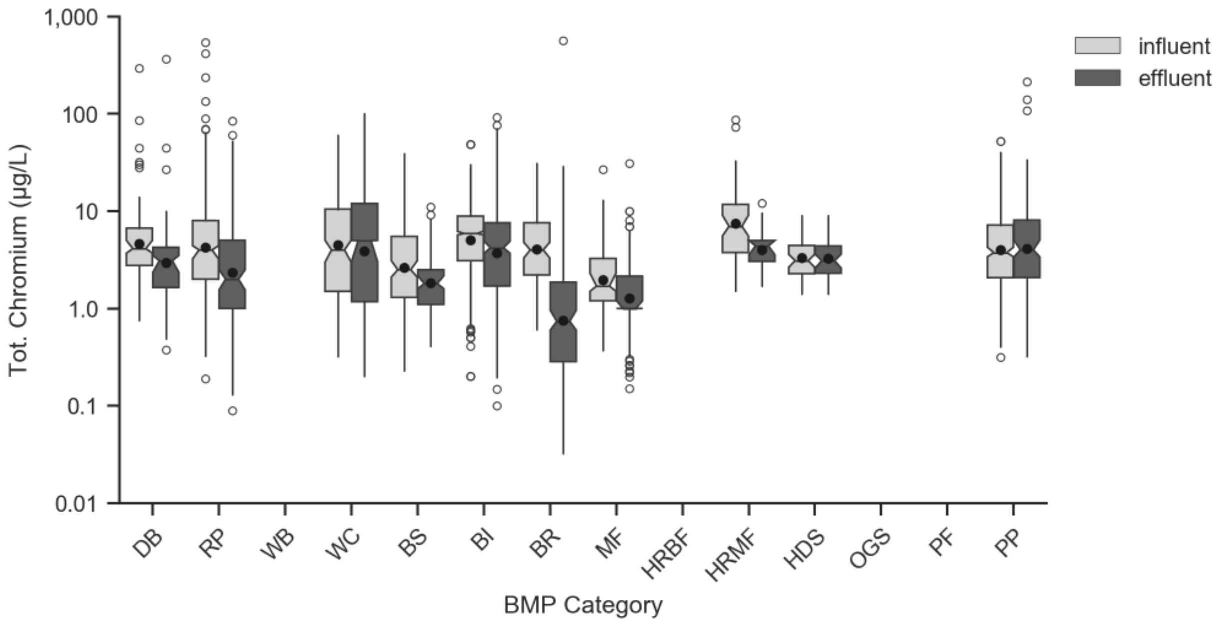

Figure 5-5. Box Plots of Influent/Effluent Total Chromium (µg/L).

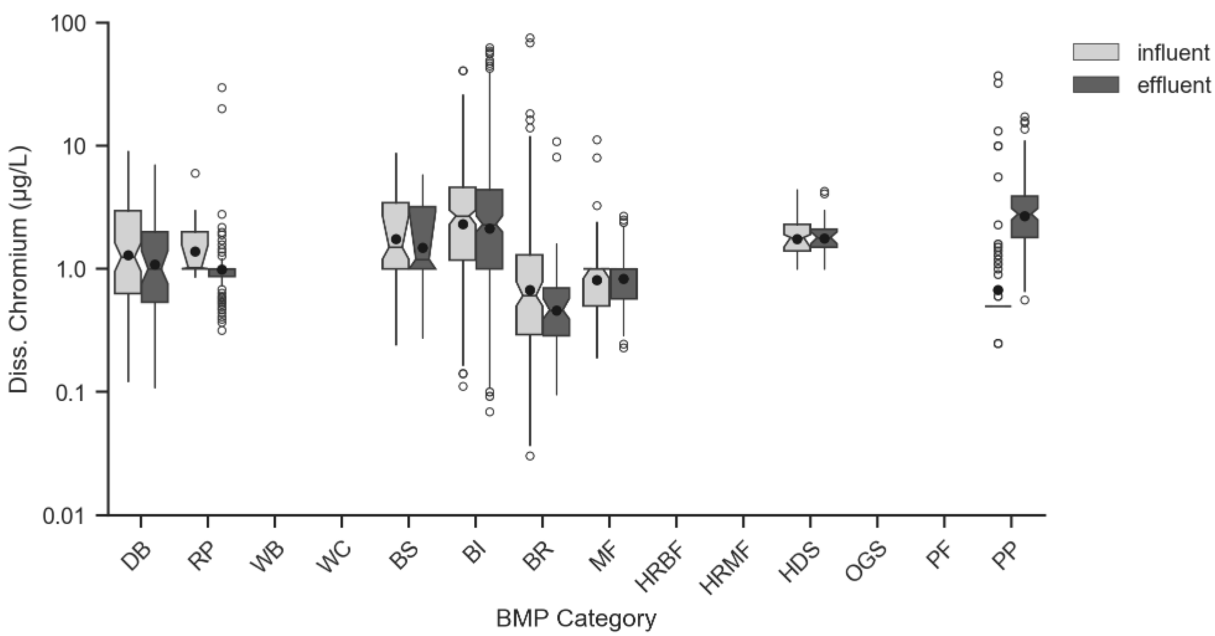

Figure 5-6. Box Plots of Influent/Effluent Dissolved Chromium (µg/L).

5.4.4 Copper

Table 5-10. Influent/Effluent Summary Statistics for Total Copper (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	23; 359 (6.4%)	23; 370 (19.5%)	4.04 - 23.5	2.00 - 12.5	8.75 (7.25; 10.0)	4.58 (3.74; 5.48)	▼▼▼
Retention Pond	52; 934 (8.8%)	54; 922 (16.9%)	4.76 - 18.3	2.70 - 8.00	9.59 (8.95; 10.0)	4.90 (4.42; 5.00)	▼▼▼
Wetland Basin	14; 298 (8.1%)	14; 258 (18.2%)	4.27 - 11.8	2.00 - 6.00	7.40 (6.46; 8.22)	3.32 (3.00; 4.00)	▼▼▼
Wetland Channel	7; 123 (6.5%)	7; 120 (5.8%)	3.79 - 14.5	4.90 - 12.0	10.0 (5.40; 10.0)	10.0 (10.0; 10.0)	◇◇◇
Grass Swale	23; 378 (8.7%)	27; 476 (9.5%)	6.00 - 24.1	3.50 - 13.9	12.1 (10.2; 14.0)	6.90 (6.00; 7.80)	▼▼▼
Grass Strip	41; 745 (0.4%)	40; 526 (0.4%)	12.0 - 52.0	5.44 - 25.0	25.0 (22.0; 26.0)	12.0 (10.0; 13.0)	▼▼▼
Bioretention	30; 512 (0.4%)	27; 469 (2.6%)	6.40 - 30.0	4.12 - 14.0	13.1 (11.4; 15.1)	7.13 (6.40; 8.20)	▼▼▼
Media Filter	27; 434 (6.9%)	30; 458 (12.7%)	5.77 - 18.0	2.30 - 9.27	10.0 (9.50; 11.0)	4.65 (4.00; 5.21)	▼▼▼
HRBF	4; 46 (2.2%)	4; 46 (6.5%)	4.33 - 11.3	3.03 - 5.57	7.95 (5.40; 8.90)	3.75 (3.20; 4.80)	▼▼▼
HRMF	15; 278 (2.2%)	15; 278 (5.8%)	6.22 - 30.8	4.00 - 16.1	12.0 (9.58; 13.2)	8.14 (6.75; 9.14)	▼▼▼
HDS	14; 215 (0.5%)	14; 209 (1.0%)	8.38 - 22.0	7.72 - 22.0	14.6 (12.0; 16.0)	13.0 (11.1; 14.2)	◇◇▼
OGS	11; 155 (0.0%)	11; 128 (0.8%)	4.90 - 25.8	3.80 - 18.4	12.8 (8.72; 15.2)	11.1 (6.25; 13.6)	◇▼▼
PFC	NA	3; 69 (0.0%)	NA	7.42 - 14.7	NA	11.2 (8.94; 13.2)	NA
Porous Pavement	14; 368 (2.2%)	17; 313 (14.1%)	8.40 - 27.8	5.00 - 14.5	12.9 (11.8; 14.3)	8.30 (7.70; 9.00)	▼▼▼

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

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

Table 5-11. Influent/Effluent Summary Statistics for Dissolved Copper (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	14; 258 (14.3%)	14; 270 (23.0%)	2.01 - 9.40	1.41 - 8.07	3.96 (3.56; 5.00)	2.99 (2.22; 3.20)	▼▼▼
Retention Pond	22; 432 (6.9%)	22; 424 (9.0%)	3.11 - 8.00	2.40 - 5.30	5.08 (4.60; 5.50)	3.50 (3.19; 3.80)	▼▼▼
Wetland Basin	9; 125 (10.4%)	8; 110 (20.9%)	2.65 - 5.90	1.24 - 4.23	3.95 (3.33; 4.30)	2.29 (1.77; 3.33)	◇▼◇
Grass Swale	16; 174 (4.0%)	16; 141 (2.1%)	3.30 - 13.7	3.56 - 9.46	6.50 (5.00; 7.80)	5.63 (4.83; 6.74)	◇◇▼
Grass Strip	39; 717 (2.1%)	38; 515 (4.1%)	5.30 - 23.0	3.60 - 14.0	12.0 (9.57; 12.0)	7.40 (6.60; 8.30)	▼▼▼
Bioretention	16; 360 (2.8%)	14; 261 (7.3%)	4.07 - 14.3	3.41 - 19.0	6.85 (5.99; 7.87)	7.54 (6.50; 8.40)	◇◇△
Media Filter	14; 210 (5.2%)	16; 233 (5.6%)	1.75 - 7.98	1.50 - 6.50	3.86 (2.99; 4.49)	3.00 (2.30; 3.50)	◇▼▼
HRBF	4; 38 (10.5%)	4; 38 (7.9%)	2.92 - 6.65	2.00 - 4.15	4.50 (2.93; 5.00)	3.40 (2.30; 3.84)	◇▼▼
HRMF	13; 217 (12.0%)	13; 217 (11.1%)	2.00 - 7.70	2.00 - 8.00	4.00 (3.58; 4.60)	4.38 (3.41; 5.00)	◇◇◇
HDS	9; 123 (4.9%)	9; 123 (4.1%)	4.75 - 14.7	4.60 - 13.0	9.00 (6.80; 9.80)	8.50 (6.50; 10.0)	◇◇▼
OGS	5; 52 (0.0%)	5; 58 (0.0%)	3.85 - 23.6	5.82 - 17.0	11.0 (7.86; 14.6)	10.1 (7.23; 14.0)	◇◇◇
PFC	NA	3; 69 (0.0%)	NA	4.88 - 11.8	NA	8.40 (5.93; 9.33)	NA
Porous Pavement	9; 310 (10.3%)	10; 229 (4.4%)	3.60 - 8.60	3.80 - 8.00	5.60 (5.10; 5.85)	5.70 (5.05; 6.00)	◇◇△

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

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◇ influent/effluent comparison test indicates no significant difference in concentrations
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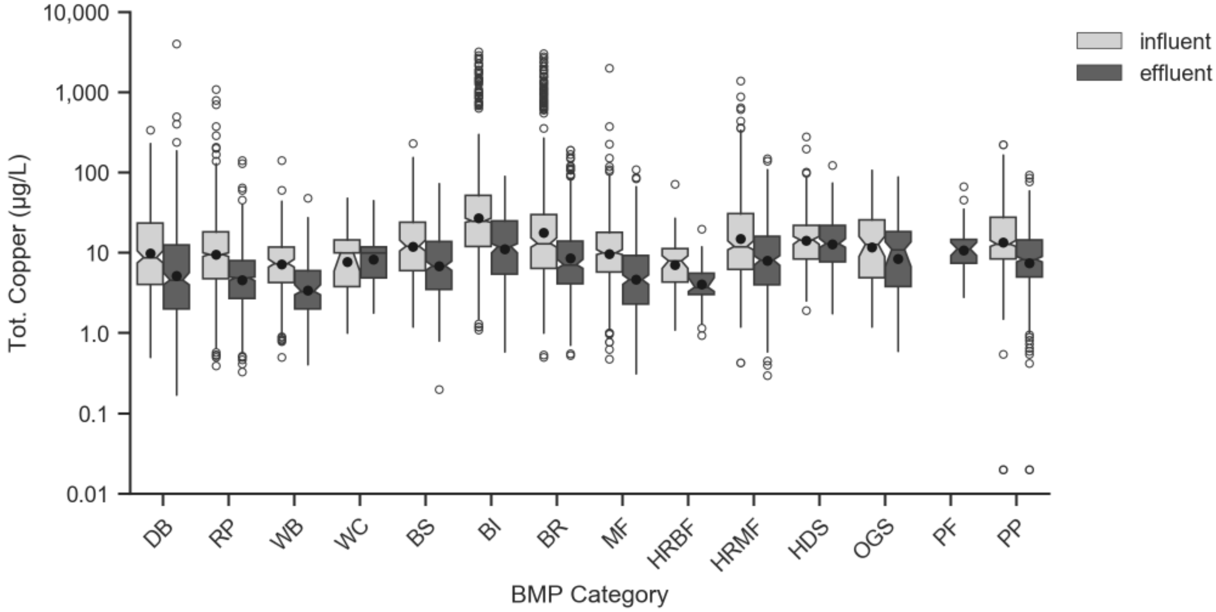

Figure 5-7. Box Plots of Influent/Effluent Total Copper (µg/L).

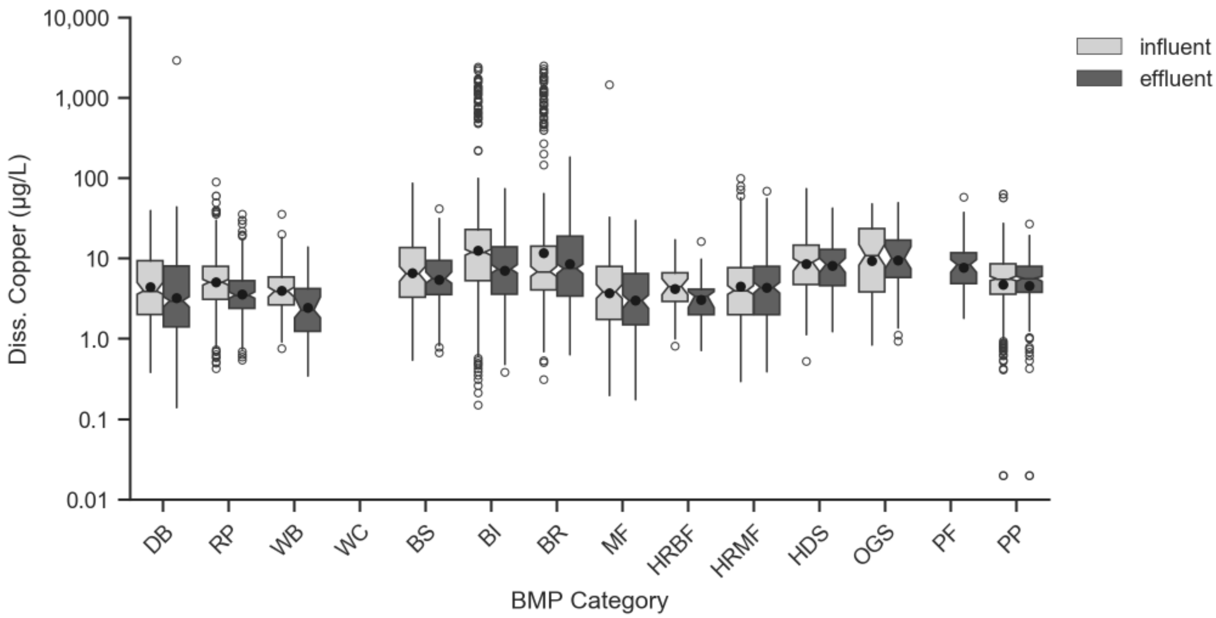

Figure 5-8. Box Plots of Influent/Effluent Dissolved Copper (µg/L).

5.4.5 Iron

Table 5-12. Influent/Effluent Summary Statistics for Total Iron (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Retention Pond	16; 317 (1.3%)	18; 345 (2.0%)	393 - 3,160	157 - 523	1,050 (830; 1,200)	285 (240; 345)	▼▼▼
Grass Swale	4; 98 (0.0%)	6; 136 (5.1%)	123 - 850	45.0 - 401	216 (172; 458)	136 (88.5; 210)	◇▼▼
Grass Strip	14; 192 (6.2%)	13; 162 (10.5%)	312 - 1,660	111 - 1,030	746 (553; 920)	320 (240; 402)	▼▼▼
Bioretention	4; 54 (0.0%)	5; 74 (0.0%)	272 - 828	200 - 1,400	556 (378; 645)	595 (384; 935)	◇◇△
Media Filter	9; 184 (0.0%)	9; 165 (1.2%)	305 - 1,430	106 - 449	685 (515; 790)	195 (163; 243)	▼▼▼
Porous Pavement	NA	3; 43 (16.3%)	NA	197 - 678	NA	365 (196; 379)	NA

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

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

Table 5-13. Influent/Effluent Summary Statistics for Dissolved Iron (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Retention Pond	6; 164 (10.4%)	5; 125 (20.8%)	31.0 - 210	27.2 - 120	90.0 (60.0; 110)	64.0 (46.0; 72.2)	◇▼▼
Grass Strip	12; 159 (36.5%)	12; 132 (25.8%)	19.5 - 123	27.8 - 162	39.0 (30.0; 49.0)	55.5 (40.3; 69.5)	◇△△
Porous Pavement	6; 320 (26.2%)	4; 146 (13.7%)	35.5 - 110	70.0 - 210	70.0 (50.0; 70.0)	110 (86.8; 115)	△△△

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

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

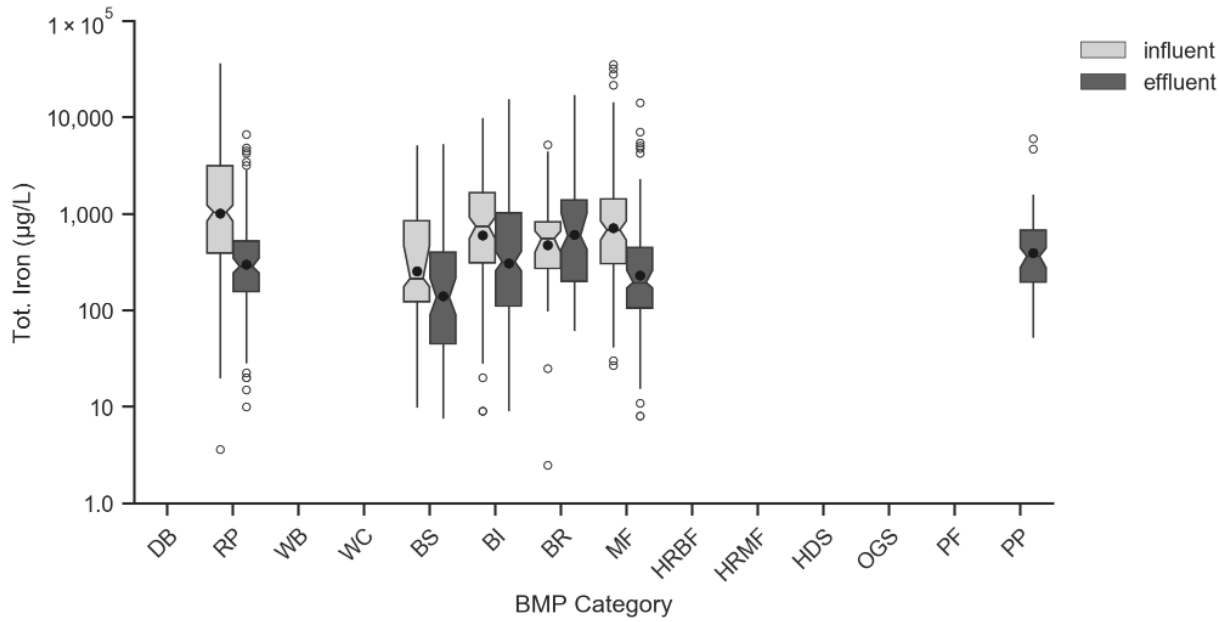

Figure 5-9. Box Plots of Influent/Effluent Total Iron (µg/L).

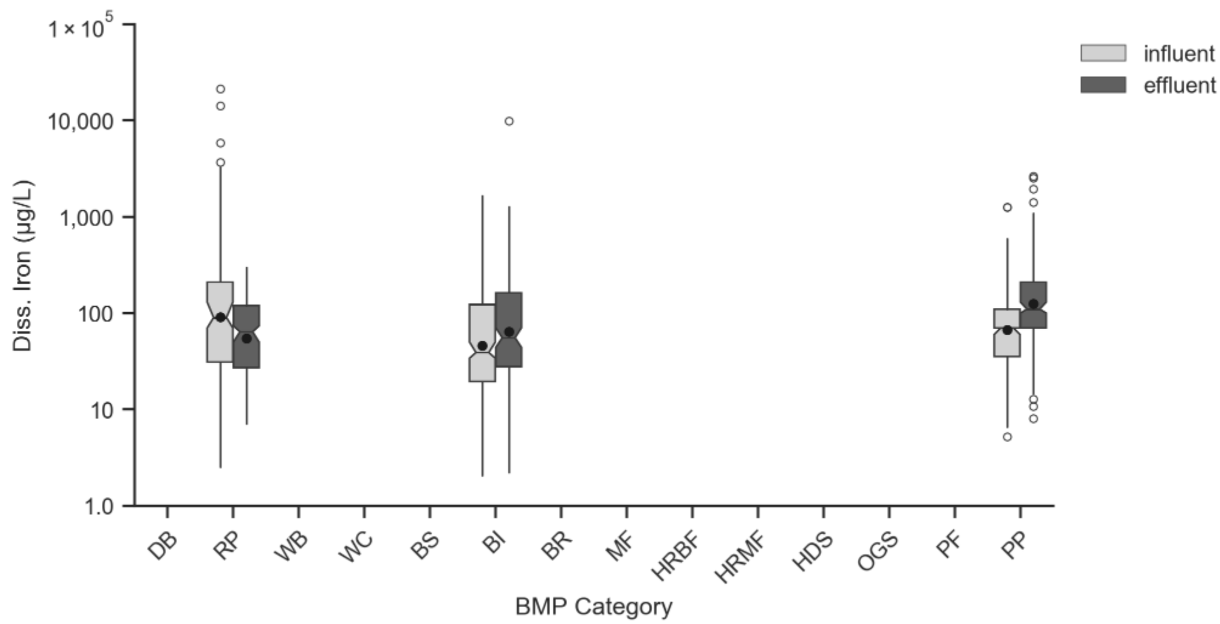

Figure 5-10. Box Plots of Influent/Effluent Dissolved Iron (µg/L).

5.4.6 Lead

Table 5-14. Influent/Effluent Summary Statistics for Total Lead (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25^{th} – 75^{th} %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	20; 315 (33.3%)	19; 289 (44.3%)	2.10 - 34.1	1.25 - 14.0	8.00 (5.44; 10.7)	3.89 (2.89; 5.16)	▼▼▼
Retention Pond	51; 832 (18.5%)	52; 850 (28.5%)	2.79 - 26.0	1.00 - 8.01	9.00 (6.90; 9.50)	3.00 (2.37; 3.00)	▼▼▼
Wetland Basin	12; 200 (3.5%)	12; 174 (23.0%)	1.51 - 10.0	0.800 - 5.00	3.48 (2.42; 4.94)	1.68 (1.00; 2.00)	▼▼▼
Wetland Channel	11; 176 (6.8%)	10; 145 (9.7%)	1.97 - 16.4	1.44 - 7.83	5.65 (4.81; 6.30)	5.00 (5.00; 5.20)	◇▼▼
Grass Swale	22; 337 (22.8%)	26; 450 (42.4%)	1.70 - 15.9	0.787 - 5.08	3.80 (2.70; 4.03)	1.90 (1.59; 2.00)	▼▼▼
Grass Strip	38; 685 (7.7%)	37; 480 (20.6%)	3.10 - 30.0	1.00 - 13.0	7.50 (6.20; 8.80)	3.40 (2.55; 3.85)	▼▼▼
Bioretention	26; 325 (15.4%)	22; 289 (36.3%)	2.20 - 13.8	0.284 - 3.00	5.70 (4.40; 6.09)	0.932 (0.723; 1.07)	▼▼▼
Media Filter	26; 388 (11.3%)	27; 397 (31.2%)	3.12 - 20.0	0.610 - 3.67	9.30 (7.53; 11.0)	1.40 (1.10; 1.70)	▼▼▼
HRMF	7; 103 (10.7%)	7; 103 (21.4%)	7.01 - 43.0	2.56 - 14.5	14.6 (9.40; 20.1)	5.00 (3.37; 5.00)	▼▼▼
HDS	10; 141 (12.8%)	10; 135 (14.1%)	4.70 - 18.0	4.01 - 14.2	9.83 (7.80; 12.0)	7.50 (6.08; 8.96)	◇▼▼
OGS	9; 117 (0.0%)	9; 89 (5.6%)	4.80 - 30.6	0.511 - 13.1	16.6 (9.96; 19.2)	1.90 (0.615; 3.75)	▼▼▼
Porous Pavement	10; 342 (44.4%)	18; 297 (62.6%)	1.25 - 11.3	0.447 - 5.90	4.30 (2.90; 5.36)	1.38 (1.09; 1.70)	▼▼▼

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

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

Table 5-15. Influent/Effluent Summary Statistics for Dissolved Lead (μg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25^{th} – 75^{th} %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	12; 210 (65.2%)	12; 209 (67.5%)	0.190 - 1.70	0.184 - 1.49	0.539 (0.385; 0.769)	0.486 (0.359; 0.649)	◇◇▼
Retention Pond	16; 203 (45.3%)	15; 209 (47.4%)	0.101 - 4.00	0.0876 - 3.00	0.753 (0.342; 1.08)	0.465 (0.262; 1.00)	◇◇◇
Wetland Basin	7; 55 (69.1%)	6; 40 (67.5%)	0.373 - 1.52	0.324 - 1.30	0.735 (0.460; 0.906)	0.602 (0.370; 0.851)	◇◇◇
Wetland Channel	3; 32 (50.0%)	3; 27 (63.0%)	0.687 - 7.80	0.0747 - 3.40	1.09 (0.853; 6.00)	0.410 (0.0418; 0.740)	▼▼◇
Grass Swale	14; 114 (15.8%)	14; 97 (19.6%)	0.600 - 6.07	0.490 - 3.21	1.30 (0.826; 1.50)	1.05 (0.760; 1.60)	◇◇▼
Grass Strip	34; 624 (47.8%)	33; 446 (55.4%)	0.0901 - 2.60	0.0900 - 1.47	0.399 (0.275; 0.480)	0.302 (0.225; 0.386)	◇◇▼
Bioretention	12; 264 (70.5%)	10; 187 (66.8%)	0.0443 - 0.196	0.0316 - 0.152	0.0935 (0.0767; 0.110)	0.0739 (0.0506; 0.0878)	◇▼◇
Media Filter	12; 162 (21.6%)	13; 178 (30.9%)	0.372 - 1.50	0.230 - 1.00	1.00 (1.00; 1.00)	1.00 (0.317; 1.00)	◇△△
HDS	7; 88 (22.7%)	7; 88 (19.3%)	0.428 - 2.59	0.500 - 3.02	0.883 (0.625; 1.10)	0.959 (0.690; 1.35)	◇◇◇
OGS	5; 52 (11.5%)	5; 59 (27.1%)	0.0460 - 0.195	0.0180 - 0.184	0.0900 (0.0555; 0.130)	0.0500 (0.0300; 0.0670)	◇▼◇
Porous Pavement	6; 296 (89.5%)	9; 206 (85.9%)	0.500 - 0.500	0.500 - 1.80	0.500 (0.500; 0.500)	0.500 (0.500; 0.500)	◇△◇

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

% ND percentage of non-detects
NA not available or less than three studies for BMP/constituent
◇ influent/effluent comparison test indicates no significant difference in concentrations
▼ influent/effluent comparison test indicates significant reduction in concentrations
△ influent/effluent comparison test indicates significant *increase* in concentrations
Shaded rows indicate data sets with high percentages of non-detects in the inflow.

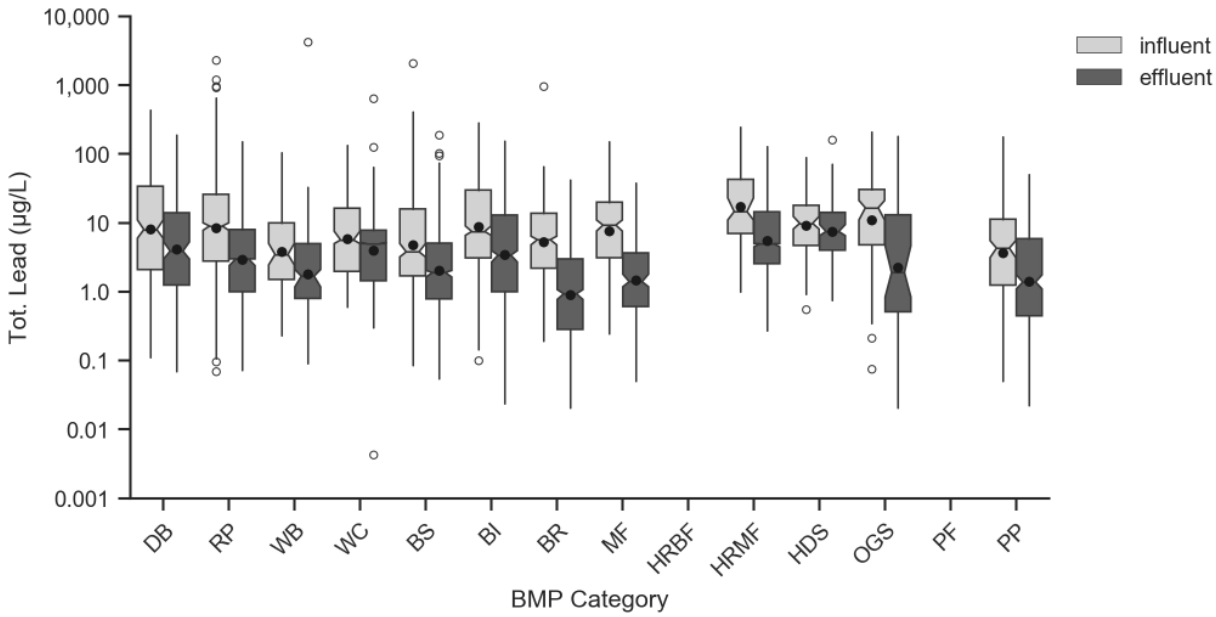

Figure 5-11. Box Plots of Influent/Effluent Total Lead (µg/L).

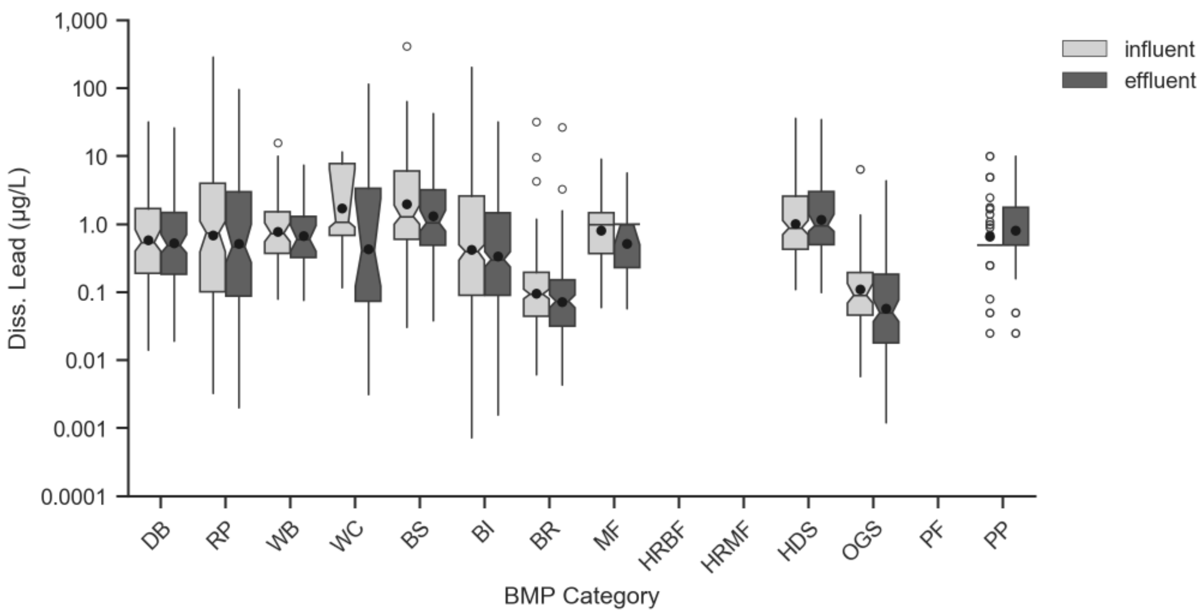

Figure 5-12. Box Plots of Influent/Effluent Dissolved Lead (µg/L).

5.4.7 Nickel

Table 5-16. Influent/Effluent Summary Statistics for Total Nickel (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	10; 102 (5.9%)	9; 87 (13.8%)	3.21 - 7.80	2.00 - 4.95	5.00 (4.75; 5.55)	3.00 (2.28; 3.30)	▼▼▼
Retention Pond	13; 187 (33.7%)	14; 169 (26.6%)	2.00 - 7.90	1.82 - 7.47	3.37 (3.00; 4.00)	2.50 (2.10; 3.00)	◇◇▼
Wetland Channel	6; 111 (21.6%)	6; 98 (27.6%)	2.69 - 32.2	2.20 - 32.0	5.00 (3.00; 7.19)	6.21 (3.18; 20.0)	◇◇◇
Grass Swale	8; 83 (0.0%)	7; 67 (0.0%)	1.55 - 8.05	1.15 - 2.55	2.90 (2.20; 4.00)	2.00 (1.30; 2.10)	▼▼▼
Grass Strip	35; 616 (10.1%)	34; 439 (14.6%)	3.20 - 8.50	2.18 - 5.20	5.20 (4.60; 5.60)	3.20 (2.90; 3.30)	▼▼▼
Bioretention	5; 144 (17.4%)	5; 132 (18.2%)	2.40 - 7.02	1.87 - 4.16	4.20 (3.45; 5.00)	2.80 (2.20; 3.07)	▼▼▼
Media Filter	12; 125 (8.8%)	13; 127 (21.3%)	2.00 - 5.10	1.41 - 4.15	3.35 (2.70; 3.63)	2.20 (2.00; 2.70)	◇▼▼
HDS	6; 75 (4.0%)	6; 75 (4.0%)	3.17 - 7.85	3.07 - 7.21	5.40 (4.00; 6.00)	5.00 (3.50; 5.20)	◇◇◇
Porous Pavement	4; 318 (13.2%)	7; 190 (16.8%)	2.40 - 6.40	1.42 - 5.00	3.65 (3.30; 3.84)	2.30 (1.82; 2.45)	▼▼▼

Table 5-17. Influent/Effluent Summary Statistics for Dissolved Nickel (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25^{th} – 75^{th} %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	8; 85 (18.8%)	8; 79 (15.2%)	1.21 - 4.00	1.22 - 3.20	2.30 (2.00; 2.80)	2.00 (1.60; 2.50)	◇◇◇
Retention Pond	4; 17 (0.0%)	4; 17 (0.0%)	1.00 - 2.00	1.13 - 4.40	1.80 (0.915; 2.00)	2.30 (1.00; 3.70)	◇◇△
Grass Swale	6; 37 (0.0%)	5; 23 (0.0%)	2.90 - 9.00	2.00 - 2.50	4.90 (4.30; 5.70)	2.00 (2.00; 2.50)	▼▼▼
Grass Strip	34; 617 (25.4%)	33; 435 (32.0%)	1.20 - 4.30	1.32 - 3.30	2.70 (2.50; 2.80)	2.10 (2.00; 2.50)	◇▼▼
Media Filter	12; 124 (21.8%)	12; 119 (31.1%)	0.892 - 2.64	0.771 - 2.15	2.00 (1.00; 2.00)	2.00 (1.03; 2.00)	◇◇◇
HDS	6; 74 (8.1%)	6; 75 (6.7%)	1.66 - 3.89	1.57 - 4.25	2.42 (2.00; 3.22)	2.60 (2.00; 3.00)	◇◇◇
Porous Pavement	6; 310 (41.3%)	4; 137 (73.0%)	0.561 - 1.69	0.338 - 0.961	1.00 (0.799; 1.05)	0.599 (0.477; 0.695)	▼▼▼

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

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

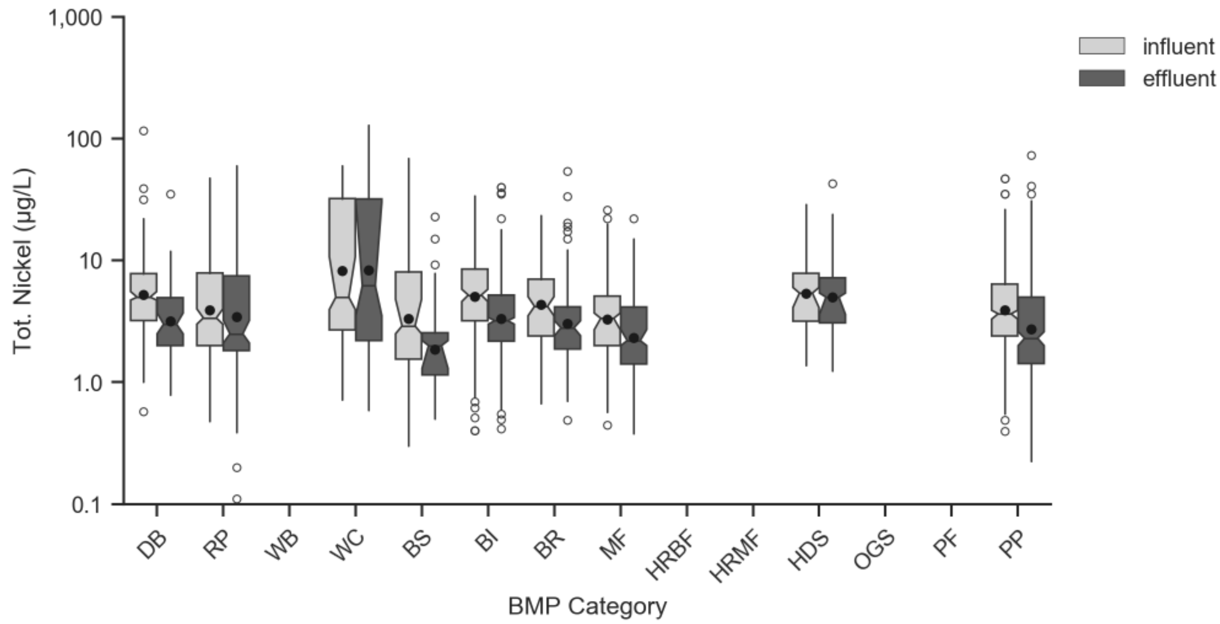

Figure 5-13. Box Plots of Influent/Effluent Total Nickel (µg/L).

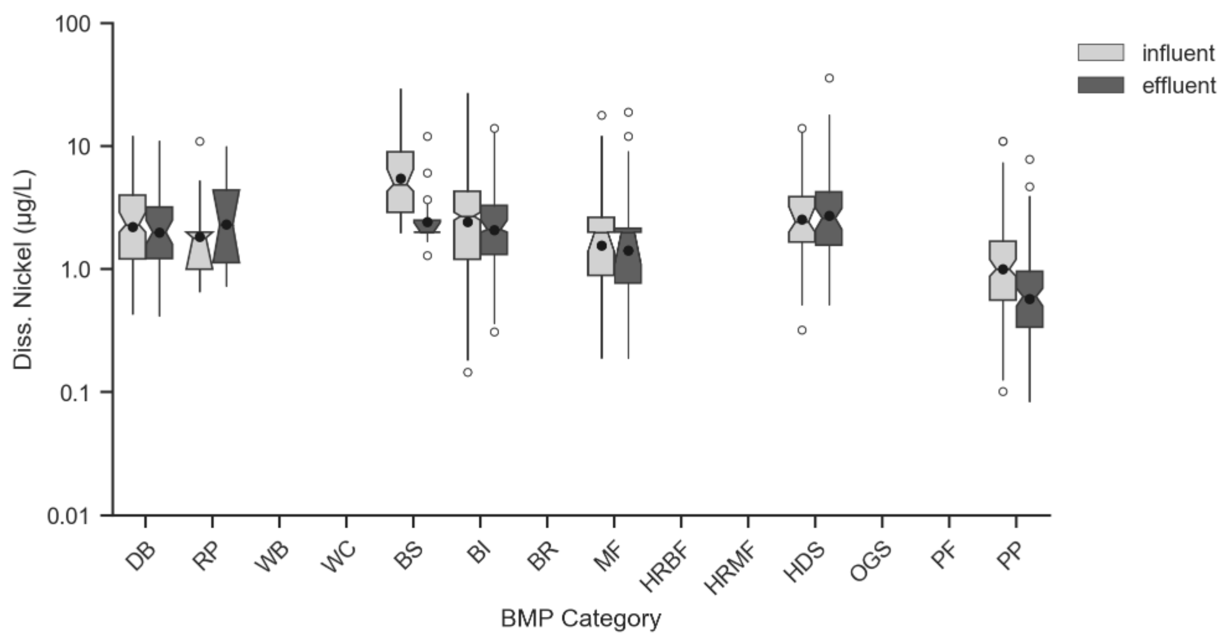

Figure 5-14. Box Plots of Influent/Effluent Dissolved Nickel (µg/L).

5.4.8 Zinc

Table 5-18. Influent/Effluent Summary Statistics for Total Zinc (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	26; 393 (4.6%)	27; 430 (8.8%)	20.0 - 119	6.94 - 58.0	51.7 (40.4; 58.3)	17.3 (14.3; 21.7)	▼▼▼
Retention Pond	60; 1032 (7.1%)	63; 995 (11.8%)	27.3 - 100	10.0 - 40.0	50.0 (43.9; 50.1)	21.2 (20.0; 23.0)	▼▼▼
Wetland Basin	19; 342 (1.2%)	19; 308 (11.0%)	34.1 - 94.6	11.5 - 37.1	52.5 (45.3; 57.6)	20.1 (17.0; 23.0)	▼▼▼
Wetland Channel	9; 161 (6.8%)	9; 153 (10.5%)	14.0 - 50.0	10.0 - 36.0	27.0 (20.0; 30.0)	20.0 (13.0; 20.0)	◇▼▼
Grass Swale	27; 425 (10.8%)	31; 513 (23.6%)	22.0 - 109	16.0 - 50.0	45.6 (40.0; 51.0)	25.8 (22.6; 28.8)	▼▼▼
Grass Strip	42; 743 (0.5%)	41; 533 (2.8%)	46.0 - 240	15.0 - 74.0	110 (93.0; 115)	36.0 (30.0; 39.0)	▼▼▼
Bioretention	29; 500 (1.2%)	26; 454 (14.3%)	31.0 - 140	6.26 - 23.4	62.0 (52.4; 69.0)	12.8 (11.0; 14.0)	▼▼▼
Media Filter	31; 508 (3.0%)	34; 531 (13.6%)	24.0 - 126	4.43 - 30.1	62.3 (55.2; 69.5)	15.0 (12.7; 16.2)	▼▼▼
HRBF	5; 54 (0.0%)	5; 54 (11.1%)	53.2 - 388	20.0 - 112	178 (82.2; 228)	60.6 (25.0; 80.5)	▼▼▼
HRMF	19; 344 (2.0%)	19; 344 (2.6%)	32.0 - 152	20.0 - 79.2	59.8 (51.0; 69.0)	38.1 (32.6; 43.0)	▼▼▼
HDS	18; 268 (0.0%)	18; 262 (1.9%)	41.0 - 130	36.9 - 120	79.0 (67.3; 89.0)	62.2 (54.1; 69.2)	◇▼▼
OGS	10; 154 (0.0%)	10; 126 (0.0%)	35.0 - 232	35.2 - 166	97.9 (80.8; 138)	83.2 (65.1; 106)	◇◇▼
PFC	NA	3; 69 (0.0%)	NA	14.6 - 31.0	NA	21.2 (15.9; 23.1)	NA
Porous Pavement	16; 393 (7.6%)	22; 346 (30.1%)	30.1 - 121	9.70 - 34.0	60.0 (50.4; 62.5)	20.0 (14.5; 20.0)	▼▼▼

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

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

Table 5-19. Influent/Effluent Summary Statistics for Dissolved Zinc (µg/L).

BMP Category	Study & Sample Count (% ND)		Interquartile Range (25th – 75th %tiles)		Median (95% Conf. Interval)*		In vs Out**
	In	Out	In	Out	In	Out	
Detention Basin	14; 258 (3.9%)	14; 271 (6.3%)	5.78 - 38.5	3.38 - 24.0	12.1 (9.15; 14.1)	9.38 (6.90; 10.4)	◇▼▼
Retention Pond	25; 431 (5.8%)	25; 413 (8.0%)	10.0 - 43.3	5.60 - 32.0	23.4 (20.0; 26.0)	16.0 (13.9; 17.6)	▼▼▼
Wetland Basin	9; 125 (3.2%)	8; 110 (3.6%)	13.7 - 35.8	4.32 - 14.8	22.6 (20.1; 25.0)	8.35 (6.62; 9.00)	▼▼▼
Wetland Channel	3; 64 (46.9%)	4; 59 (47.5%)	4.61 - 20.0	3.96 - 19.6	10.1 (6.37; 16.9)	10.0 (4.47; 10.0)	◇◇◇
Grass Swale	16; 174 (2.9%)	16; 141 (5.0%)	17.1 - 69.4	13.3 - 32.0	34.2 (27.3; 35.8)	19.8 (16.7; 21.7)	▼▼▼
Grass Strip	37; 669 (5.4%)	36; 478 (12.8%)	13.0 - 79.0	7.62 - 33.0	33.6 (30.0; 39.0)	17.0 (15.0; 19.0)	▼▼▼
Bioretention	13; 292 (9.6%)	11; 215 (11.2%)	11.9 - 49.3	3.47 - 19.5	20.8 (16.9; 22.3)	12.5 (9.00; 13.8)	▼▼▼
Media Filter	13; 207 (1.0%)	15; 228 (17.1%)	12.0 - 88.5	2.20 - 19.0	32.0 (24.3; 37.2)	7.15 (4.49; 8.93)	▼▼▼
HRBF	4; 38 (0.0%)	4; 38 (7.9%)	109 - 377	28.2 - 212	189 (148; 312)	79.0 (53.5; 105)	▼▼▼
HRMF	14; 228 (0.4%)	14; 228 (1.8%)	9.00 - 35.2	11.0 - 38.5	16.2 (14.0; 18.6)	18.8 (15.7; 20.1)	◇◇◇
HDS	9; 122 (1.6%)	9; 123 (1.6%)	18.1 - 85.0	20.0 - 79.0	43.3 (31.4; 48.0)	42.0 (30.1; 52.0)	◇◇◇
OGS	5; 51 (0.0%)	5; 59 (0.0%)	18.1 - 146	31.4 - 159	31.9 (24.0; 58.0)	70.0 (44.8; 83.4)	◇◇◇
PFC	NA	3; 68 (0.0%)	NA	8.38 - 19.5	NA	13.1 (10.0; 16.4)	NA
Porous Pavement	9; 310 (11.3%)	10; 229 (50.2%)	10.8 - 30.0	1.60 - 11.6	17.8 (15.9; 19.9)	4.09 (3.05; 5.50)	▼▼▼

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

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

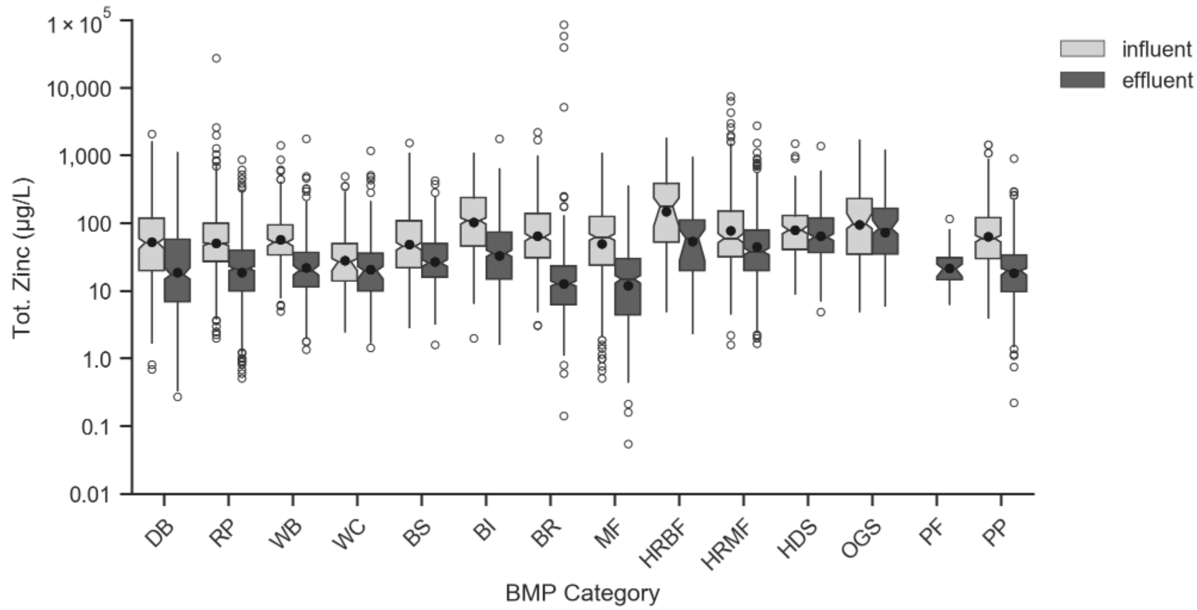

Figure 5-15. Box Plots of Influent/Effluent Total Zinc (µg/L).

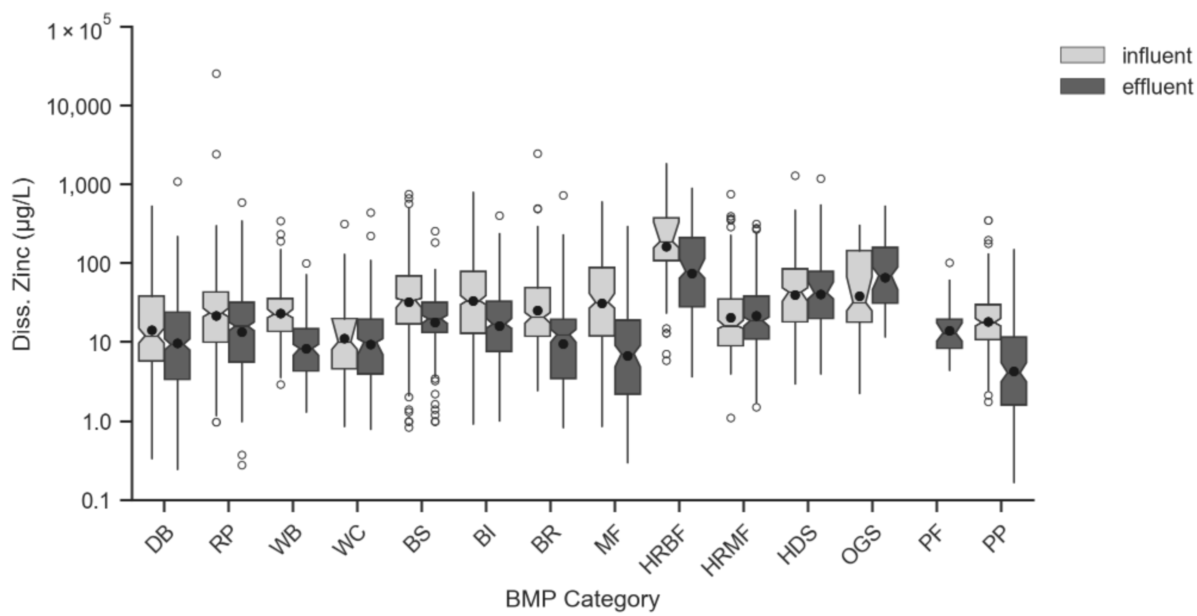

Figure 5-16. Box Plots of Influent/Effluent Dissolved Zinc (µg/L).

5.5 Performance Findings and Discussion

Metals in this analysis include the total and dissolved forms of arsenic, cadmium, chromium, copper, iron, lead, nickel and zinc. Overall, most BMP categories provided good pollutant removal for most total metals. Performance for dissolved metals are more mixed. Many conventional BMP types do not provide unit processes expected to be effective for dissolved metals. In some cases, inconclusive findings for dissolved metals may also be affected by low influent concentrations and large percentages of non-detects in the data set.

Findings for arsenic include:

- Sufficient data for analysis for total arsenic are available for detention basins, retention ponds, grass swales, grass strips, bioretention, and media filters. Interpretation of porous pavement results are limited due to a high percentage of non-detects in the inflow data set.
- Only detention basins, media filters and grass buffers and swales had dissolved arsenic data. None of these practices were observed to reduce dissolved arsenic concentrations.
- Grass strips and bioretention indicate an increase in arsenic concentrations, which is likely due to the presence of naturally occurring arsenic in soils. Another potential contributor could be dry deposition from an adjacent land use being remobilized in runoff.
- Detention basins, retention ponds and grass swales show marginal arsenic concentration reductions, but no BMP type provides consistent reductions.

Findings for cadmium include:

- When influent concentrations are detectable, most BMP types show statistically significant reductions for both total and dissolved cadmium, with the exception of wetland channels and high rate media filtration.
- Media filters and bioretention achieve the lowest total cadmium median effluent concentrations of approximately 0.08 µg/L.
- A high percentage of non-detects are present for dissolved cadmium for half of the BMP categories. Grass swales, grass strips, and media filters showed reductions in dissolved cadmium. Hydrodynamic separators and oil-grit separators all showed reductions when considering paired monitoring events.

Findings for chromium include:

- When influent concentrations are detectable, most BMP types show statistically significant reductions for total chromium. Exceptions include wetland channels and hydrodynamic separators.
- Bioretention followed by media filters achieves the lowest total chromium median effluent concentrations ranging from 0.7 to 1.0 µg/L.
- Detention basins, retention ponds, high rate media filtration, and swales also perform relatively well at reducing total chromium concentrations.
- For dissolved chromium, fewer BMP types show significant reductions. Additionally, interpretation of performance is affected by non-detects.
- Statistically significant increases in the detection of dissolved chromium for porous pavement indicates that pavement itself may be a source. This finding aligns with research summarized by Kayhanian at al. (2019) that indicates dissolved chromium may leach from the cement contained in concrete pavement.

Findings for copper include:

- Many BMP types show statistically significant reductions for both total and dissolved copper.
- With total median effluent concentrations less than 5 µg/L, the best performing BMPs are detention basins, retention ponds, wetland basins, media filters, and high rate biofiltration.

- The relatively poor dissolved copper removal performance for bioretention may be due to leaching of copper from sites that included a high percentage of compost in their media mixes. A study in Washington found that dissolved copper export was as high as 600% for bioretention cells containing 40% compost (Herrera Environmental Consultants 2012). While the export of copper is concerning, there is research that indicates that most of the dissolved copper leaching from bioretention systems is strongly bound to dissolved organic matter and is less bioavailable to aquatic organisms (Chahal et al. 2016).

Findings for iron include:

- Sufficient data for analysis are available for retention ponds, grass swales, grass strips, bioretention and media filters. Statistically significant reductions are observed for these BMP types with the exception of bioretention, with export of total iron indicated for paired data sets.
- Fewer data sets are available for dissolved iron. Retention ponds show significant reductions in dissolved iron, whereas grass strips and porous pavement indicate increases in dissolved iron. Porous pavement may have a potential source of iron within the pavement itself, which could be naturally occurring in the concrete aggregate.

Findings for lead include:

- All BMP types show statistically significant reductions for total lead.
- Wetland basins, bioretention, media filters, and porous pavement have the lowest total median effluent concentrations ranging from 0.9 to 1.4 µg/L.
- Grass swales and oil-grit separators also perform very well with median effluent concentrations below 2 µg/L.
- There is a high percentage of non-detects for dissolved lead (i.e., the influent levels are low), which could be due to lead being primarily associated with particulates coupled with the phase out of leaded gasoline from 1985 to 1996. While there are about 20 sites that were installed and monitored prior to the complete phase out of leaded gasoline, all lead data for highway sites is from 1995 to current. Nonetheless, lead in the environment may persist in some studies following the leaded gasoline ban.

Findings for nickel include:

- Sufficient data for analysis are available for detention basins, retention ponds, wetland channels, grass swales, grass strips, bioretention, media filters, hydrodynamic separators, and porous pavement. Except for wetland channels and hydrodynamic separators, all of these BMP types show statistically significant reductions for total nickel with median effluent concentrations ranging between 2.0 and 3.2 µg/L.
- Dissolved nickel data is limited for several BMP types but for those with data, statistically significant reductions were indicated for grass swales, grass strips, and porous pavement.

Findings for zinc include:

- Most BMP types show statistically significant reductions for both total zinc and many also reduced dissolved zinc.
- Bioretention, media filters, and detention basins are the top performers with total zinc median effluent concentrations of 13 to 17 µg/L. Retention ponds, wetland basins and channels, swales, and PFC are not far behind, with total median effluent concentrations less than 30 µg/L.
- Many BMP categories also removed dissolved zinc. Exceptions include wetland channels and manufactured device categories other than high rate biofiltration.

- Hydrodynamic separators and oil-grit separators are the lowest performers for dissolved zinc removal. Median concentrations for oil-grit separators more than doubled between the inflow and outflow, indicating there may be a source of zinc in some of these devices, potentially certain construction materials used in the device.

Design-related implications for effective removal of metals are that BMPs should be designed to address the characteristics of the metal(s) of interest, often requiring a treatment train approach that integrates sedimentation and filtration components for most effective removal of metals. Pitt and Clark (2010) provide these specific design recommendations based on results of extensive research related to optimization of BMP performance to remove metals to low levels:

- **Design to the Pollutant(s) of Interest:** For most BMPs, treatment effectiveness varies depending on the pollutant of interest and the influent characteristics of the targeted pollutants (e.g., filterable fraction, ionic forms, associations with different particle sizes, etc.). BMP selections and design features should be targeted to these characteristics. Pollutants of interest may be driven by an existing or forthcoming total maximum daily load (TMDL), pollutants commonly associated with a particular land use, or basin-specific water quality issues. The National Stormwater Quality Database (NSQD) provides information on pollutant concentrations in runoff for various land uses and climates (Pitt et al. 2018). The NSQD can be downloaded from www.bmpdatabase.org and is a separate companion product of the BMP Database.
- **Treatment Train**: In many cases, a combination of treatment processes is needed. A treatment train incorporating different unit processes that target different pollutant characteristics can be designed as separate units dispersed throughout a drainage area, or they can be adjacent. In the case of strict numeric discharge limits, redundancy is often necessary to provide the most robust control. In many cases, and similar to wastewater treatment facilities, an effective treatment train is composed of gross solids and floatables control, sedimentation unit processes followed by filtration unit processes (media filtration, infiltration through amended soils, bioretention/biofiltration devices, etc.) with the logic being to remove first the particles that will interfere with and/or shorten the life of the filtration devices.
- **Sedimentation:** Well-designed sedimentation practices typically are effective in removing particulates and associated particulate-bound pollutants down to approximately 10 to 25 µm for properly sized facilities (i.e., low surface overflow rates) and possibly lower depending the shape and density of suspended particles.
- **Filtration/Sorption:** Even though sedimentation may remove particles smaller than 10 µm, the reliable removal of pollutants and their associated particulates with diameters smaller than about 10 to 25 µm is typically accomplished using filtration techniques (such as biofiltration, media filter or bioretention BMPs). Packed bed filters with small pore spaces and tortuous flow paths can retain particles as small as 1-2 µm. The removal of "dissolved" metals depends on the metal form (ionic, complexed, etc.) and on the chemical composition of the sorption/ion-exchange media.

Other treatment processes that have been shown to be effective at enhancing metals removal include using flocculants such as polyacrylamide or chitosan prior to sedimentation and filtration. Wetlands may provide additional benefits through biologically mediated control processes (WERF 2003).

Although most metals migrate poorly through soils, infiltration of stormwater may be a concern in industrial areas that have high concentrations of dissolved metals and in areas with shallow groundwater (particularly areas with sandy soils). Amended soils have been shown to substantially reduce the migration of metals to groundwater and may enable use of infiltration in areas with sandy soils, depending on site-specific circumstances (WERF 2003).

CHAPTER 6

Conclusions and Research Needs

6.1 Conclusions

The International Stormwater BMP Database is an evidence-based resource for characterizing BMP performance. This summary report provides statistics useful for estimating effluent concentrations achievable by various BMP types for various pollutants and for identifying BMP types that have demonstrated ability to reduce pollutant concentrations. Overall observations from this analysis include:

1. **Solids:** All of the BMP types evaluated demonstrated statistically significant reduction in TSS. The lowest effluent concentrations observed for TSS include bioretention, media filters, high rate biofiltration devices, and retention basins. These BMPs enable sedimentation and filtration, which are effective treatment processes for sediment removal. Conversely, none of the BMP types evaluated showed statistically significant reductions in TDS.
2. **Bacteria:** The fecal indicator bacteria data set for EPA-recommended fecal indicators remains limited. Nonetheless, several observations can be made from the available data. Most BMP types analyzed are not able to consistently reduce bacteria concentrations to primary contact recreation receiving water standards. However, some BMP types show the ability to significantly reduce currently recommended fecal indicator bacteria concentrations, including bioretention, wetland basins, retention ponds, media filters and dry extended detention basins. Bacteria load reductions may be more significant than concentration reductions due to volume reduction provided by BMPs that provide infiltration such as bioretention. Based on these findings and given the many diffuse sources of fecal indicator bacteria in watersheds, source identification and control should be the first steps in addressing fecal indicator impairments for receiving waters (Clary et al. 2014).
3. **Nutrients – Phosphorus:** Phosphorus in the particulate form can be removed from a variety of BMP types; however, removal of soluble forms is more challenging. Many BMPs show statistically significant reductions for phosphorus, but grass swales, grass strips, and bioretention show phosphorus export, which is likely due to the presence of phosphorus-rich soils and planting media (e.g., containing compost) for many of the studies in the BMP Database. Detention basins effectively remove total phosphorus, but not dissolved phosphorus or orthophosphate. The best performing BMPs for total phosphorus reduction are media filters, high rate biofiltration, and high rate media filtration with total phosphorus median effluent concentrations of 0.05 to 0.09 mg/L. The best performing BMPs for orthophosphate are retention ponds and media filters. Retention ponds also show reductions for dissolved phosphorus. Most practices do not show statistically significant reductions for dissolved phosphorus and orthophosphate. Grass swales, grass strips and bioretention export dissolved phosphorus and orthophosphate in this data set. Bioretention had the most elevated phosphorus concentrations in effluent; therefore, careful attention to the phosphorus content of media in bioretention facilities is important.
4. **Nutrients – Nitrogen:** Many BMPs show statistically significant reductions in total nitrogen forms, with media filters producing the lowest median effluent concentrations of 0.9 and 0.6 mg/L for total nitrogen and TKN, respectively. Conversely, bioretention, media filters, and porous pavement show nitrate export, indicating that ammonification and nitrification of organic nitrogen is likely occurring. For the removal of nitrate, the best performing BMPs are retention ponds, wetland basins, and wetland channels.
5. **Metals:** As was the case for nutrients, total forms of metals are more readily removed than

dissolved forms. For example, most of the BMPs evaluated showed statistically significant reduction of total copper, lead and zinc. Performance varies depending on the individual pollutant and unit treatment processes provided by the BMP. When evaluating metals performance, it is particularly important to be cognizant of influent concentrations – in cases where influent concentrations are already very low often indicated by non-detects in influent samples), then additional reductions of metals concentrations may not be feasible. Additionally, data sets with high percentages of non-detects and/or widely varying detection limits can complicate statistical analysis. See the summary tables provided in this report to assess expected performance for various BMP-metal combinations.

6.2 Research Needs

Although the International Stormwater BMP Database is the largest known repository of the BMP performance data with over 770 individual BMP sites, data gaps remain for many locations, BMP categories, constituents, and study meta-data. Study sites are particularly needed in Midwest, Southwest, Northern Plains, and Rocky Mountain States.

Based on the analysis of the 2020 BMP Database, several research needs are readily apparent:

1. More BMP performance data sets are needed for fecal indicator bacteria for multiple BMP types, particularly for enterococcus and *E. coli*, which are the current EPA-recommended fecal indicator bacteria. Given that pathogens are the top cause of waterbody impairments nationally, this is a major research need.
2. Other urban stormwater analytes with limited data sets for analysis purposes include:
   - Heavy metals other than copper, lead, and zinc.
   - Oxygen demanding substances such as BOD, COD, and TOC.
   - Organic pollutants, such as TPH, PAHs, PCBs, phthalates, and dioxins.
3. More robust design information in BMP performance study submittals would be valuable for all BMP categories. This information is important for identifying the factors that lead to the best performance for various BMP types and would support more detailed evaluation within subgroups of BMP categories. For example, additional media filter and biofiltration studies with engineered media mixes (e.g., peat, biochars, zeolites, oxide-coated sands, etc.) other than sand and innovative designs (e.g., outlet control, internal water storage zone, etc.) could be useful in understanding which design variations are most effective.
4. Of the BMP categories evaluated, porous pavement and permeable friction course (overlay) studies, followed by wetland basins and engineered media filters (other than sand filters), are among the least represented in the database. Considering the high level of treatment that these BMP types appear to provide and their potential applicability in ultra-urban settings and the highway environment, additional studies are needed. This is also true for manufactured devices that provide high rate biofiltration and high rate media filtration. Available data indicates that these devices are performing well for multiple water quality constituents and may be the only option for highly constrained locations in need of treatment.
5. Although some studies in the BMP Database include long-term performance data, many studies are monitored for a few years or less, often relatively soon after installation. More long-term studies and/or studies that resume monitoring at previously monitored sites would be useful to better understand how BMP performance varies over time, ideally with maintenance practices, intervals and costs documented. This research need is particularly relevant for vegetated infiltration-oriented practices where root structure develops over time and may influence infiltration rates and for media filter practices where depth filtration clogging or exhaustion of sorption sites may occur.

6. Although not a research need in terms of new monitoring, additional meta-analysis of existing studies in the BMP Database may be warranted given the significant growth in the BMP Database since Geosyntec and WWE (2013) completed *International Stormwater Best Management Practices (BMP) Database Advanced Analysis: Influence of Design Parameters on Achievable Effluent Concentrations*. Further evaluation of BMPs in treatment trains or Low Impact Development sites could also be included.

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