International Stormwater Best Management Practices (BMP) Database Pollutant Category Summary:

Solids (TSS, TDS and Turbidity)

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Under Support From
Water Environment Research Foundation
Federal Highway Administration
Environment and Water Resources Institute of the
American Society of Civil Engineers

May 2011

Disclaimer

The Project Team's tasks have not included, and will not include in the future, recommendations of one BMP type over another. However, the Project Team's tasks have included reporting on the performance characteristics of BMPs based upon the entered data and information in the Database, including peer reviewed performance assessment techniques. Use of this information by the public or private sector is beyond the Project Team's influence or control. The intended purpose of the Database is to provide a data exchange tool that permits characterization of BMPs solely upon their measured performance using consistent protocols for measurements and reporting information.

The Project Team does not endorse any BMP over another and any assessments of performance by others should not be interpreted or reported as the recommendations of the Project Team or the Sponsors.

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INTERNATIONAL STORMWATER BMP DATABASE
www.bmpdatabase.org

POLLUTANT CATEGORY SUMMARY: SOLIDS

1 INTRODUCTION

As of 2010, the U.S. Environmental Protection Agency (EPA) has identified over 6,270 waterbodies across the country as sediment-impaired (USEPA, 2011b). Excessive sediment can adversely impact aquatic life and fisheries, source waters for drinking water supplies, and recreational uses (USEPA, 1999). Fine particulates also often carry other pollutants such as heavy metals (e.g., lead, copper, zinc), PCBs, PAHs, and other pollutants. Therefore, removal of suspended sediment from runoff can also reduce sediment-bound pollutants. This technical summary has been developed to assist federal, state and local governments, watershed organizations, environmental groups and other interested parties in selecting, designing, and developing reasonable performance expectations for stormwater best management practices (BMPs) with regard to stormwater solids, with primary emphasis on suspended sediment.

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

- Regulatory context for sediment in receiving waters

Basic Terminology
(Adapted from USEPA, 1999; EWRI, 2009; Roesner, 2007; USGS, 2011)

Adsorption. Adsorption is the adherence of nutrients or pollutants to particles via a loose chemical bond with the surface of clay particles.

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 sediment 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).

Turbidity. The degree to which light is scattered or absorbed by a fluid. Turbidity is usually associated with suspended sediment, but it can also be caused by the presence of organic matter.

- Sources of sediment
- Removal mechanisms and associated BMP design considerations for sediment
- Overview and analysis of solids data included in the International Stormwater BMP Database (BMP Database)
- Conclusions and recommendations

1.1 Regulatory Context

Under the Clean Water Act (CWA) Section 401(a)(1), the EPA is required to develop criteria for water quality based on the latest scientific knowledge. Criteria are developed by the EPA pursuant to CWA Section 304 requirements; however, these are not laws or regulations, but rather represent scientific assessments for ecological and human health effects that EPA recommends to States and authorized Tribes for establishing water quality standards. Under Section 303(c) of the CWA, States and authorized Tribes have the primary responsibility for adopting water quality standards as laws or regulation. In establishing standards, they can 1) adopt the EPA's criteria, 2) modify them to reflect local conditions, or 3) adopt their own criteria using scientifically defensible methods.

EPA provides quantitative and narrative criteria for "Solids (Suspended, Settleable) and Turbidity" in its Quality Criteria for Water (USEPA, 1986). For freshwater fish and other aquatic life, EPA provides this quantitative criterion:

> *Settleable and suspended solids should not reduce the depth of the compensation point for photosynthetic activity by more than 10 percent from the seasonally established norm for aquatic life.*

Most states have not adopted this quantitative criterion (USEPA, 2006), but many have adopted EPA's narrative criteria which state:

> *All waters [shall be] free from substances attributable to wastewater or other discharges that 1) settle to form objectionable deposits; 2) float as debris, scum, oil, or other matter to form nuisances; 3) produce objectionable color, odor, taste, or turbidity; 4) injure or are toxic or produce adverse physiological responses in humans, animals or plants, and 5) produce undesirable or nuisance aquatic life.*

There are many different approaches used by states in developing sediment water quality standards. A study of published suspended and bedded sediment criteria for 53 states, territories and tribes and the District of Columbia (USEPA, 2001) showed that numeric criteria existed in 32 cases, 25 of which had criteria for turbidity only, two had criteria for suspended solids only and five had both. Narrative criteria were used in 36 states, with 13 states having both narrative and numeric criteria.

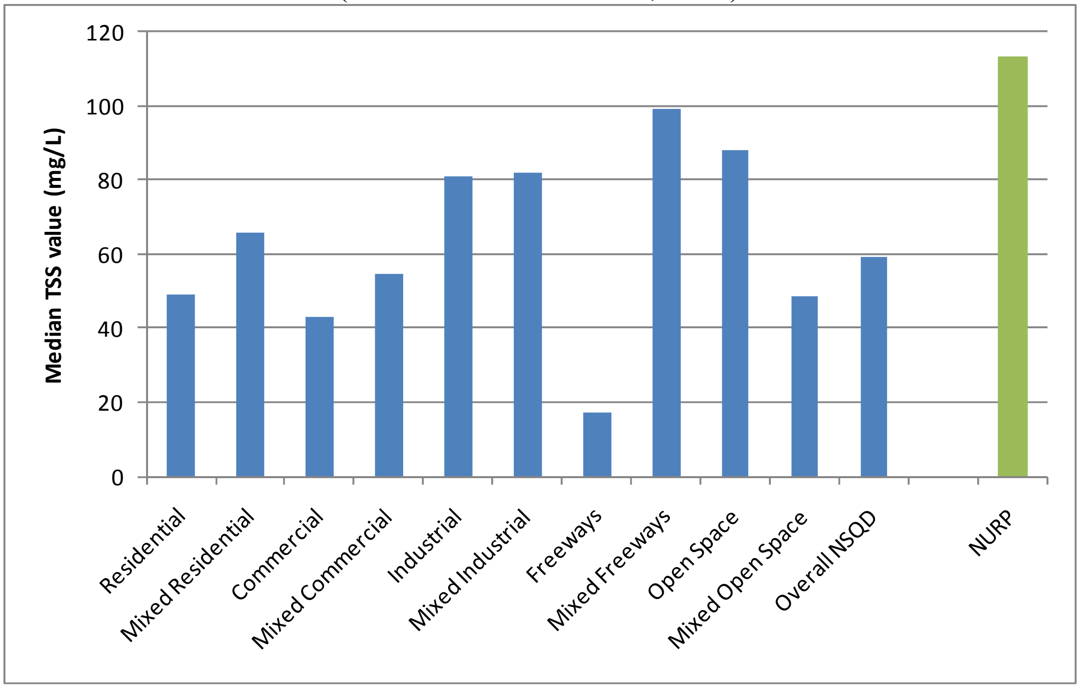
Once the water quality standards are developed by the individual states, these serve as the basis for a biennial assessment of water body use attainment. As a result of biennial assessments, states develop "303(d)" lists of waters not attaining water quality standards. States are then required to initiate the TMDL process to address these impairments. The TMDL process typically involves the assignment of pollutant load allocations to various watershed sources, including wasteload allocations (WLAs) for point sources and load allocations (LAs) for non-point sources. The WLAs may then be incorporated into NPDES permits as numeric water quality-based effluent limits or technology-based requirements, making permittees legally responsible for TMDL compliance. Historically, such requirements typically have been based on BMPs, as opposed to numeric limits (EPA 2002); however, potential use of numeric limits in the context of stormwater discharges is an ongoing consideration and topic of discussion (USEPA, 2010; USEPA, 2011a). (*Note: this paper discusses post-construction solids issues, as opposed to dewatering or construction-phase permitting where numeric limits for TSS or turbidity may be required*.)

1.2 Typical Sources and Composition of Sediment

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, 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, durations and volumes from urban runoff, with the extent of erosion varying based on site-specific factors.

The National Stormwater Quality Database (NSQD) (Maestre & Pitt, 2005) and the National Urban Runoff Program (NURP) (USEPA, 1983) characterized median effluent concentrations of TSS in urban stormwater, as shown in Figure 1. The NURP median TSS concentrations are nearly double the overall NSQD median. Maestre and Pitt (2005) suggested that this difference may be explained by differences in geographic distribution of samples from around the country. Specifically, the NURP data set was more heavily weighted toward areas of the country with lower rainfall amounts, which tend to be correlated to higher TSS concentrations. Differences in distributions of land use types and watershed size are also expected to affect TSS concentrations, with the median drainage size for the NSQD data being about half that of the NURP drainage areas. Additionally, the NURP data sets were collected from runoff prior to the municipal, industrial and construction site NPDES permitting program, which may have resulted in improved runoff quality.

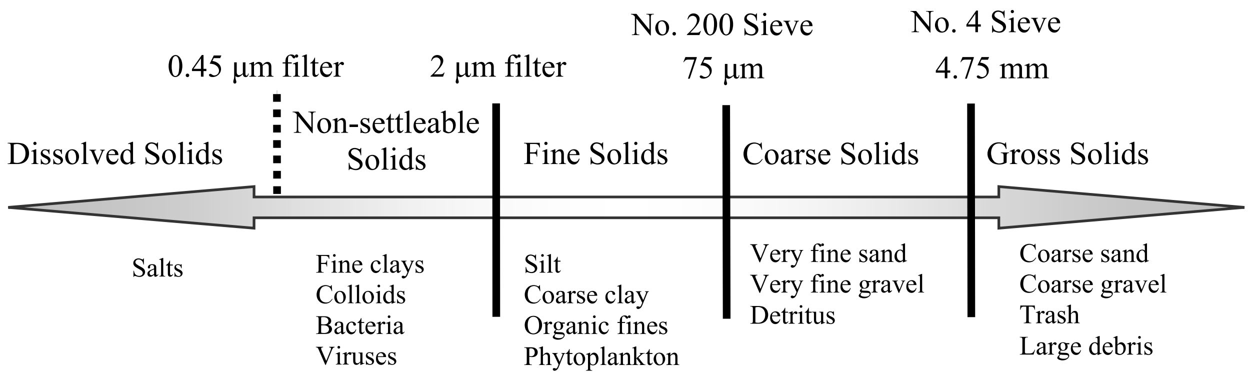
Figure 1. Median Stormwater TSS Concentrations from NSQD and NURP Databases
(Source: Maestre & Pitt, 2005)



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 & Bachoc, 1992; Muthukaruppan, Chiew, & Wong, 2002; Roesner, Pruden, & 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 carrying heavy metals and nonpolar organics (Krein & Schorer, 2000; Roesner, Pruden, & Kidner, 2007). However, large particles comprised of organic materials have also had high concentrations of associated pollutants in some cases. Ellis and Revitt (1982) found that particles smaller than 100 micrometers (µm) (15% of the total sampled mass) carried 70% of the metal pollution.

Solids in urban stormwater have been classified by size using various approaches. Figure 2 provides a solids classification approach illustrating the types of solids by size in runoff (adapted from Roesner, Pruden, & 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.

Figure 2. Solids Classification Scheme (adapted from Roesner, Pruden, & Kidner, 2007)



In the context of stormwater, the primary concern has traditionally been the fine solids fraction because these particles tend to be 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 75µm 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.

1.3 Quantifying Sediment in Urban Runoff

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", the discussion below provides a broader overview of several measures of sediment in urban runoff, including TSS, suspended solids concentration (SSC), gross solids, and turbidity. As discussed below, characteristics such as particle size distribution and associated settling velocity distributions are also important information for characterizing sediment in runoff; 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 (Environmental Water Resources Institute, 2009; Geosyntec Consultants and Wright Water Engineers, 2010; Clark & Siu, 2008; Bent, Gray, Smith, & Glysson, 2000).

1.3.1 TSS and SSC[2]

A variety of methods have been employed in stormwater quality studies for quantifying sediment concentrations in the water column. The most frequently cited parameter is "TSS" or total suspended solids; however, this label is often generically used to refer to multiple sample collection and sample analysis methods, including:

- EPA Method 160.2: Total Suspended Solids (TSS) (Gravimetric, Dried at 103-105ºC). (USEPA, 1999).
- American Society for Testing and Materials (ASTM) Method D3977-97(B): Standard

[2] Discussion adapted from *Urban Stormwater BMP Performance Monitoring* (Geosyntec and WWE 2009).

Methods for Determining Sediment Concentration in Water (ASTM 1997). The USGS employs this suspended sediment concentration (SSC) method. SSC data are often described as TSS data, although results from the two methods may be significantly different in many cases.

- Standard Method (SM) 2540D: This TSS analytical method originated in wastewater analysis and is promulgated by the American Public Health Association in Standard Methods for the Examination of Water and Wastewater (Eaton, Clesceri, Rice, Greenberg, & Franson, 2005).

Differences in nominal filter pore size, sample mixing, aliquot size and method of aliquot collection can result in significantly different results from these methods (Clark & Siu, 2008). Guo (2007) conducted tests to determine the relationships between the various test methods and found that SSC (using ASTM D3977-97(B)) results were very close to the true concentration of solids in laboratory tests, whereas the EPA Method 160.2 TSS measure was well correlated with SSC, but TSS using SM 2540D was not well correlated with SSC. The study also found that the difference between the SSC and EPA TSS results were well correlated with particle size, with increasing differences as particle size increased. Clark and Siu (2008) also concluded that correlations between the results and the known sample concentration could be established for TSS samples, dependent on the sample's particle size distribution and on the aliquot collection technique. These results emphasize the need to report not only the analytical method but also the particle size information on the solids in stormwater runoff.

One of the key differences between methods is sample size—the SSC method analyzes the entire sample, whereas the TSS method uses a sub-sample. The process of collecting a representative sub-sample containing larger sediment particles is problematic because large sediment particles (e.g., sand) often settle quickly. Differences between the results obtained from SSC and TSS analytical methods become apparent when sand-sized particles exceed 25 percent of the sample sediment mass (Gray, Glysson, Turcios, & Schwartz, 2000). Other factors affecting TSS and SSC results include the nominal pore size of the filter used by the analytical lab. Regardless of the analytical methods used, the sampling methodology often introduces the largest bias to sediment data (Clark, Siu, Roenning, & Treese, 2009).

To resolve potential interpretation issues regarding suspended sediment, it is recommended that both TSS (for comparison to existing data sets) and SSC be measured, when budgets allow. (A few of the recent data sets in the BMP Database report both SSC and TSS for a few storms, then typically switch to TSS only for the majority of the study.) One of the reasons that this issue has received much attention is that various state and local regulations and technology verification protocols have chosen to use TSS as a performance measure, so a clear understanding of the TSS method and procedure used is important to performance evaluations.

The discrepancies in sampling and analysis methodologies currently employed in the field highlight the importance of particle size distribution (PSD) analysis as an essential component of any BMP monitoring study to serve as a common denominator for comparing different analytical methods for sediment in runoff (Clark & Siu, 2008). PSD data provide the information necessary to meaningfully interpret the ability of a BMP to remove suspended materials.

A final note regarding SSC and TSS analysis methods is that the differences between TSS and SSC methods are more likely to affect analysis approaches that rely on percent reduction than those that focus on comparison of effluent quality. Larger particles, which are the most significant source of discrepancy between the methods, are typically relatively easy to remove from a reasonably functioning BMP; therefore, these particles are a less significant issue in analysis of effluent concentrations. Influent concentrations are likely more affected by the differences in these methods, with the influent concentrations represented in the BMP Database potentially being lower than those that might result using SSC analysis methods. In summary, the effluent analyses results reported later in this technical summary are less affected by the error associated with variability in measurements resulting from the different sampling and analysis methods than would be the case if percent removal approaches were used.

1.3.2 Gross Solids

Closely related to measurement of TSS and SSC is the measurement of gross solids. 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.

In 2010, EWRI's Urban Water Resources Research Council Gross Solids Technical Committee published "Guideline for Monitoring Stormwater Gross Solids," which defined gross solids in three categories including litter, organic debris and coarse sediments (EWRI 2010). The purpose of the ASCE guideline is to standardize data collection procedures used in evaluating the removal of gross solids by BMPs and also to allow for direct comparison of field data from separate studies by using the same collection methodologies.

To date, researchers have not typically submitted gross solids data to the BMP Database; however, a number of researchers have collected such data and expressed interest in providing it in the future to the BMP Database.

1.3.3 Turbidity

Turbidity is sometimes used as a surrogate of sediment concentration in water. Turbidity is the measure of a sample's tendency to scatter light, and is typically measured in nephelometric turbidity units (NTU). It captures the effects of both colloidal particles and suspended sediment, including algae. Because turbidity is easy to continuously measure, it is commonly used in streams and can be used to evaluate changes over time. Correlations between turbidity and TSS concentration are possible, but these are generally site-specific (Packman, Comings, & Booth, 1999), and a large number of data points is required to create a good correlation. Turbidity readings are also affected by particle shape, size, and color (Clifford, Richards, Brown, & Lane, 1995; Packman, Comings, & Booth, 1999), which are attributes that are not all directly related to TSS concentration. Available turbidity data in the BMP Database are presented in Section 3.

1.3.4 Other Solids Measurements

Although the primary focus of this technical summary is TSS, measurements such as total solids, total dissolved solids (TDS), total volatile solids (TVS), total volatile suspended solids (TVSS) and others 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 includes 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.

Of these various solids measurement, TDS is the only one reported somewhat frequently in the BMP Database. 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 presented in Section 3.

2 SUMMARY OF REMOVAL MECHANISMS

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

2.1 Dominant Removal Mechanisms

Dominant removal mechanisms for sediment include sedimentation and filtration. Both processes are enhanced by coagulation and flocculation. The discussion that follows provides the engineering theory involved in these processes.

2.1.1 Sedimentation[3]

Sedimentation is the process in which particulates settle to the bottom of a water column. Stokes (1851) was the first researcher to derive an equation to predict the settling velocity of particles in a fluid. This equation, shown below, balances the effects of gravitational force, buoyancy, and drag force. It is applicable to spherical particles with settling velocities with relatively low Reynolds numbers (where viscous effects are relatively minor).

$$v_s = \frac{g}{18\mu}(\rho_p - \rho_f)d_p^{\,2}$$

Where

v_s = settling velocity
g = gravitational acceleration
ρ_p = particle density
ρ_f = fluid density
d_p = particle diameter
μ = dynamic viscosity

[3] This discussion has been adapted directly from Strecker et al. (2009).

As shown, the settling velocity is dependent upon the density differences between the fluid and the particle, as well as the diameter and shape of the particle. All of these tend to be highly variable when stormwater particles are considered (see Section 2.2.3 below on particle density). This variability is critically important with regard to sedimentation processes in stormwater BMPs. For a given sample of stormwater having a range of particles of equal density, 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 5µm and larger than 50 µm, the particle size distribution (see Section 2.2.2) is a key factor when selecting and designing stormwater BMPs.

Two major factors not accounted for in Stokes' work are non-spherical particles and the presence of turbulent eddies in the flow. In many situations, an eddy in which water has an upward vertical velocity will keep particles in suspension longer or may resuspend previously settled particles. Natural particles have a variety of shapes and roughnesses that can affect their settling velocities, particularly for small particles (e.g., <100 µm) where viscous effects are more dominant. The inadequency of Stokes' law under a variety of flow conditions and particle characteristics has led some researchers to develop empirical settling formulas (Dietrich, 1982; Jimenez & Madsen, 2003; Ferguson & Church, 2004; Gibbs et al., 1971). However, Stokes' ideal settling formula is still the most often used in practice and some references, such as Chapra (1997), include a dimensionless multiplier, where spherical particles are given a value of one and non-spherical particles are given values between zero and one to account for non-ideal settling rates.

Camp (1946) developed one of the most fundamental models for settling by gravity. In his model, water enters along one end of an ideal horizontal plug flow reactor with constant flow and volume. As the water travels horizontally through the reactor, particles carried by the water fall toward the bottom at a constant settling velocity. This conceptual model can be used as an approximation in stormwater systems with a relatively constant water level such as wetlands and wet ponds. To account for particles of various sizes distributed at various heights throughout the water column, the following removal efficiency equation can be used:

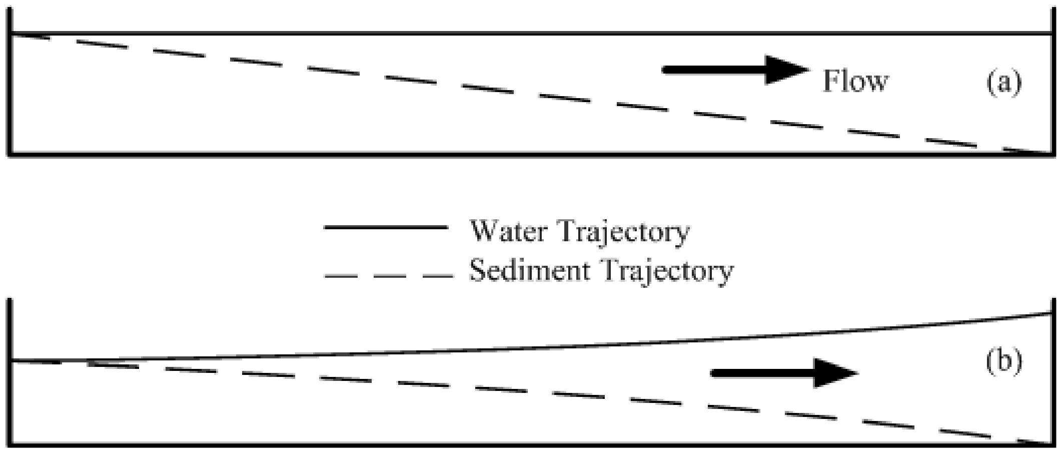
$$R = (1 - f_o) + \int_0^{f_0} \frac{v_s}{v_{or}} df$$

where:

R = removal efficiency (ranges from 0 to 1)
ν_s = particle settling velocity
ν_{or} = overflow velocity (calculated by dividing the inflow rate by the reactor surface area)
f_o = fraction of suspended solids associated with settling velocities greater than or equal to the overflow velocity, ν_{or}
f = fraction of suspended solids associated with any ν_s

Unfortunately, many stormwater systems do not fit this model well. Swales and dry detention basins fill during a storm event to an arbitrary water level and then drain again at the end of the event, resulting in radically different water levels as the storm event progresses. This has a substantial impact on the trajectory of both particles and water molecules within the system. As shown in Figure 3a, the Camp model results in both water molecules and sediment particles having straight flow paths. In contrast, as shown in Figure 3b, the path lines of the sediment particles and water molecules are curved during the filling period of a dry detention basin (Landphair, et al., 2007). Parties interested in determining removal efficiencies for these situations are referred to work by Takamatsu, Barrett, and Charbeneau (2010).

Figure 3. Trajectory of water and sediment particle released from water surface with critical settling velocity in (a) an ideal horizontal flow reactor and (b) rectangular stormwater detention basin during the filling period. (Source: Landphair, et al., 2007)



2.1.2 Filtration[4]

Media filtration removes sediment by directing the influent through a bed of media, which may be composed of materials such as sand, peat, sand, 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 & Eddy, 2003):

1) straining
2) sedimentation
3) impaction
4) interception
5) adhesion
6) flocculation
7) chemical adsorption
8) physical adsorption
9) biological growth

[4] Parts of this section have been adapted from WERF (2005).

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. If depth clogging occurs, the media must be replaced. To reduce the frequency of media replacement, sedimentation pre-treatment is generally recommended for all stormwater filtration systems.

Three general classes of filtration mechanisms can be approximated based on filter media size (as d_m, the mass-based median filter media size) and filtrate particle size (as d_p, the mass-based median particle size). When $d_m/d_p < 10$, the dominant mechanism is surficial straining. When $20 > d_m/d_p > 10$, the dominant mechanism is depth filtration (mechanisms 2 – 6 and 9 in the list above), and when $d_m/d_p > 20$, the dominant mechanism is physical and chemical adsorption (mechanisms 7 and 8 above) (Sansalone & Teng, 2004; Teng & Sansalone, 2004). The discussion below focuses on the physical mechanisms in inert media filters.

Urbonas (1999) used field data to show that the flow rate through a sand filter becomes primarily a function of the sediment accumulation depth according to the equation:

$$q = k_i * L_m^{-c}$$

where q is flow velocity through the filter (ft/day)
k_i is an empirical flow-through constant
L_m is the cumulative unit TSS load accumulated on the filter's surface (lb/ft^2)
c is an empirical constant

Li and Davis (2008) used a model that included both cake layer and depth filtration effects. They calculated the change in hydraulic conductivity due to depth filtration with the equation:

$$\frac{K}{K_o} = \frac{1}{(1 + \gamma\sigma_v)^2}$$

where K is the hydraulic conductivity of the filter bed
K_0 is the initial hydraulic conductivity of the clean bed
γ is an empirical constant, and
σ_υ is the volumetric specific deposit (volume of deposited particles per unit filter volume)

Both of these models reinforce the importance of pretreatment (usually by sedimentation) to decrease the maintenance frequency necessary for maintaining the permeability of the filter bed. In practice, effective media filtration generally requires stormwater with an influent sediment concentration below 50 mg/L, depending on the media type, filter design, and maintenance schedule. Periodic maintenance schedules usually involve a series of progressively involved steps, such as scarifying the surface, then later removing the surface layer of media, and finally replacing the entire media bed (Urbonas, 1999).

2.1.3 Coagulation/Flocculation[5]

Coagulation involves destabilizing suspensions in which particles carry a negative charge and therefore tend to repel each other to maintain the suspension. Flocculation is the physical process through which smaller particles aggregate and form larger "flocs". *Note: Neither coagulation nor flocculation are removal mechanisms themselves; rather, they are processes that improve the performance of filtration and sedimentation.*

Flocculation occurs through particle collisions resulting from the following transport processes (Metcalf & Eddy, 2003):

1) Brownian motion – random movement of suspended particles
2) Differential settling – contact between particles as they settle along the same path at different velocities
3) Fluid shear – contact between particles resulting from velocity gradients along the interface between segments of water moving in different directions

Coagulation/flocculation processes in stormwater can be grouped as active and passive. Active coagulation/flocculation processes involve the controlled addition of a coagulation agent followed by mixing (both to distribute the coagulation agent and promote fluid shear), and finally sedimentation. 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 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).

[5] This section has been adapted from Strecker et al. (2009).

2.2 Stormwater Characteristics and Environmental Conditions Influencing Dominant Removal Mechanisms

2.2.1 Temperature

Temperature has a substantial impact on settling velocities of stormwater particles, with settling velocities decreasing as temperature decreases (Guy, 1969). The viscosity of the water more than doubles as the temperature declines from 80 degrees F to near freezing. In Stokes' formulation, this has the effect of reducing the settling velocity by half, making sedimentation a much less effective process in cold water situations.

2.2.2 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 & Sansalone, 2008). These changes may result from differences in antecedent dry period, rainfall intensity, rainfall duration, vegetation density, and other factors. Such changes in particle size distributions may help to explain some of the variation in TSS effluent concentrations from BMPs.

2.2.3 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. Similar to findings related to particle size distribution, it is expected that the densities also would vary from event to event based on rainfall intensity, storm duration, season, and other environmental factors.

2.2.4 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. They have a sheet-like structure with a net negative charge. 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 readily available 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 available, 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 must be destabilized by coagulation before they can be easily removed via sedimentation or filtration.

2.3 BMP Design Considerations

Influent flow rates, sediment loading, and physical particle characteristics (e.g., size, shape, density, and charge) as well as the desired effluent volume and quality are key considerations for BMP designs. Sedimentation processes are most effective for larger and denser particles. In general, BMPs with long retention times and laminar flows will provide effective sedimentation. Shallow flow depths and the presence of vegetation or engineered structures in the flow path can also accelerate sedimentation by increasing Manning's roughness and creating localized quiescent zones. If removal of finer particles is an objective, then longer settling times or shallower depths are often needed. Enhanced sedimentation devices, such as clarifiers, tube settlers, and inclined plates, may be employed where space is limited and high removal rates are needed. In the case of colloids, coagulant addition may be necessary to remove particles, but may not be allowed or appropriate in all situations, depending on site-specific conditions, long-term maintenance requirements, and local regulations.

Sedimentation BMPs are recommended as pretreatment upstream of media filters, bioretention facilities and larger detention/retention systems. Removal of sediment upstream of these facilities helps to reduce clogging in infiltration BMPs and decrease the frequency of major rehabilitation efforts involving sediment removal from ponds. If stormwater contains large quantities of sediment or if active coagulation/flocculation is utilized, then sediment removal may be a routine maintenance requirement and BMPs should be designed to facilitate such maintenance.

In the absence of active coagulant dosing followed by settling, stormwater filtration is typically needed to remove fine particles (<20 µm). Media filters, bioretention, disposable or rechargeable filter cartridges, or other infiltration-based BMPs provide filtration. For all of these facilities, regular maintenance is necessary to minimize clogging. The gradation and effective pore size of media beds relative to the target particle size should be carefully considered in design. A small effective pore size will remove small particles, but will also be more prone to clogging. Vegetation can be planted on the top of media beds and infiltration basins to help maintain flow-through rates by breaking up surface crusts and providing preferential flow paths along stems and roots. Large trees and shrubs that generate large quantities of leaf litter may seal the surface of the filter and reduce infiltrative capacity and may also increase rehabilitation costs if tree and shrub removal/replacement is needed.

3 GENERAL BMP PERFORMANCE DATA CHARACTERISTICS AND AVAILABILITY

3.1 Inventory of Available Data in Database

As of August 2010, the BMP Database contained over 7,000 analysis results for sediment-related measurements. These include measurements for TSS, TDS, and turbidity, with the vast majority of the samples being TSS. Although SSC and particle size data are also available for a few studies, the data set is not adequate for a categorical BMP performance assessment.

For the constituents analyzed, basic data screening was completed prior to statistical analysis. Representative data screening included exclusion of base flow samples from BMP studies, exclusion of studies with a gross imbalance in the number of inflow and outflow sample results, and exclusion of studies with fewer than three runoff event mean concentration (EMC) inflow and outflow results for the constituent of interest. Additionally, analysis was not conducted for BMP categories with less than three BMP studies.

Table 1 summarizes studies and individual data points by BMP category and measurement type, following basic data screening. For BMP categories without permanent pools, these data points were restricted to EMC data. For BMPs with permanent pools (i.e., retention ponds and wetland basins) where the variability in effluent concentrations would be expected to be lower, grab samples were also allowed and averaged to represent the storm event. As shown in the tables, some BMP categories are well represented in the database, while others are not. Several BMP sub-classes are included in the database that were not analyzed due to limited data sets.

In Table 1 below, the term "manufactured device" is listed as a BMP category. Manufactured devices included in the BMP Database incorporate a broad range of unit treatment processes that may result in widely varying performance for individual devices within this broad category. For example, some manufactured devices rely on hydrodynamic gravitational separation only, some provide filtration, others provide peak attenuation, and some provide a treatment train of multiple unit processes. The "manufactured device" category summarized in this document provides only a gross characterization of the range of performance provided by this overly broad category. More refined analysis is required based on finer segmentation by unit treatment processes in order to draw conclusions for a particular type of device. (Such analysis was beyond the scope of this technical summary, but may be conducted in the future.) As of 2010, each manufactured device is characterized according to primary, secondary and tertiary unit treatment processes in place for the device, so additional unit process-based analysis can be conducted independently, if desired.

Four "filter" and three "porous pavement" BMP categories are included in Table 1. As shown in the table, the number of studies for many constituents is very limited for these BMP sub-classes. While the performance of these BMP sub-classes may differ, the limited number of data points does not allow for a robust analysis of statistical differences. Therefore, these BMP sub-classes were lumped into the two parent BMP categories of "media filter" and "porous pavement." Again, as more studies are received that include these sub-classes of BMPs, then it may be appropriate to analyze these sub-classes separately.

While "biofilter - grass strips" and "biofilter - grass swales" have been kept separate for this analysis, the two "biofilter - wetland vegetation swale" studies have been combined with the "wetland channel" category for analysis purposes.

Finally, four porous pavement studies and two grass swale studies utilized a reference (control) watershed approach to characterize the influent concentrations. The analysis presented here assumes the reference watershed effluent was representative of the influent concentrations to these BMPs; therefore, the reference outflows were included in the data sets representing inflow to the BMPs.

Table 1. Number of BMP Studies and Data Points for TDS, TSS and Turbidity

	Total dissolved solids				Total suspended solids				Turbidity			
	No. of Studies		No. of Data Points		No. of Studies		No. of Data Points		No. of Studies		No. of Data Points	
BMP Category	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Biofilter - Grass Strip	12	12	188	151	14	14	232	175	0	0	0	0
Bioretention	0	0	0	0	6	6	105	96	0	0	0	0
Biofilter - Grass Swale	12	12	95	82	17	19	243	265	0	0	0	0
Detention Basin (Dry) - Surface Grass-Lined Basin (Empties between Storms)	6	6	66	62	19	19	239	265	7	7	85	111
Filter - Combination of Media or Layered Media	0	0	0	0	0	1	0	6	0	1	0	6
Filter - Other Media	1	1	9	9	4	4	78	67	0	0	0	0
Filter - Peat Mixed With Sand	2	2	10	10	2	2	18	18	1	1	3	3
Filter - Sand	9	10	106	112	13	13	198	195	3	3	40	39
Manufactured Device	12	19	175	207	40	47	555	608	9	9	140	122
Porous Pavement - Porous Asphalt	0	0	0	0	2	3	14	17	0	0	0	0
Porous Pavement - Pervious Concrete	0	0	0	0	1	2	11	14	0	0	0	0
Porous Pavement - Modular Blocks	0	0	0	0	2	3	39	42	0	0	0	0
Retention Pond (Wet) - Surface Pond With a Permanent Pool	9	9	101	93	41	40	605	605	5	6	89	102
Wetland - Basin With Open Water Surfaces	0	0	0	0	14	15	300	289	0	0	0	0
Wetland - Channel With Wetland Bottom	0	0	0	0	5	5	91	88	0	0	0	0
Wetland - Basin Without Open Water (Wetland Meadow Type)	0	0	0	0	1	1	3	6	0	0	0	0

3.2 Category-level BMP Analysis

An overview of BMP performance for sediment is provided in the subsections below. The analysis focuses on the distribution of effluent water quality for individual events by BMP category, thereby providing greater weight to those BMPs for which there are a larger number of data points reported. In other words, the performance analysis presented in this technical summary is "storm-weighted," as opposed to "BMP weighted."[6] Data sets included in the analysis were screened and categorized according to the criteria in Section 3.1.

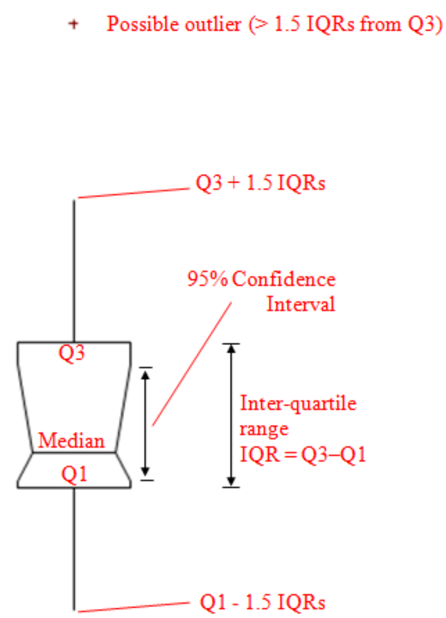
The BMP categories included in this analysis are bioretention, bioswales, dry detention basins (surface/grass-lined), filter strips, manufactured devices, media filters, porous pavement, retention ponds (surface pond with a permanent pool), wetland basins (basin with open water surface), and wetland channels (swales and channels with wetland vegetation). The effectiveness

[6] There are several viable approaches to evaluating data in the BMP Database. Two general approaches that have been presented in the past (Geosyntec Consultants and Wright Water Engineers, 2008) are the "BMP-weighted" and "storm-weighted" approaches. The BMP-weighted approach represents each BMP with one value representing the central tendency and variability of each individual BMP study, whereas the storm-weighted approach combines all of the storm events for the BMPs in each category and analyzes the overall storm-based data set. The storm-weighted approach has been selected for this memorandum as it provides a much larger data set for analysis.

and range of unit treatment processes present in a particular BMP may vary depending on the BMP design. Several other BMP categories and sub-classes are included in the database, but these have been excluded from this analysis due to limited data sets available for meaningful categorical comparisons.

In the subsections below, side-by-side box plots for the various BMPs sediment measurements 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 key to the box plots is provided in Figure 4.

Figure 4. Box Plot Key



In addition to the box plots, tables of influent/effluent medians, 25th and 75th percentiles, and number of studies and data points are provided, along with 95% confidence intervals about the medians. The median and interquartile ranges were selected as descriptive statistics for BMP performance because they are non-parametric (do not require distributional assumptions for the underlying data set) and are less affected by extreme values than means and standard deviations. Additionally, the median is less affected by assumptions regarding values below detection limits and varying detection limits for studies conducted by independent parties over many years. Simple substitution was used to represent values below detection limits with one-half of the reported detection limit being substituted for non-detects. Other metrics for central tendency and spread are available and may be useful in many circumstances. However, the median, along with its 95% confidence interval, is deemed appropriate for reporting the average performance of BMPs based on many data points from a variety of individual studies.

Confidence intervals in the figures 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 restrictive distributional assumptions. Following guidance by McGill et al. (1978): "The notches surrounding the medians provide a measure of the rough significance of differences between the values. Specifically, if the notches about two medians do not overlap in this display, the medians are, roughly, significantly different at about a 95% confidence level." Given the broad nature of the analysis contained in this paper, these general comparisons of differences are considered adequate; however, more robust hypothesis testing has also been provided in Attachment 1. Specifically, the Mann-Whitney test for independent data sets (unpaired samples) and the Wilcoxon signed rank test for paired inflow-outflow data have been provided. Out of the 20 BMP-constituent combinations (e.g., bioswale-TSS, detention basin-TDS, etc.) analyzed in Attachment 1, comparison of the overlap of the confidence intervals for the median influent and effluent values (i.e., notches on the box plots), the Mann-Whitney test and Wilcoxon test resulted in similar conclusions regarding whether the influent and effluent for the BMP differed significantly. In two cases where minor overlaps of influent and effluent confidences intervals occurred (i.e., unclear whether significant differences were present), the Mann-Whitney and Wilcoxon tests confirmed significant differences in the influent and effluent data sets. In one case, the unpaired analysis approach (Mann-Whitney and comparison of confidence intervals) did not show a significant difference, whereas the paired analysis approach (Wilcoxon) showed a statistically significant increase in effluent concentrations. These cases are footnoted in Tables 2-4 below.

In the summary tables which follow, effluent values in **bold green** indicate the effluent medians are significantly less than the influent medians. Effluent values in ***red bold italics*** indicate the effluent medians are significantly greater than the influent medians. Values with no emphasis indicate no significant differences between the influent and effluent central tendencies. 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 this does not necessarily imply that the BMP would not have been effective at higher influent concentrations.

Attachment 1 to this memorandum is a data analysis report for TSS, TDS and turbidity, organized by BMP type. The report contains additional summary statistics (e.g., mean, median, standard deviation, skewness, 25^{th} and 75^{th} percentiles) and hypothesis testing, as previously described. Influent/effluent box plots, probability plots and scatter plots are also presented in the Attachment 1 summary report. Although the narrative of this report presents the median for purposes of category-level performance evaluations, other researchers may choose to evaluate and utilize other statistical measures provided in Attachment 1.

Performance analysis results for TSS, TDS and turbidity are summarized below, followed by tabular and graphical summaries for each constituent.

3.2.1 TSS

Ten BMP categories had sufficient data for statistical analysis, with all BMP categories showing statistically significant reductions in TSS concentrations. Figure 5 contains box plots of influent and effluent TSS concentrations for each BMP category. Table 2 summarizes the non-parametric summary statistics for TSS. All BMP types appeared to significantly reduce TSS concentrations and median effluent concentrations were all below 25 mg/L. Bioretention, detention basins, media filters, retention ponds and wetland basins showed particularly good performance with median effluent concentrations on the order of 10 mg/L. Swales and filter strips do not appear to be able to consistently achieve effluent concentrations below about 20 mg/L. For swales and filter strips, TSS reductions generally occur as a result of shallow sedimentation and vegetative filtration (straining) and can be prone to resuspension of previously captured sediment during high flow events.

It should be noted that the category-level analysis for bioretention, porous pavement and wetland channels only included five to six studies each, whereas the other categories include 14 to 41 studies. From this analysis, it is not possible to extrapolate performance for manufactured devices as a whole to specific devices that may rely on widely varying unit treatment processes.

3.2.2 TDS

Six BMP categories had sufficient data for statistical analysis, with no category showing statistically significant reduction in TDS, as summarized in Figure 6 and Table 3. Bioswales, detention basins, and manufactured devices showed no statistically significant change in TDS based on evaluation of the unpaired data set; however, filter strips, media filters, and retention ponds showed statistically significant increases in TDS. When limiting the analysis data set to paired inflow-outflow data only, the Wilcoxon test (Attachment 1) shows statistically significant increase in TDS for manufactured devices, as well. Possible theoretical explanations for increases in TDS could include leaching of mineral salts, nutrients, or humic substances from planting soils or possibly due to bacterial growth in the water column; however, these speculative explanations are not justified without additional site-specific investigation.[7] Further exploration of the underlying media filter data set indicates similar increases in TDS for inorganic sand filters and those having peat mixed with sand.

Note that the manufactured device category contained one study in Madison, WI with extremely high TDS relative to the other manufactured devices and other BMP categories. The Madison study contained most of the TDS values greater than 5,000 mg/L. Researchers conducting additional analysis of the manufactured device category may choose to focus analysis on ranges of influent TDS most comparable to those at their site conditions. For example, although the Madison results appear high compared to the rest of the data set, they could be representative of conditions during snowmelt or runoff where de-icing has occurred.

3.2.3 Turbidity

Only four BMP categories had sufficient data for statistical analysis of turbidity, as shown in Figure 7 and Table 4. Detention basins, media filters, retention ponds and manufactured devices showed statistically significant decreases, consistent with the results for TSS. Media filters, retention ponds and manufactured devices had low effluent concentrations (e.g., 2-5 NTU), whereas the median turbidity for detention ponds was higher at 19 NTU; however, median inflow turbidity for detention basins was roughly twice that of the other categories for unknown reasons.

[7] While bacteria are not technically “dissolved”, the analytical method for TDS may result in some free-floating bacteria that pass through a filter to be included in the TDS measurement.

Figure 5. Box Plots of Influent/Effluent TSS Concentrations by BMP Type

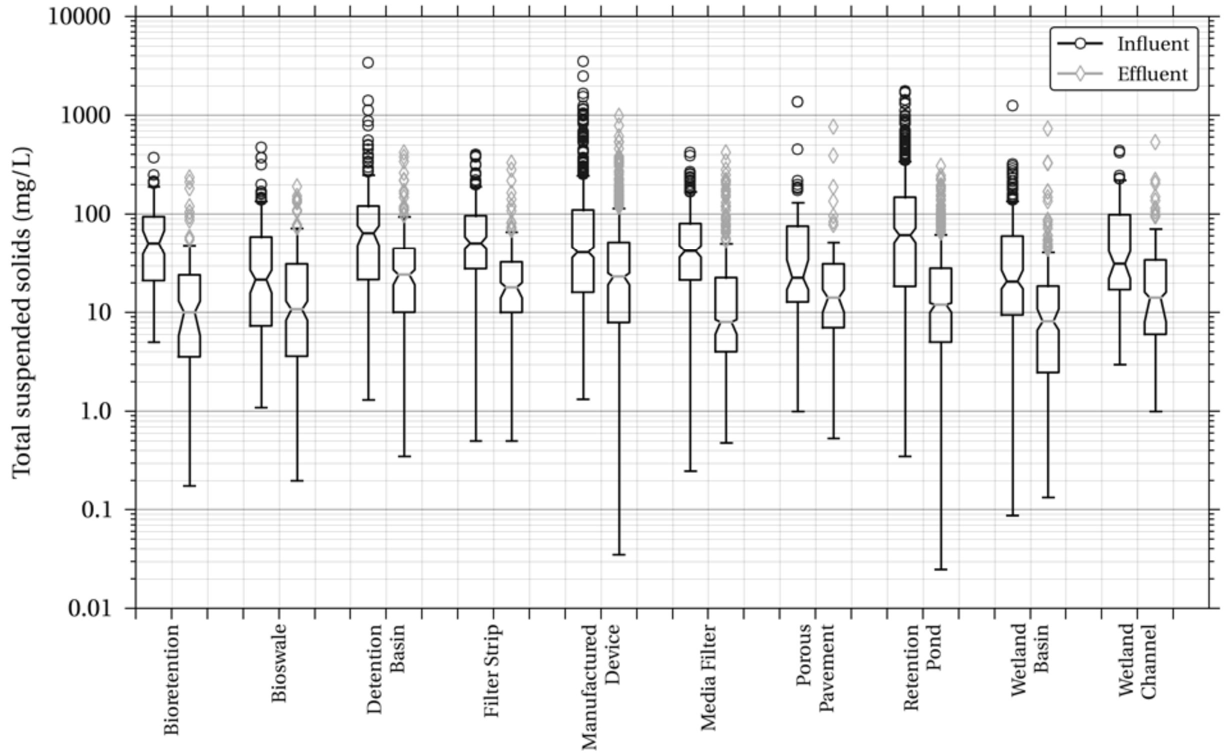


Table 2. Influent/Effluent Summary Statistics for TSS

BMP Type	Count (Studies/Data Pts.)		25th Percentile (mg/L)		Median (95% Conf. Interval) (mg/L)		75th Percentile (mg/L)	
	In	Out	In	Out	In	Out	In	Out
Bioretention	6, 105	6, 96	21.0	2.8	50.0 (39.0, 68.0)	**10.0 (6.0, 13.0)**	94.0	24.0
Bioswale	17, 243	19, 265	7.0	3.0	21.0 (15.0, 26.0)	**10.0 (7.0, 11.0)**	58.5	31.0
Detention Basin	19, 239	19, 265	21.5	10.0	64.0 (47.0, 76.0)	**24.0 (19.0, 27.0)**	121.0	44.0
Filter Strip	14, 232	14, 175	27.8	10.0	50.5 (44.5, 58.5)	**18.0 (14.0, 20.0)**	96.0	32.5
Manufactured Device	40, 555	47, 608	16.0	7.0	41.0 (36.0, 46.0)	**23.0 (19.0, 25.0)**	109.0	51.3
Media Filter	19, 294	20, 286	21.0	4.0	42.0 (36.0, 47.5)	**8.0 (6.0, 8.0)**	79.8	22.0
Porous Pavement	5, 64	8, 73	12.8	7.0	22.0 (16.0, 27.5)	**14.0 (10.0, 17.0)**[1]	75.0	31.0
Retention Pond	41, 605	40, 605	18.0	5.0	60.0 (49.0, 70.0)	**12.0 (10.0, 12.0)**	148	28.0
Wetland Basin	15, 303	16, 295	9.0	2.0	20.0 (16.0, 26.0)	**8.0 (6.0, 9.0)**	59.0	18.0
Wetland Channel	5, 91	5, 88	17.0	6.0	31.0 (22.0, 42.0)	**14.0 (8.0, 16.0)**	98.0	34.0

[1]Determination of statistically significant reduction for porous pavement is based on the Mann-Whitney test in Attachment 1 since there is minor overlap of confidence intervals for the inflow and outflow medians.

Figure 6. Box Plots of Influent/Effluent TDS Concentrations by BMP Type

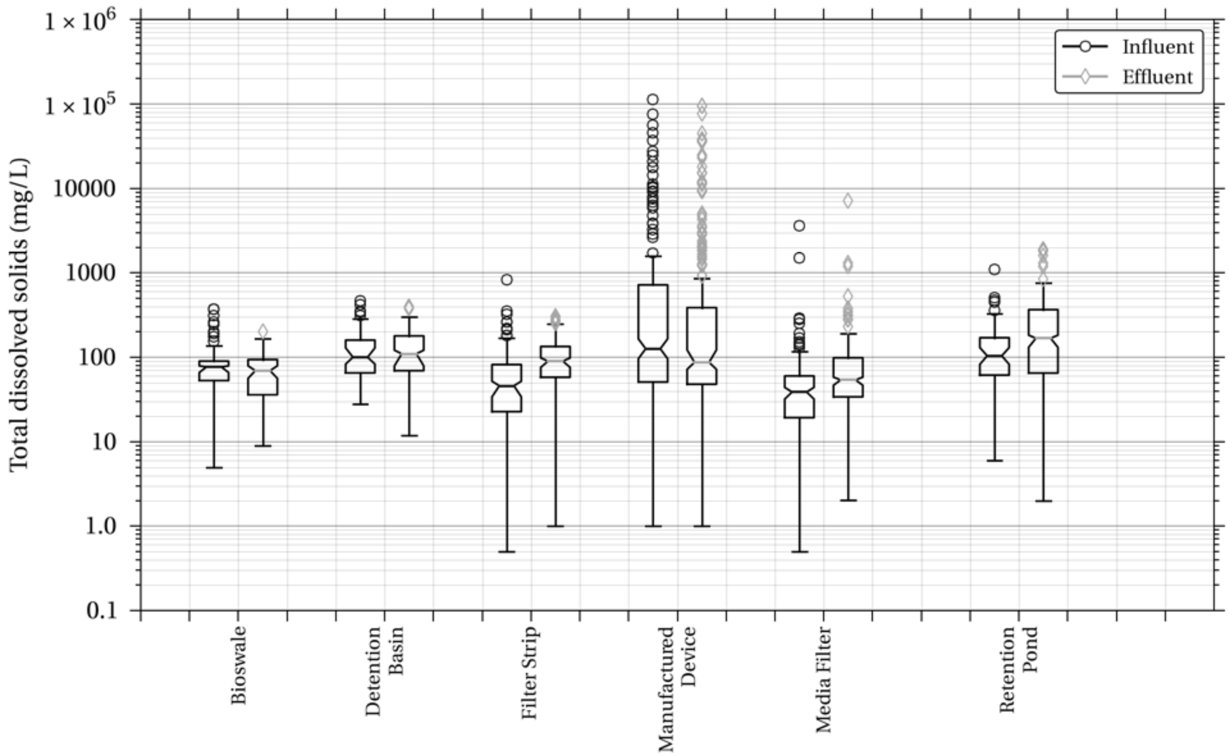


Table 3. Influent/Effluent Summary Statistics for TDS

BMP Type	Count (Studies/Data Pts.)		25th Percentile (mg/L)		Median (95% Conf. Interval) (mg/L)		75th Percentile (mg/L)	
	In	Out	In	Out	In	Out	In	Out
Bioretention	NA	NA	NA	NA	NA	NA	NA	NA
Bioswale	12, 95	12, 82	53	36	77 (66, 79)	70 (56, 79)	90	94
Detention Basin	6, 66	6, 62	65	69	100 (83, 129)	110 (79, 121)	160	179
Filter Strip	12, 188	12, 151	23	58	46 (34, 52)	***90 (76, 98)***	82	134
Manufactured Device	12, 175	19, 207	51	48	126 (96, 165)	87 (72, 122)[1]	717	386
Media Filter	12, 125	13, 131	19	34	38 (27, 40)	***54 (46, 58)***	60	99
Porous Pavement	NA	NA	NA	NA	NA	NA	NA	NA
Retention Pond	9, 101	9, 93	61	65	104 (79, 124)	***167 (130, 181)***	170	365
Wetland Basin	NA	NA	NA	NA	NA	NA	NA	NA
Wetland Channel	NA	NA	NA	NA	NA	NA	NA	NA

[1]Hypothesis test results for paired and unpaired data sets differ for TDS at manufactured devices. Unpaired data sets show no statistically significant difference in influent and effluent data sets, whereas the Wilcoxon test for the paired data subset shows statistically significant differences in inflow and outflow concentrations, with effluent concentrations higher than influent concentrations.

Figure 7. Box Plots of Influent/Effluent Turbidity Concentrations by BMP Type

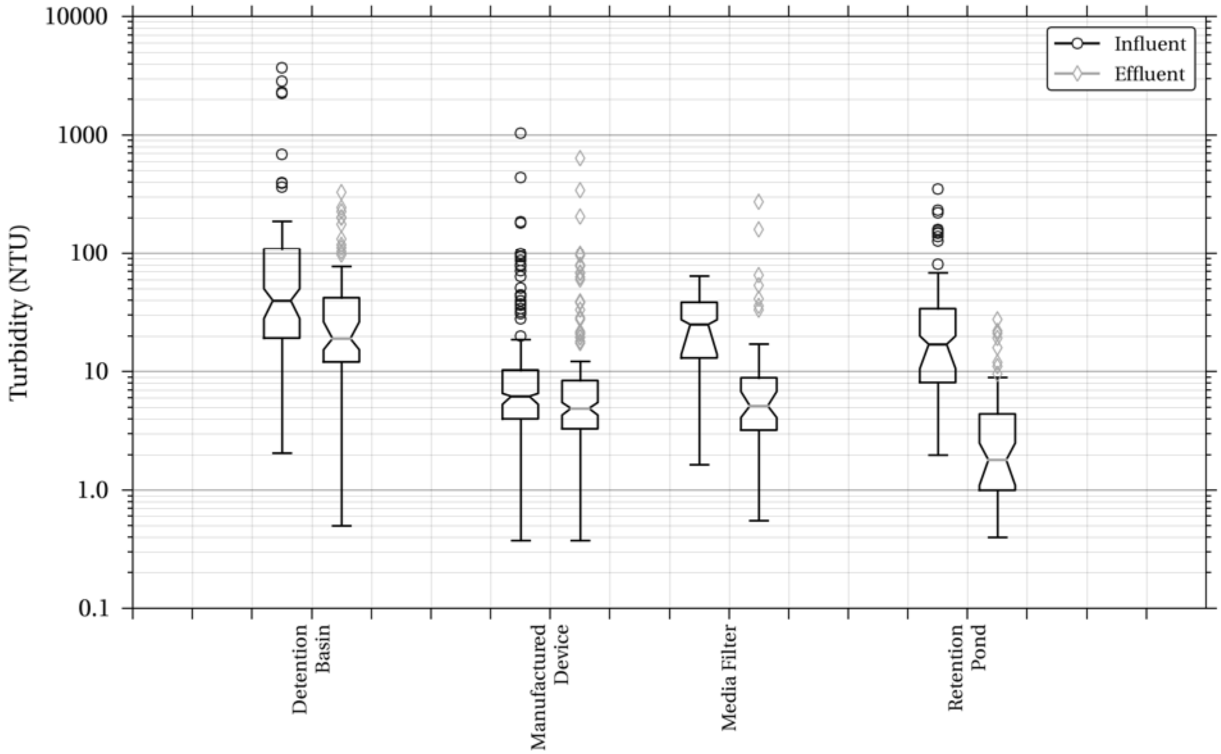


Table 4. Influent/Effluent Summary Statistics for Turbidity

BMP Type	Count (Studies/Data Pts.)		25th Percentile (NTU)		Median (95% Conf. Interval) (NTU)		75th Percentile (NTU)	
	In	Out	In	Out	In	Out	In	Out
Bioretention	NA	NA	NA	NA	NA	NA	NA	NA
Bioswale	NA	NA	NA	NA	NA	NA	NA	NA
Detention Basin	7, 85	7, 111	19.0	12.0	39.0 (27.0, 50.0)	**19.0 (15.0,26.0)**	109	42.0
Filter Strip	NA	NA	NA	NA	NA	NA	NA	NA
Manufactured Device	9, 140	9, 122	4.0	3.0	6.0 (5.0, 6.0)	**4.0 (4.0, 5.0)**[1]	9.5	8.0
Media Filter	4, 43	5, 48	13.0	3.0	25.0 (14.0, 27.0)	**5.0 (3.5, 6.0)**	38.0	8.3
Porous Pavement	NA	NA	NA	NA	NA	NA	NA	NA
Retention Pond	5, 89	6, 102	8.0	1.0	17.0 (10.0, 20.0)	**1.0 (1.0, 1.0)**	34.0	4.0
Wetland Basin	NA	NA	NA	NA	NA	NA	NA	NA
Wetland Channel	NA	NA	NA	NA	NA	NA	NA	NA

[1]Determination of statistically significant reduction for manufactured devices is based on the Mann-Whitney test in Attachment 1 since there is minor overlap of confidence intervals for the inflow and outflow medians.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Recommendations for BMP Selection and Design

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. Similar findings were present for BMPs with turbidity data available for analysis, although this data set was more limited. Conversely, no BMPs showed statistically significant removal of TDS, with filter strips, media filters and retention ponds showing increases in TDS effluent concentrations.

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. The lowest effluent concentrations achieved based on the available data set include bioretention, detention basins, media filters, retention ponds, and wetland basins. In general, these mechanisms are anticipated to be more effective as the hydraulic residence time increases. Hydraulic residence can be increased in wetlands and ponds by increasing flow paths through the use of berms, baffles, and dense vegetation. In media filters and bioretention, increasing bed thickness and evenly distributing flows would likely improve performance. 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; 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.

The focus of this technical summary is sediment in urban runoff that is treated and managed through the use of BMPs prior to discharge to reaching receiving waters. Note that instream channel processes that are impacted by urban runoff can be significant sources of sediment in urban areas and are not addressed in this summary. Channel stabilization and/or flow duration or volume management or combinations of these are also often necessary in urbanized areas to mitigate bed and bank erosion and should be considered as part of strategies for controlling sediment impacts to receiving waters.

4.2 Recommendations for Appropriate Uses of Data

The BMP Database sediment data set can be useful for characterizing the treatment performance for selected BMP categories. However, the number of studies and number of data points 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 or climatic conditions comparable to those expected for their site.

Sediment removal data may be useful for assessing the effectiveness of BMPs to remove pollutants that are highly associated with sediments. For example, although the performance data for removal of PCBs, dioxins and PAHs are severely lacking, TSS removal data combined with knowledge of sediment concentrations of these or other pollutants may be useful for selecting and design BMPs to address other constituents. Particle size distributions of influent and effluent sediments along with knowledge of associated sediment concentrations would be even more useful.

4.3 Recommendations for Additional Research

- Obtain more studies with larger numbers of storm events and additional within-storm sample collection and analyses in a range of geographical locations to draw more statistically rigorous conclusions for all BMP types, particularly under-represented categories such as bioretention, porous pavement and wetland channels.
- Obtain and analyze results for more studies that clearly identify analysis methods as SSC or TSS, and ideally include both results for at least a portion of the storm events sampled.
- Analyze influent and effluent data pairs to identify whether functional relationships (e.g., linear) may exist. (Attachment 1 provides initial information on this subject.)
- Obtain more studies with particle size distribution information, especially those comparing influent and effluent data pairs.
- Compare design attributes, unit treatment processes and maintenance characteristics of BMPs that perform well and those that perform poorly.
- Critically evaluate the influence of individual studies within a BMP category on influent and effluent summary statistics.
- Compare BMP performance for constituents with differing influent concentration ranges (i.e., "bins") to assess how influent concentration affects performance for the BMP-constituent combination.
- Divide manufactured devices by fundamental unit processes and analyze separately.
- Evaluate organic fraction of TDS for influent and effluent data pairs for BMPs with increases in TDS. An evaluation of other dissolved constituents that may contribute to the TDS measurement may also be useful.

5 ATTACHMENTS

Attachment 1. Statistical Summary Report
Attachment 2. Analysis Data Set in Excel

6 REFERENCES

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Last Update: May 13, 2011