Stormwater Biofilter Media Performance Updates for WinSLAMM: Data Summary for Unit Process Components, Example Calculations and Model Use

R. Pitt,¹ S. E. Clark,² R. Sileshi,³ and J. Voorhees⁴

¹University of Alabama, Tuscaloosa, Alabama; ²Penn State–Harrisburg, Middletown, Pennsylvania; ³University of North Georgia, Gainesville, Georgia; ⁴PV and Assoc., Madison, Wisconsin.

Abstract

This paper focuses on specific information needed to model various aspects of the pollutant retention processes in stormwater biofilters. Updates currently being incorporated in WinSLAMM (Source Loading and Management Model) are building on expanded data from laboratory and field research mostly conducted by Pitt's research group at the University of Alabama, Tuscaloosa, by Dr. Shirley Clark's research group at Penn State–Harrisburg, and the Wisconsin Department of Natural Resources and the U.S. Geological Survey (DNR/USGS). These processes and data can be used in manual calculations or other models. Extensive summaries of these data sources and associated statistical analyses, plus additional references, are included in an online white paper available at the PV & Assoc. [website](#). These tests were conducted to provide the details needed for modeling the performance of biofilters, specifically focusing on: methods to predict treatment flow rates through the media; particulate and associated particulate bound pollutant retention for several particle sizes; maintenance requirements due to sediment clogging and pollutant breakthrough; and retention of filterable pollutants. This multiyear research program also examined issues not commonly described in the biofilter performance literature, such as failure due to excessive salt loadings on media having large amounts of fines, problems associated with compaction of the media, and leaching of previously captured material from the media.

This paper consolidates the information from many prior research projects and dissertations and illustrates how these data can be used together for calculating the benefits of stormwater biofilter systems. This paper summarizes the data and the major calculation components to determine biofilter performance. This is followed by a numeric example using these data along with a description of how WinSLAMM describes a biofilter installation and an example development of a production function to assist in the design and evaluation of biofilter options.

1 Introduction

This paper describes the data and calculations that are being used to update the biofilter performance calculations in WinSLAMM. The literature and online resources describe many biofilters (with underdrains) and bioinfiltration (usually without underdrains, with most of the stormwater treatment associated with infiltration) performance studies. This paper does not include a comprehensive review of these data, as it focuses on the specific information needed to model the various parts of the pollutant retention processes. Most of the data supporting the WinSLAMM model enhancements are from several long term laboratory and field studies:

- Clark's master's thesis and dissertation research using laboratory and pilot scale field testing of different media (Clark 1996, 2000; Clark and Pitt 1999);

- Pitt and Clark's research for The Boeing Company to develop biofilter media mixtures suitable for a wide range of pollutants at an industrial site being restored to open space use (Pitt and Clark 2010), along with full scale multiyear testing of biofilters at this location (Pitt et al. 2021a, 2021b); and
- Sileshi's dissertation on soil and sand media for biofilter treatment flow rates, underdrain design, and retention of particulate sizes (Sileshi 2013).

In addition, several full scale biofilter monitoring projects also contain information and data useful for this summary. Wisconsin DNR and USGS have been monitoring test biofilters to compare the performance of various media mixtures (Bannerman, personal communication). The *Kansas City Demonstration Project of Green Infrastructure in Areas served by Combined Sewers*

(Pitt et al. 2014) included monitoring of many biofilters throughout a large area and examined their benefit at a large scale. Pitt and Talebi (2012) monitored changes in stormwater pollutant concentrations during dry well performance studies as the stormwater passed through underlying soils. Pitt et al. (1999) also conducted monitoring at compost-amended test sites to determine the removal benefits of these soil mixtures.

A comprehensive overview of the performance of biofilters and other stormwater controls is given by the International BMP Database. Unfortunately, few of these studies include detailed data concerning the partitioning of the particulates and pollutants by particle size and by total and filtered forms. In addition, rate kinetics associated with contact times, clogging by particulates, and retention capacity of the media for the wide variety of pollutants of interest are also needed for modeling. This information is needed when modeling the expected behavior of these systems, which rely on a wide range of media for stormwater quality improvements. In addition, the selection of which media (and combinations) to meet desired treatment objectives is also elusive. Clark and Pitt (2012) wrote a summary on targeting treatment technologies (such as media selection) with specific objectives. The use of a comprehensive model that addresses these many issues enables comparisons of alternative biofilter designs.

WinSLAMM, the Source Loading and Management Model, is an urban stormwater model that can be used for single urban lots to complex urban catchments. WinSLAMM is based on field monitoring observations covering a wide range of scales with unique hydrologic and pollutant related components that focus on urban systems. It is mainly used as a planning tool to assess both stormwater and pollutant runoff production and the capability of many stormwater control strategies to reduce stormwater discharges from urban sources (Pitt and Voorhees 2002). Several presentations and papers associated with the annual urban water modeling conferences and the *Journal of Water Management Modeling* have described WinSLAMM and its attributes (including Avila et al. 2008; Avila and Pitt 2009; Myllyoja et al. 2001; Pitt 1998, 1999; Pitt and Lantrip 2000; Pitt and Lalor 2001; Pitt et al. 2003, 2008, 2011, 2012; Pitt and Talebi 2013; Pitt and Voorhees 2007, 2011; Sileshi et al. 2014; and Talebi and Pitt 2014).

WinSLAMM continuously models flows and associated hydrographs through stormwater controls. The performance of each stormwater treatment device is dependent on storage volumes, hydraulic controls, and underlying native soils, which can vary greatly. A simple percentage reduction of runoff volume (and concentrations) cannot accurately describe their performance, especially when considering antecedent conditions and variable rainfall characteristics throughout the study period, in addition to complex interconnections of stormwater controls throughout a site. WinSLAMM uses actual long term rainfall history and continuously calculates and routes the flows through stormwater controls. It also considers the undrained volume of water from previous rain events remaining in the control, including moisture levels in treatment media. Runoff volume is infiltrated, and the

hydrograph shape is modified based on the stormwater control design. The effluent from an upstream control is then directed to the next downstream control where the runoff volume and hydrograph are similarly altered based on that control design. This process continues until a junction is reached where the multiple flows and hydrographs are combined. This flow and hydrograph routing process continues through the drainage system (which may also incorporate controls, such as grass swales) until the outfall is reached. Outfall controls can also be used to alter the runoff volume and hydrograph before the final discharge.

The calculation scheme to predict the performance of biofilters and bioretention controls in WinSLAMM, as described in this paper, has some uncertainties. The predicted results should not be considered extremely precise (as with all stormwater modeling). The data presented in this paper includes measures of uncertainty, expressed as the coefficient of variation (COV), the ratio of the standard deviation to the average value. These can be used in the calculation procedures as part of Monte Carlo calculations where values for a parameter are randomly selected from a probability distribution (as defined by the COV values and distribution type). When this option is selected in WinSLAMM, a random value is selected from the probability distribution for a parameter for each rain event; if the model is run multiple times using the same information and rain series, the final outcomes will vary depending how these random variables interrelate. The final distribution of outcomes usually reasonably represents actual observed variabilities during field monitoring.

With much of the data relying on controlled laboratory and pilot scale experiments, an important question is therefore: How well do these results represent actual full scale field measurements as represented in WinSLAMM? A major source of information described in this paper was the laboratory experiments conducted by Pitt and Clark (2010) while developing a media treatment mixture for Boeing for use at the Santa Susana Field Laboratory site in Southern California. The recommended media mixture has been used at many locations on this site. Extensive performance monitoring of the media treatment controls has been conducted over many years. A current set of papers (Pitt et al. 2021a, 2021b) describe how the laboratory test results reasonably agree with the full scale field results, and how performance has changed over many years of operation, as predicted by the laboratory tests and as represented in WinSLAMM.

The steps in sizing a stormwater treatment biofilter, as detailed in the following sections, can be summarized as follows:

1. Characterize the stormwater to be treated (focusing on critical pollutants needing removal together with constituents that affect maintenance), along with the expected runoff volume and flow rates for the drainage area.
2. Determine the required concentrations and mass reductions of the constituents of concern.
3. Identify the chemically active media to target these constituents (including necessary contact times)

and other factors affecting performance, such as anaerobic conditions and degradation of the media along with leaching of constituents from the media).

4. Inventory other site characteristics potentially affecting the biofilter (maximum area available, depth to groundwater and seasonal changes to the water table, underlying natural soil characteristics, snow-melt sodium adsorption ratio, SAR, problems).
5. Prepare preliminary designs addressing these factors (size of facility, selection of media, outlet controls or underdrains, and maintenance intervals).
6. Evaluate alternative designs using long term continuous stormwater quality modeling and evaluate life cycle costs and other decision support factors.

The following section describes some of the data sources and summarizes the statistical tests that were conducted. Illustrative uses of these data are also presented in a later section of this paper.

2 Data Summaries

The data and process discussions are separated into three groups: flow rates, particulate retention by particle size, and retention of filterable pollutants. Table 1 lists some characteristics of these materials: percentage of organic matter (affects treatment flow rates), cation exchange capacity (CEC; may affect the retention of cations), % fines (affects SAR failures with snowmelt), phosphorus content (indicates leaching of phosphorus from media), saturated water content, field capacity, and permanent wilting point (all affect evapotranspiration, ET, losses from media), and the infiltration rates measured for each of these components and mixtures. Table 1 also shows the maximum accumulation of sediment before clogging. An expanded program documentation memo that contains much additional biofilter media information is posted as a white paper on the PV & Assoc. [web page](#).

Treatment flow rates through biofilter media affect the design and performance of these stormwater controls. High treatment flow rates allow for smaller sized facilities, but also provide reduced contact time between stormwater and media, possibly reducing chemically active treatment in the media. Low treatment flow rates provide longer contact time, and usually better treatment, but require larger treatment areas. Chemically active media also has specific capacities (typically based on ion exchange or sorption processes). Small biofilter facilities with smaller amounts of chemically active media will require more frequent media replacement. In addition, low treatment flow rates and small biofilter surface areas may result in extended standing water above the treatment media, leading to nuisance conditions. The capture of particulate-associated pollutants is not so dependent on the treatment flow rates. However, rapid treatment flow rates with small biofilter surface areas (especially in areas having high sediment loads and lacking pretreatment) can lead to premature failure due to clogging or silting. The media

treatment flow rates can be controlled using outlet controls and underdrains, or through mixtures of media components.

Extensive information referenced in Table 1 that was used to calculate the various factors, along with the associated statistical analyses, are included in the appendices and in the white paper available at the WinSLAMM [web page](#).

Table 1 General physical characteristics, treatment flow rates, and retention of stormwater particulates by biofilter media components and mixtures.

(See Appendix)

2.1 Treatment Flow Rates for Biofilter Media Components and Mixtures

Biofilter media treatment flow rate measurements were obtained from laboratory and field measurements. The following paragraphs describe the treatment flow rates obtained during two of these research activities. Again, descriptions and data for all of the data are presented in the on-line extended white paper.

Sileshi (2013) conducted a large number of laboratory column tests examining treatment flow rates for various mixtures of stormwater biofilter media as part of his dissertation research. These tests and data are described in his dissertation, available [here](#), and in Sileshi et al. (2014, 2017, 2018). Sileshi (2013) found that the biofilter media treatment flow rates were mostly affected by the median mixture particle size (D50) and the uniformity coefficient (D60/D10) of the media mixture, and the amount of organic matter. As expected, larger particles with small uniformity coefficients had the largest treatment flow rates. Compaction had minor effects if the organic matter content was low, but had significant effects on the flow rates for high organic matter content.

[Appendix A1](#) of Pitt, Clark et al. (2019) lists the characteristics of the media that were tested in the laboratory column tests by Sileshi (2013). The 22 test sand mixtures were prepared to cover the typical range of biofilter media characteristics: the median sizes ranged from 270 μm to 1900 μm and the uniformity coefficients ranged from 1.3 to 39. The organic matter content ranged from a low of 1.5% to a high of about 50%. Tests also included four Tuscaloosa, Alabama area soils and three biofilter media mixtures from existing biofilter facilities. Each test was conducted in triplicate and the resulting saturated flows in the columns were determined together with the media coefficients of variation for three levels of compaction. About 200 column tests were conducted to obtain these data. The test methods, detailed chemical and physical analyses and other supporting information are all described by Sileshi (2013).

Appendix A2 of Pitt, Clark et al. (2019) presents the statistical analyses of these data, building on the factorial test results and analyses presented by Sileshi (2013). The following equations are the resulting significant regression equations developed to calculate the expected saturated flows (F_c , cm/h) in log10 space, based on the D50 (μm) and C_u values. These equations are

divided by organic matter content (low is <10% organic matter and high is >10%) and level of compaction. It is expected that the lowest level of compaction is most commonly used for biofilters, but field monitoring has identified biofilters having high compaction levels. Compaction (listed below as hand compaction, the lowest level of compaction, proctor compaction, and modified proctor compaction, the highest level of compaction normally available) is most important for media mixtures having high organic matter content.

Low Organic Matter Content (<10% OM):

$$\text{hand log } Fc = -1.72 \times 10^{-6}(D_{50})^2 + 0.00410(Cu)^2 + 0.00469(D_{50}) - 0.162(Cu) \quad (1)$$

$$\text{proctor log } Fc = -1.291 \times 10^{-6}(D_{50})^2 + 0.00356(Cu)^2 + 0.00407(D_{50}) - 0.175(Cu) \quad (2)$$

$$\text{modified proctor log } Fc = 0.00162(D_{50}) - 0.0590(Cu) \quad (3)$$

High Organic Matter Content (>10% OM):

$$\text{hand log } Fc = 1.84 + 0.000522(D_{50}) - 0.0648(Cu) \quad (4)$$

$$\text{proctor log } Fc = 1.31 + 0.000683(D_{50}) - 0.0594(Cu) \quad (5)$$

$$\text{modified proctor log } Fc = 1.28 + 0.000640(D_{50}) - 0.070(Cu) \quad (6)$$

Appendix A2 of Pitt, Clark et al. (2019) contains all of the statistical and regression analyses of variance indicating the significance of the equation terms. The regression behaviors are all reasonable and all coefficients and equations are statistically significant, with the exception of the Cu^2 and Cu terms in the low organic matter low compaction equation which have marginally significant p values at the 0.08 and 0.09 levels, compared to the other coefficients that have significant p values <0.05.

In another research example that investigated treatment flow rates, Pitt and Clark (2010) conducted a series of tests while developing treatment media for an industrial site in Southern California. Detailed study descriptions and results are available [here](#).

2.2 Retention of Stormwater Particulates by Biofilter Media

Particulate Retention Equations

Four main data sources present information for the particulate retention calculations by particle size ranges: column tests (Sileshi 2013); Boeing media tests (Pitt and Clark 2010); Kansas City–USEPA demonstration project biofilters (Pitt et al. 2014); and Wisconsin DNR–USGS biofilter media tests (Bannerman, personal communication). These data are all presented and analyzed in Pitt, Clark et al. (2019).

The following is an example of the test results from one of the test mixtures (the mixture being used by Boeing at many of their stormwater treatment systems) developed by Pitt and Clark

(2010). Extensive laboratory and pilot scale tests were conducted to test and develop this high performance biofilter media mixture to treat a wide range of stormwater pollutants at the Santa Susana Field Laboratory (SSFL), an aerospace and atomic energy test facility located in Southern California, for the Boeing Company, which is being restored. The research report describes the series of different tests conducted with these media. Stormwater particulate retention for different particle sizes was an important parameter in these tests. Table 2 (Pitt and Clark 2010) includes regression equations that were developed and are being used in the WinSLAMM biofilter calculations (an example of one of many media mixtures investigated). Clark and Pitt (2009a) also describe a power equation for particulate retention in the media, while Clark et al. (2006) summarizes some of the earlier test results.

Table 2 Example of removals for rhyolite sand–surface modified zeolite–granular activated carbon mixture (R-SMZ-GAC) for full depth column tests (X is the influent concentration and Y is the calculated effluent concentration).

(See Appendix)

Full scale test data of biofilter performance (including retention of stormwater particulates) were also used to confirm biofilter media performance derived from controlled column tests. The Kansas City project was a demonstration project funded by the U.S. Environmental Protection Agency (USEPA) to show how green infrastructure can be integrated into areas having combined sewers (Pitt et al. 2014; summarized in Pitt and Talebi 2013). This was an extensive project and included the construction of several hundred stormwater controls in the test area. An adjacent area with no stormwater controls was used for comparison. The monitoring program lasted for ~2 y and included >50 storms during the test period. The monitored biofilters worked very well and only 6 events produced underdrain flows that could be sampled and analyzed, with the remainder of the stormwater completely infiltrated after treatment by the media. The media consisted of 30% planting soil, 20% organic compost, and 50% sand (Seattle mix). The performance data for these biofilters are summarized below and the details are shown in the online Appendix C4, with some particulate retention data presented in Table 3 (Pitt et al. 2014).

Full scale biofilter tests were conducted in Neenah, WI by the USGS and Wisconsin DNR (Bannerman, personal communication). These were specially constructed biofilters to compare different mixtures and biofilter designs, specifically targeting phosphorus removal. The data shown below are for mix 2, which consisted of 86% sand, 11% peat moss, and 3% Imbrium phosphorus removal material. The biofilters were sealed under the storage layer and all of the treated effluent was collected by underdrains and analyzed, resulting in 44 sets of data. The performance data for these tests are shown in Table 4 (Bannerman, personal communication), with details provided in the online Appendix C5.

The summary performance data in these tables indicate the range of influent concentrations for each particle size category, along with the regression equations and the statistical significance of the overall equations and coefficients. In some cases, only the intercepts are significant. In these cases, the effluent is not related to influent concentrations and is a constant value (the COV values can be used with a Monte Carlo procedure to account for the remaining variation). The data from the Wisconsin tests indicated that the data were not normally distributed, so log10 transformations were used to develop the equations. The Kansas City data did not indicate nonnormal conditions so those data were not transformed. Some of the equations are shown to be highly significant, but there is a lot of variation when the predicted effluent concentrations are compared to the observed effluent concentrations. Therefore, the observed effluent COV values should also be applied to these calculated effluent values using a Monte Carlo process to account for the variability.

Table 3 Kansas City biofilter tests (Seattle biofilter mix; x is the influent concentration and y is the calculated effluent concentration).

(See Appendix)

Table 4 Wisconsin media 2 Neenah biofilter tests (mix 2 only available) (x is the influent concentration and y is the calculated effluent concentration).

(See Appendix)

Effects of Solids Accumulation on Flow Rate Reductions

As solid material accumulates in the biofilter media, the treatment flow rate decreases. Clark (2000) developed clogging equations associated with accumulated loading. Figure 1 shows example plots of the resulting equations for two groups of data: all granular media combined, and a separate plot for compost-sand mixtures.

Figure 1 Example of solids accumulation on biofilters and associated treatment flow rate reductions.

These plots show treatment flow rates (m/d) vs sediment accumulation (kg/m²). The coarse-grained granular media is seen to lose an order of magnitude of flow capacity after about 10 kg/m² accumulation. The finer texture and highly variable particle size distribution of the compost-sand resulted in flow rate losses that were much more rapid, with 1 order of magnitude of flow capacity lost after about 0.5 kg/m² of sediment accumulation.

2.3 Retention of Filtered Pollutants by Biofilter Media Components and Mixtures

The third component of the biofilter calculations is the determination of the retention of filtered pollutants in the media. In most cases, the retention of particulate-bound pollutants will be responsible for most of the total stormwater pollutant reductions in biofilters, but chemically active filter media has also been found to reduce some of the filterable pollutant forms. If the biofilter also has significant infiltration (such as in rain gardens or bioretention facilities with no underdrains, or with high native soil infiltration capacities even with underdrains), it is likely that most of the filtered pollutant mass reductions would be associated with infiltration. The following addresses three aspects of filtered pollutant retention: observed concentration reductions as a function of influent concentrations (with some additional information for bacteria retention and for phosphorus leaching from compost media), media capacity, and the effects of contact time on filtered pollutant retention.

The data associated with these topics for each category are described, with additional background and statistical analysis information given in the on-line appendices. As for the treatment flow calculations, Table 1 includes information for many individual components along with some mixtures. Mass-weighted values for the components are used to calculate these factors for other mixtures, with some restrictions (such as maximum amounts of peat allowed in the mixtures at 50% to reduce

compaction issues). Only statistically significant removals are summarized in this paper. If a constituent is not listed for one of the categories, it is assumed that no retention of filtered pollutants occurs (effluent = influent) or that it was not tested.

2.4 Filterable Pollutant Retention by Media Components and Mixtures

Boeing Media Tests

The Boeing long term column test report (Pitt and Clark 2010) also included detailed analyses of many pollutants in both total and filtered forms. The report statistically analyzed their retention times, which are shown in Table 5 for one example media mixture, with similar data and background statistical tests described in the full report which is available online. Data are shown for conditions generally having p values ≤ 0.05 (some at 0.06). Gross alpha and gross beta removals for the mixtures are shown with p values ~ 0.13 due to the small number of tests available. Relationships not shown are for larger p values and in these cases it is assumed that no statistically significant removal occurs (based on the number of samples available) or that it was not tested (listed in the online appendix of Pitt, Clark et al. (2019), available [here](#)) and therefore they were not included in the WinSLAMM calculations.

Table 5 Example of filterable pollutant removals for rhyolite sand–surface modified zeolite–granular activated carbon mixture (R-SMZ-GAC) for full depth column tests (x is the influent concentration and y is the calculated effluent concentration).

(See Appendix)

Wisconsin Neenah Media 2 Biofilter Tests

Additional biofilter data investigating the retention of filtered pollutants is available from the Wisconsin Neenah DNR/USGS tests (Bannerman, personal communication). Table 6 summarizes the observed retention relationships for the media 2 mixture (86% sand, 11% peat moss and 3% Imbrium phosphorus removal media). The Wisconsin data are combined from three biofilters, having media depths of 1 ft–3 ft (0.3 m–0.9 m); no significant differences were noted for the different depths so the data were therefore combined. The influent TDS and chloride values had many nondetectable values, while the effluent values all increased. The increases were due to leaching of salts from the media during long term monitoring.

Table 6 Summary of filtered pollutant retention in Wisconsin media 2 biofilters (Wisconsin Neenah mix: 86% sand, 11% peat moss, and 3% Imbrium) (x is the influent concentration and y is the calculated effluent concentration, both in $\log_{10}$ space).

(See Appendix)

2.5 Phosphorus Leaching from Compost Amendments

The addition of compost to biofilter mixtures has been shown to add phosphorus to underdrain flows due to leaching of the nutrients from the material. In most cases, relatively small amounts of compost are added (just a few inches of material to the top of the biofilter to support plant growth, or about 10% of the mixture, for example). The International BMP Database includes effluent concentrations from many typical biofilters indicating about 0.25 mg/L filtered phosphorus in the effluent. An extreme example of compost amendments is illustrated in the USEPA report by Pitt et al. (1999), where soil and compost were mixed 50:50 with phosphate subsurface concentrations of about 1.8 mg/L in the underdrain (compared to about 0.17 mg/L for soil only test plots).

2.6 Retention Capacity of Filtered Pollutants in Biofilter Media Components and Mixtures

There are usually limits on how much of the filtered pollutants can be retained by the biofilter media. Extensive capacity tests were conducted by Pitt and Clark (2010) as part of the Boeing biofilter media development research, as summarized in Tables 7 and 8 (Pitt and Clark 2010). These were determined by long term spiked stormwater column tests to identify when breakthrough occurred. Conventional batch capacity tests are not particularly comparable to field observations, likely because the batch tests use concentrations that are much higher than observed in the field and usually use single component mixtures (Clark and Pitt 2009a, 2009b). These capacities were determined by knowing the amount of pollutants loaded onto the columns during the tests with time until breakthrough, using spiked stormwater mixtures with concentrations similar to those found at the site.

Table 7 Media capacities for filtered pollutants for biofilter media components and mixtures.

(See Appendix)

Table 8 Media mixture capacities for radioactive stormwater constituents.

(See Appendix)

2.7 Effects of Contact Time of Filtered Pollutant Retention by Biofilter Media Components and Mixtures

The Boeing media tests (Pitt and Clark 2010) included measurements to determine the effects on pollutant retention of different contact times of stormwater with the media. These tests were conducted using conventional batch reactor tests and a series of column tests having different media depths. Some losses of retention with increased contact time were noted. This can be caused by leaching of pollutants from the media, additional ion exchange of these constituents with other constituents, or decomposition of the media and release of prior retained

pollutants. In most cases, the additional contact time results in increased pollutant retention. Some media use (especially peat moss) results in substantial retention of heavy metals with short contact times, while other media may require more than an hour of contact time for the reported retention levels. The following are some of the findings from these media tests for the different media components:

- Granular activated carbon (GAC): most consistent removal and reasonably fast (10 min) removal for organic and metallic compounds; however, rapid (6 min) leaching of nutrients and slow leaching (>6 h) for major ions occurred;
- Surface modified zeolite (SMZ): relatively slow (≥ 1 h) and less consistent for most constituents: leaching occurred after ~20 min for nutrients and after ~2 h for metals;
- Rhyolite sand: relatively fast (~15 min) for nutrients and slow for major ions and metals (>1.5 h–2.5 h) and no leaching observed;
- Peat: very fast (<5 min) for metals, very slow and inconsistent for other constituents: leaching (or ion exchange additions) of carbon-containing constituents (organic surrogates) occurred after ~10 min and after ~30 min for some major ions and nutrients; and
- Site zeolite: very fast (1 min) for some organics and nutrients, slow (>1 h–2 h) for major ions and metals; rapid leaching (after 1 min) occurred for some major ions and metals.

These contact time tests were only conducted on the individual media components. The combined effects of mixtures in typical biofilters can be calculated based on each constituent. Most biofilters with 0.5 m of media provide substantial media contact time (up to several hours). WinSLAMM calculates the contact time and modifies the resultant retention associated with leaching.

3 Numeric Example for Biofilter Media Performance Included in WinSLAMM

The following is an example that shows how the information from the first part of this paper is used in WinSLAMM to calculate the flow rate through a biofilter, its particulate removal, and filtered pollutant removal performance. Clogging calculations and media sorption capacity are also calculated. This information and process can be used for manual calculations, or alternative models, as desired.

The following describes the hypothetical site and runoff conditions (for one example 25 mm rain; WinSLAMM is normally used to conduct a continuous simulation of many rains over many years).

Drainage Area

- 0.4 ha (1 acre) paved commercial parking area.

Stormwater Characteristics

Particulate-bound pollutants are removed along with the suspended sediment concentration (SSC); only a selection of filtered pollutants is used as examples here (ammonia, nitrates, phosphates, and filtered copper).

- SSC: 300 mg/L (Table 9 shows the particle size distribution, PSD);
- Ammonia as N: 0.9 mg/L;
- Nitrates as N: 20 mg/L;
- Phosphates as P: 2.3 mg/L; and
- Cu, filtered: 15 μ g/L.

Table 9 Example particle size distribution of stormwater particulates.

(See Appendix)

Biofilter Area

- 4% of paved drainage area (1700 ft², 160 m²).

Media Mixture (Well Mixed, Not Layered)

- Granular activated carbon (30%);
- Peat moss (30%); and
- Fine sand (40%).

Media Depth and Void Ratio

- Media depth: 1.5 ft (0.46 m); and
- Void ratio: 25%.

3.1 Step 1: Particle Size Distribution of the Media Mixture

The particle size distribution (PSD) of the media mixture allows the median size (D_{50}) and the uniformity coefficient ($C_u = D_{60}/D_{10}$) to be determined. These values are needed to determine several performance aspects of the biofilter, including the flow rate through the media mixture and the stormwater particulate retention by the media. Table 10 shows the calculations to obtain the mixture PSD. Figure 2 is the PSD plot for the resulting mixture.

Table 10 Calculations to obtain media mixture PSD.

(See Appendix)

Figure 2 Calculated PSD plot for media mixture.

The following particle sizes correspond to the associated percentage distributions:

- D_{10} : 120 μm ;
- D_{50} : 850 μm ; and
- D_{60} : 1100 μm .

The median size for the media mixture is 850 μm and the uniformity coefficient C_u (D_{60}/D_{10}) is 9.2.

3.2 Step 2: Stormwater Particulate Removal by Particle Size Range

Stormwater particulate capture for each particle size range is dependent on the influent concentrations and the particle size of the media. The online white paper and appendices (Pitt, Clark et al. 2019) have several tables of removal equations for different conditions, based on Sileshi's (2013) research. Table 11 shows the calculated effluent concentrations using the equations for low to high SSC concentrations (50 mg/L–500 mg/L) and intermediate sized media (~1000 μm –2000 μm).

Table 11 Particulate solids removal calculations.

(See Appendix)

The particulate solids concentrations decreased from 300 mg/L to 81 mg/L for this example event (~73% reduction in concentration). The mass concentration reduction could be greater, depending on the runoff volume losses due to infiltration. Particulate forms of other pollutants would also be reduced depending on their association with each particle size range. Currently, WinSLAMM applies the bulk solids reduction (here 73%) to the particulate pollutant fraction. An upcoming update to WinSLAMM will calculate pollutant reductions based on their specific associations with each size range.

3.3 Step 3: Stormwater Flow Rate Through Media

Table 1 listed the treatment flow rates for individual media components and for selected mixtures, which are shown in Table 12 for the three components in this example.

Table 12 Treatment flow rate for media components.

(See Appendix)

Because of the peat content, special equations using the median particle size and uniformity (and compaction) values are used to calculate the infiltration rate for the media mixture. In this case, the organic content is high (>10%), as the peat fraction is 30%. The equation for hand compaction with high organic matter is:

$$\log Fc = 1.84 + 0.000522(D_{50}) - 0.0648(C_u) \quad (7)$$

For this example, the calculated $\log Fc$ is 1.68, and the resulting Fc is therefore 48.7 cm/h (19.2 in./h). This is the initial flow rate through the media before it is decreased by clogging.

3.4 Step 4: Flow Rate Decreases due to Clogging

Table 1 also includes information concerning the maximum particulate solids loading expected before clogging failure. The clogging value for a mixture is calculated based on the weighted mixture components. Final values much larger than ~20 kg/m²–50 kg/m² are suspicious, as that is the value associated with clogging observed in the field. Also, if this value is reached before ~10 y, the biofilter will likely cease to function due to clogging. However, if this load value occurs after 10 y, and the plants in the biofilter remain healthy and vigorous, the plants can incorporate this material into the surface soil material and the plant roots can keep the system operating (but with reduced surface storage volumes). Table 13 shows this weighted calculation for the maximum sediment load before clogging.

Table 13 Maximum sediment load before clogging for mixture.

(See Appendix)

The biofilter being examined has a surface area of ~162 m². The sediment discharged to the biofilter is calculated for each individual event, and the amount retained is calculated. For a 25 mm (1 in.) rain over a 0.4 ha (1 acre) paved parking area, the runoff volume would be ~87 m³ (assuming an R_v of 0.85 for this drainage area). The SSC concentration is 300 mg/L and 73% is retained in the biofilter, based on prior calculations. The total sediment load retained in the biofilter for this event is therefore ~0.12 kg/m². The next event would therefore have a slightly reduced flow rate (reduced by the ratio of 0.12/21.4), or about 48.4 cm/h (19.06 in./h). After 1 y, the total annual accumulation is examined. If it is >10% of the maximum (or 2.14 kg/m²), then the rate continues to decrease after each event and the biofilter is shut down due to clogging when the 21.4 kg/m² maximum accumulation is reached. For this example, the maximum load may be reached after about 4.6 m (180 in.) rain. For sites having more than ~0.5 m (18 in.) rain/y, the biofilter may prematurely clog. If the total accumulation after one year is <10% of the maximum, the biofilter is likely to continue to function without clogging (which requires excellent vegetation cover). In this case, the flow rate is not decreased any further after the first year. However, the surface storage of the biofilter is always decreased after each event based on the accumulated sediment after each rain.

3.5 Step 5: Retention of Filtered Pollutants

The online white paper and appendices (Pitt, Clark et al. 2019) contain many equations relating effluent to influent filtered pollutant concentrations for many media types and conditions. Table 5 previously included one media mixture example, from Pitt and Clark (2010). These calculations are only for the filtered forms of the pollutants as the particulate forms are removed along with the particulate solids. Tables 14 and 15 show how these are applied to this example calculation.

Table 14 Filtered pollutant removal equations for example.

(See Appendix)

Table 15 Filtered pollutant removal calculations.

(See Appendix)

Step 5.1 Residence and contact time effects on filtered pollutant removal

The contact time of stormwater with the media only affects the filtered pollutants, not the particulate-bound pollutants. Table 16 shows the increased removals (or leaching) after the minimum contact time is reached for the media components in this example. These modifications in removals are only applicable for thin media (<0.5 m). The prior removal calculations are based on full depth media (~0.5 m) for well mixed media. Thin layered media results in uneven contact times for each media type, while finer media material mixed with coarse material results in a moderated and constant contact time for all media. The calculated contact time for this media mixture example is ~14 min. Longer contact times can also occur with slowly draining underlying soils beneath biofilters and restricted underdrains. Table 16 shows the contact time effects for the media components for the four filtered pollutants in this example.

Table 16 Effects of contact times on filtered pollutant removals for example.

(See Appendix)

Ammonia is mostly removed by the rhyolite sand due to the very long contact times required for the GAC and peat for ammonia removal. Nitrate is only shown to be removed by the GAC, while GAC and rhyolite sand affect phosphate, and GAC and peat affect copper for the contact times available.

Step 5.2 Media capacity before breakthrough

Table 17 lists the media capacities of the different filtered pollutants for various media components for this example.

Table 17 Media pollutant retention capacities of example.

(See Appendix)

Table 18 shows the weighted capacity of the media mixture for the four filtered pollutants.

Table 18 Total media filtered pollutant retention capacity of example.

(See Appendix)

Step 5.3 Media run time before breakthrough

These media capacity values are tracked after each event by WinSLAMM. The filtered pollutant removals do not change as the capacity is consumed, but abruptly cease being retained when the capacities are reached (breakthrough, with effluent concentrations = influent concentrations). Tables 19 and 20

illustrate the media capacity and expected run times before breakthrough for selected pollutants.

Table 19 Total media capacity of example.

(See Appendix)

Table 20 Expected run times before breakthrough.

(See Appendix)

The media mixture has limited capacity for phosphate; the ammonia capacity is expected to last slightly longer than for the SSC clogging period; and the capacity for the filtered copper is very large and expected to last for a long period. Negative removals (such as for nitrates) do not imply recovered media capacity but indicate release from the media material.

4 WinSLAMM Example to Calculate Biofilter Performance

The following is an example of analysis of a hypothetical biofilter using WinSLAMM. The calculations are performed within the biofilter component of WinSLAMM to assist in the evaluation of alternative media and biofilter designs. Figure 3 shows a simple flow schematic of a biofilter placed after a 1 acre (0.4 ha) paved parking area in a commercial area. Biofilters can be located at many locations in WinSLAMM, including at many source areas (and in combination with other controls) in many land uses. Figure 4 is the main biofilter input screen where the selection of the components of the biofilter and sizing information is described. Figure 5 shows part of the media selection menu which calculates the physical properties of the media mixtures, and Figures 6 and 7 are output summaries for this biofilter example.

Figure 3 Main WinSLAMM screen showing drainage area and control locations.

WinSLAMM Biofiltration Control Device

Drainage System Control Practice

Device Properties

Bioreactor Number 1

Top Area (sf) 1300
Bottom Area (sf) 1000
Total Depth (ft) 4.00
Typical Width (ft) (Cost est. only) 25.00
Native Soil Infiltration Rate (in/hr) 1.0
Inflow Rate Fraction Bottom (0.001-1) 1.000
Inflow Rate Fraction Sides (0.001-1) 1.000
Rock Filled Depth (ft) 1.00
Rock Fill Porosity (0-1) 0.44
Engineered Media Infiltration Rate 13.00
Engineered Media Infiltration Rate COV N/A
Engineered Media Depth (ft) 1.5
Engineered Media Porosity (0-1) 0.36
Percent media reduction due to in-flow hydrograph peak to average flow rate N/A
Number of Devices in Source Area or Upstream Drainage System 1
Estimated Surface Drain Time = 0.92 hrs.

Add Sharp Crested Weir

Weir Length (ft) 10.00
Height from datum to bottom of weir opening (ft) 1.00
Weir crest width (ft) 1.00
Height from datum to bottom of weir opening (ft) 3.50

Add Vertical Stand Pipe

Pipe Diameter (ft) 0.33
Height above datum (ft) 1.00
Invert elevation above datum (ft) 0.50
Number of pipes at invert elev. 1

Add Surface Discharge Pipe

Pipe Diameter (ft) 0.33
Height above datum (ft) 1.00
Invert elevation above datum (ft) 0.50
Number of pipes at invert elev. 1

Remove Drain Tile/Underdrain

Pipe Diameter (ft) 0.33
Height above datum (ft) 1.00
Invert elevation above datum (ft) 0.50
Number of pipes at invert elev. 1

Other Outlet

Stage Number 1
Stage (ft) 1
Other Outflow Rate (cfs) 1

Evaporation

Month Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Evaporation (in/day) 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05
Evaporation (in/day) 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05 0.05

Soil porosity (saturation moisture content, 0-1)

Soil field moisture capacity (0-1)
Permanent wilting point (0-1)
Supplemental irrigation used? 1
Fraction of available capacity when irrigation starts (0-1)
Fraction of available capacity when irrigation stops (0-1)
Plant Types 1 2 3 4
Plant type Root depth (ft) C1 Cup Adjustment Factor

Bioreactor Geometry Schematic

Press F1 for Help

Figure 4 Main WinSLAMM biofilter/bioinfiltration data input form.

Soil, Media Mixtures and Components Table

Soil Type Texture	Saturation Water Content % (Porosity)	Field Capacity (Percent)	Permanent Wilting Point (Percent)	Infiltration Rate (in/hr)	Fraction of Soil Type Texture in Engineered Soil (0-1)	
Sandy Clay	40	34	17	0.05		
Silty Clay	55	33.5	18	0.015		
Clay	55	33.5	18	0.015		
Other Media						
Fine Rhyolite Sand	38	8	2.5	13		
Fine Sand	38	8	2.5	13		
Filter Sand	38	8	2.5	13	0.700	
Coarse Sand	32	4	0	40		
Gravel	32	4	0	40		
Light Media for Green Roofs	50	20	5	13		
Chemically Active Amendments						
Activated Carbon	32	4	0	40	0.200	
Fine Zeolite	32	4	0	40		
Coarse Zeolite	32	4	0	40	0.100	
Compost	61	55	5	3		
Peat Moss	78	59	5	5.8		
User Defined Amendments						
Phosphorus Sorption Media						
Biochar						
Pre-Defined Media Mixtures						
Rhyolite Sand - SMZ	43	4	0	25		
Rhyolite Sand - SMZ-GAC	41	4	0	25		
Rhyolite Sand - SMZ-GAC-PM	43	10	0.5	25		
Iron Fillings (7.5%) / Sand	38	8	2.5	13		
Iron Fillings (10.2%) / Sand	38	8	2.5	13		
Biofilter Media Mixtures						
Kansas City	40	12	10	55		
Wisconsin 1	40	10	5	25.1		
Wisconsin 2	40	10	5	20.5		
North Carolina	40	7	5	18.7		
Composite Soil Mixture Properties	36.2	6.8	1.8	13.000	1.000	
Apply Soil Mixture Values as a User Defined Soil Mixture	☒	Apply Porosity ☒	Apply Field Capacity ☒	Apply Wilting Point ☒	Apply Infiltration Rate ☒	Apply All Values ☒

Cancel Continue

Figure 5 Media component input form.

File Name: C:\WinSLAMM Files\Example Files\biofilter media tests\BF1.mdb

Outfall Output Summary

	Runoff Volume (cu. ft.)	Percent Runoff Reduction	Runoff Coefficient (Rv)	Particulate Solids Conc. (mg/L)	Particulate Solids Yield (lbs)	Percent Particulate Solids Reduction
Total of All Land Uses without Controls	75906		0.65	130.0	616.0	
Outfall Total with Controls	36939	51.34 %	0.32	43.69	100.8	83.64 %
Current File Output: Annualized Total After Outfall Controls	37041			1.00	101.0	

Current File Output: Annualized Total After Outfall Controls 37041 Years in Model Run: 1.00 101.0

Pollutant (1)	Concentration - No Controls	Concentration - With Controls	Concentration - With Controls	Pollutant Yield - No Controls	Pollutant Yield - With Controls	Percent Yield Reduction
Particulate Solids	130.0	43.69 mg/L	616.0	100.8 lbs	100.8 lbs	83.64 %
Total Phosphorus	0.2150	0.09217 mg/L	1.019	0.2126 lbs	0.2126 lbs	79.14 %
Total Copper	21.15	13.88 ug/L	0.1002	0.03200 lbs	0.03200 lbs	68.06 %

Print Output Summary to .csv File
Print Output Summary to Text File
Print Output Summary to Printer

Total Area Modeled (ac) 1.000

Receiving Water Impacts Due To Stormwater Runoff (Cv/P Impermeable Cover Model)

	Calculated Rv	Approximate Urban Stream Classification
Without Controls	0.65	Poor
With Controls	0.32	Poor

Perform Outfall Flow Duration Curve Calculations

Figure 6 WinSLAMM output summary.

Land Uses		Junctions		Control Practices							Outfall		Output Summary	
Runoff Volume				Part. Solids Yield (lb)							Part. Solids Conc. (mg/L)		Summary Table	
Data File: C:\WinSLAMM Files\Bdb														
Run File: WinReg - Madison.wt														
Date: 02/07/20 Time: 03:59:18														
Site Description:														
Col. #	2	4	5	6	7	8	9	10	11	12	13	14	15	
Control Practice No.	Control Practice Type	Total Inflow Volume (cf)	Total Outflow Volume (cf)	Percent Volume Reduction	Total Inflow Load (lb)	Total Effluent Load (lb)	Percent Load Reduction	Flow Weighted Inflow Conc. (mg/L)	Flow Weighted Effluent Conc. (mg/L)	Percent Reduction	Influent Median Part. Size (microns)	Effluent Median Part. Size (microns)	Notes	
1	Boiloff		75906	36939	51.34	616.0	100.8	83.64	130.0	43.69	66.391	7.80	2.31 No Boiloff Overflows	
4														
Junctions		Control Practices							Outfall		Output Summary			
		Part. Solids Yield (lb)							Part. Solids Conc. (mg/L)		Summary Table			
</														

Figure 7 Control practice output screen.

This example was rerun several times with varying paved drainage areas, while keeping the biofilter design constant. Figure 8 is the resulting production function comparing the annual runoff volume and particulate reduction for different footprint areas of the biofilter.

Figure 8 Production function comparing biofilter performance for different biofilter sizes.

As the biofilter area increases (as a percentage of the paved parking area), the percentage reductions in the runoff volume and the particulate loads increase. As an example, if there was a requirement for 80% particulate reductions, the biofilter in this example would need to be about 2% of the paved drainage area. A biofilter of this relative size would also provide about 40% runoff volume reductions. Obviously, this production function relationship varies for different media, hydraulic outlets and controls, rain amounts, and maintenance intervals.

The analyses also provided data to calculate the particulate mass loading on the biofilter, as shown on Figure 9. The unit area clogging associated load is about 25 kg/m² of biofilter area. If this occurs over ~10 y or longer (<2.5 kg/m²/y) for a well vegetated and well maintained biofilter, the biofilter is likely to retain satisfactory treatment flow rates without clogging failure (but with potential chemical breakthrough failure). This particulate solids accumulation rate would require a biofilter of at least 2.5% of the paved drainage area. Smaller biofilters would likely clog prematurely as the plants may not be able to incorporate the deposited material into the surface soils and root zone of the system. If the biofilter was only about 1% of the paved parking area, this critical load could occur within 2 y–3 y, requiring relatively frequent media replacement.

Figure 9 Plot of cumulative load and useful life of media in biofilter.

5 Conclusions

Performance data from a number of laboratory and field studies of biofilter media were used to examine the important unit operation components that could be used to calculate the water quality and quantity benefits of different media mixtures in WinSLAMM. Treatment flow rates are mostly affected by the texture of the media (median size and uniformity coefficient) and organic content. Compaction of the media also can significantly decrease the treatment flow rates. Mixtures of media, such as the use of fine sands with coarse media, or with compost or peat, moderate the flow rates and contact times while protecting the organic media from excessive compaction.

The retention of stormwater particulates in biofilters (and subsequent clogging) is also dependent on the media texture. It is important that the retention and clogging calculations be applied to different stormwater particle size classes. Large particulates greater than about 100 µm are very effectively retained, while small particles are less effectively retained by most media mixtures. Fine silt and clay particles also move further through the media while the coarse material is mostly retained on the media surface. This behavior also affects the clogging of the media and only a temporary benefit is associated with replacing the top layers of the media, rather than total media replacement, when excessive surface ponding occurs.

Pollutants associated with the particulates in the stormwater are retained along with the particulates. The particulate strengths (mg pollutant/kg SSC) vary for different stormwater particle sizes and pollutants, so these factors are also used in the performance calculations. Filtered forms of the stormwater pollutants are retained in the media usually through combinations of ion exchange and sorption on to the media. This retention is dependent on the ability of the media to capture the specific pollutants for the available contact times of the stormwater with the media. Thus media having high treatment flow rates can result in smaller biofilter footprints to capture stormwater from a drainage area compared to media having lower flow rates. Particulate retention is not greatly affected by flow rate, so media selection may be determined by the service life of the media before clogging requires media replacement and the need to retain specific pollutants for desirable contact times.

This paper only contains summaries of some of the available data used in WinSLAMM. The web-posted white paper modeling documentation, (Pitt, Clark et al. 2019; [available here](#)) shows the full datasets used, along with the statistical analyses and final equation forms used in the model. As with any model, uncertainty is associated with both the processes and the data. The data presented in this paper represent a wide range of conditions and locations, but it is possible that greater uncertainty may occur for specific uses and locations. The white paper includes considerations of confidence associated with the analyses, and the presented data and processes rely only on statistically significant relationships and findings. In all cases, all models require calibration and verification for local use.

This paper also shows how these data are used to calculate the performance of biofilters and contains an example of biofilter performance calculations using WinSLAMM. These processes and data can be used in manual calculations or other models. The calculation processes consist of the following components:

- Particle size distribution of the media mixture;
- Stormwater particulate removal by particle size range;
- Stormwater flow rate through media;
- Flow rate decreases due to clogging; and
- Retention of filtered pollutants (including effects of contact time and capacity before breakthrough).

Media selection dramatically affects the treatment flow rate and the pollutant retention capacity of a biofilter. Most of the pollutant removals in bioinfiltration are likely through infiltration into the underlying native soils (with pretreatment provided by the media), while physical capture of particulates and associated particulate bound pollutants is mostly affected by the texture and uniformity of the media. Filtered pollutant retention in biofilters can be targeted by the selection of chemically active media. Biofilter performance can be limited by poor media selection causing compaction and clogging. The most robust biofilters are sized properly to decrease the effects of sediment induced clogging and to provide moderate treatment flow rates. The use of WinSLAMM can be used to produce production functions that relate cumulative load with size of the biofilter and useful life for specific site conditions and expected rainfall.

Acknowledgments

We thank the many sponsors who supported the biofilter research noted in this paper, especially the Boeing Company for developing treatment media for the Santa Susana Field Laboratory, and the USEPA's Storm and Combined Sewer Section in Edison, NJ. These research projects were conducted at the University of Alabama at Birmingham, the University of Alabama, and Penn State-Harrisburg, with the dedicated assistance of many undergraduate and graduate students. This support over the past 30 plus years is gratefully acknowledged.

References

- Avila, H., and R. Pitt. 2009. "Scour in Stormwater Catchbasin Devices—Experimental Results from a Full-Scale Physical Model." *Journal of Water Management Modeling* 17: R235-19. <https://doi.org/10.14796/JWMM.R235-19>.
- Avila, H., R. Pitt, and S.R. Durrans. 2008. "Factors Affecting Scour of Previously Captured Sediment from Stormwater Catchbasin Sumps." *Journal of Water Management Modeling* 16: R228-13. <https://doi.org/10.14796/JWMM.R228-13>.
- Clark, S. 1996. *Evaluation of filtration media for stormwater runoff treatment*. Birmingham, AL: University of Alabama at Birmingham. MScE thesis.
- Clark, S. 2000. *Urban stormwater filtration: optimization of design parameters and a pilot-scale evaluation*. Birmingham, AL: University of Alabama at Birmingham. Ph.D. Dissertation.
- Clark, S., and R. Pitt. 1999. *Evaluation of filtration media for stormwater treatment*. Stormwater Treatment at Critical Areas, Vol. 3. Cincinnati, OH: U.S. Environmental Protection Agency, Water Supply and Water Resources Division, National Risk Management Research Laboratory. EPA/600/R-00/016.
- Clark, S., and R. Pitt. 2009b "Stormwater filter media pollutant retention under aerobic versus anaerobic conditions." *Journal of Environmental Engineering* 135 (5): 367-71.
- Clark, S., and R. Pitt. 2009a "Solids removal in stormwater filters modeled using a power equation." *Journal of Environmental Engineering* 135 (9): 896-9.
- Clark, S., and R. Pitt. 2012. "Targeting treatment technologies to address specific stormwater pollutants and numeric discharge limits." *Water Research* 46: 6715-30. <http://www.sciencedirect.com/science/article/pii/S0043135412004915>
- Clark, S., R. Pitt, P.D. Johnson, S. Gill, and M. Pratap. 2006. "Media filtration to remove solids and associated pollutants from stormwater runoff." In *Best Management Practices (BMP) Technology Symposium: Current and Future Directions*, ch. 7, 141-163. Reston, VA: American Society of Civil Engineers.
- Myllyoja, R., H. Baroudi, R. Pitt, and J. Paluzzi. 2001. "Use of SLAMM in Evaluating Best Management Practices." *Journal of Water Management Modeling* 09: R207-08. <https://doi.org/10.14796/JWMM.R207-08>.
- Pitt, R. 1997. "Unique Features of the Source Loading and Management Model (SLAMM)." *Journal of Water Management Modeling* 06: R200-02. <https://doi.org/10.14796/JWMM.R200-02>.
- Pitt, R. 1999. "Small Storm Hydrology and Why it is Important for the Design of Stormwater Control Practices." *Journal of Water Management Modeling* 07: R204-04. <https://doi.org/10.14796/JWMM.R204-04>.
- Pitt, R.E., S. Chen, S. Clark, J. Lantrip, C.K. Ong, and J. Voorhees. 2003. "Infiltration Through Compacted Urban Soils and Effects on Biofiltration Design." *Journal of Water Management Modeling* 11: R215-12. <https://doi.org/10.14796/JWMM.R215-12>.
- Pitt, R., and S. Clark. 2010. *Evaluation of biofiltration media for engineered natural treatment systems*. Seattle, WA: Geosyntec Consultants and The Boeing Co. <http://www.boeing.com/principles/environment/santa-susana/technical-reports.page> (under Expert Panel/Expert Panel Evaluation of Biofiltration Media for Engineered Natural Treatment Systems May 10, 2010).
- Pitt, R., S. Clark, R. Sileshi, and J. Voorhees. 2019. "Biofilter media performance updates for WinSLAMM." <http://winslamm.com/docs/biofilter%20media%20performance%20updates%20Dec%2026%202019.pdf>
- Pitt, R., and M. Lalor. 2001. "The Role of Pollution Prevention in Stormwater Management." *Journal of Water Management Modeling* 09: R207-01. <https://doi.org/10.14796/JWMM.R207-01>.

- Pitt, R., and J. Lantrip. 2000. "Infiltration Through Disturbed Urban Soils." *Journal of Water Management Modeling* 08: R206-01. <https://doi.org/10.14796/JWMM.R206-01>.
- Pitt, R., J. Lantrip, R. Harrison, C. Henry, and D. Hue. 1999. *Infiltration through disturbed urban soils and compost-amended soil effects on runoff quality and quantity*. Cincinnati, OH: U.S. Environmental Protection Agency, Water Supply and Water Resources Division, National Risk Management Research Laboratory. EPA 600/R-00/016.
- Pitt, R., M. Otto, A. Questad, S. Isaac, M. Coyer, B. Steets, R. Gearheart, J. Jones, M. Josselyn, M. Stenstrom, S. Clark, P. Costa, and J. Wokurka. 2021a. "Laboratory media test comparisons to long-term performance of biofilter, media filter, and treatment-train stormwater controls." *Journal of Sustainable Water in the Built Environment*.
- Pitt, R., M. Otto, A. Questad, S. Isaac, M. Coyer, B. Steets, R. Gearheart, J. Jones, M. Josselyn, M. Stenstrom, P. Costa, and J. Wokurka. 2021b. "Changes in performance during long-term monitoring of full-scale media filter stormwater controls at an industrial site." Submitted to *Journal of Sustainable Water in the Built Environment*.
- Pitt, R., and L. Talebi. 2012. *Evaluation and demonstration of stormwater dry wells and cisterns in Milburn Township, New Jersey*. Edison, NJ: U.S. Environmental Protection Agency, Urban Watershed Management Branch.
- Pitt, R., L. Talebi, D. O'Bannon, D. Bambic, and J. Wright. 2014. "Modeling of green infrastructure components and large-scale test and control watersheds at Kansas City, MO," Prepared for USEPA and Tetra Tech. http://unix.eng.ua.edu/~rpitt/Publications/5_Stormwater_Treatment/GI_controls/Green_Infrastructure_and_WinSLAMM_Modeling_at_KC.pdf
- Pitt, R., and J. Voorhees. 2002. "SLAMM, the Source Loading and Management Model." *Wet-Weather Flow in the Urban Watershed* (Edited by Richard Field and Daniel Sullivan). CRC Press, Boca Raton. pp 103–139.
- Pitt, R.E., and J. Voorhees. 2007. "Using Decision Analyses to Select an Urban Runoff Control Program." *Journal of Water Management Modeling* 15: R227-04. <https://doi.org/10.14796/JWMM.R227-04>.
- Pitt, R., and J. Voorhees. 2011. "Modeling Green Infrastructure Components in a Combined Sewer Area." *Journal of Water Management Modeling* 19: R241-08. <https://doi.org/10.14796/JWMM.R241-08>.
- Pitt, R.E., J. Voorhees, and C. Burgess. 2012. "Simple Hydrograph Shapes for Urban Stormwater Water Quality Continuous Analyses." *Journal of Water Management Modeling* 20: R245-16. <https://doi.org/10.14796/JWMM.R245-16>.
- Pitt, R.E., S. Clark, P. Johnson and J. Voorhees. 2008. "Evapotranspiration and Related Calculations for Bioretention Devices." *Journal of Water Management Modeling* 16: R228-19. <https://doi.org/10.14796/JWMM.R228-19>.
- Pitt, R.E., J. Voorhees, and S. Clark. 2011. "Continuous Long-term Simulations for Evaluating Storage Treatment Design Options of Stormwater Filters." *Journal of Water Management Modeling* 19: R241-07. <https://doi.org/10.14796/JWMM.R241-07>.
- Sileshi, R. 2013. *Soil physical characteristics related to failure of stormwater bioinfiltration devices*. PhD dissertation. Birmingham, AL: The University of Alabama, Department of Civil, Constructions, and Environmental Engineering. PhD dissertation. http://unix.eng.ua.edu/~rpitt/Publications/11_Theses_and_Dissertations/Redi_dissertation.pdf
- Sileshi, R., R.E. Pitt, and S. Clark. 2014. "Laboratory Column Test for Predicting Changes in Flow with Changes in Various Biofilter Mixtures." *Journal of Water Management Modeling* 22: C373. <https://doi.org/10.14796/JWMM.C373>.
- Sileshi, R., R. Pitt, and S. Clark. 2017. "Impacts of soil media characteristics on stormwater biofiltration system performance." *International Advanced Research Journal in Science, Engineering and Technology (IARJSET)* 4 (3). <http://www.iarjset.com/upload/2017/march-17/IARJSET%2022.pdf>
- Sileshi, R., R. Pitt, and S. Clark. 2018. "Performance evaluation of an alternative underdrain material for stormwater biofiltration systems." *ASCE Journal of Sustainable Water in the Built Environment*.
- Talebi, L., and R.E. Pitt. 2014. "Evaluation and Demonstration of Stormwater Dry Wells and Cisterns in Millburn Township, New Jersey." *Journal of Water Management Modeling* 22: C376. <https://doi.org/10.14796/JWMM.C376>.
- Talebi, L. 2014. *Assessment of Integrated Green Infrastructure-Based Stormwater Controls in Small to Large Scale Developed Urban Watersheds*. Ph.D. Dissertation, Dept. of Civil, Construction, and Environmental Engineering, University of Alabama. http://unix.eng.ua.edu/~rpitt/Publications/11_Theses_and_Dissertations/Leila_Dissertation.pdf

An expanded white paper with appendices describing the data sources and references, along with the statistical analyses used in this paper, is available at the PV & Assoc. web site.

Appendix: Tables

Table 1 General physical characteristics, treatment flow rates, and retention of stormwater particulates by biofilter media components and mixtures.

		% organic matter	CEC (meq/100 g)	% fines (silt and clay)	P content*	Saturation water content % (porosity)	Field capacity (%)	Permanent wilting point (%)	Treatment flow rate (cm/h)	Max. accum of sediment before clogging (kg/m ²)
Soil	sand	1	2.5	2.5	low	38	8	2.5	33	10
	loamy sand	5	5	5	high	39	13.5	4.5	6.4	10
	sandy loam	10	8	25	high	40	19.5	6.5	2.5	10
	loam	15	12	17	high	43	34	14	0.38	10
	silt loam	10	12	15	high	43	34	14	0.38	10
	silt	10	15	5	high	42	30	12	0.76	5
	sandy clay loam	10	15	25	high	42	26.5	10.5	1.3	5
	clay loam	10	20	32	high	50	34.5	17	0.25	5
	silty clay loam	10	20	33	high	50	34.5	17	0.25	5
	sandy clay	5	25	41	low	40	34	17	0.13	5
	silty clay	2	30	47	low	55	33.5	18	0.038	5
	clay	1	30	66	low	55	33.5	18	0.038	5
Sand	fine Rhyolite sand	0.3	2.5	0	low	38	8	2.5	33	35
	fine sand	0	2.5	0	low	38	8	2.5	33	10
	filter sand	0	2.5	0	low	38	8	2.5	33	20
	coarse sand	0	1	0	low	32	4	0	100	35
	gravel	0	1	0	low	32	4	0	100	very large (interstitial settle)
	light media for green roofs	0	1	0	low	50	20	5	33	very large (interstitial settle)
Amendments**	activated carbon	0	6	0	low	32	4	0	100	38
	fine zeolite	0	7	0	low	32	4	0	100	28
	coarse zeolite	0	7	0	low	32	4	0	100	17
	compost	35	18	0	very high	61	55	5	7.6	20
	peat moss	35	22	0	low	78	59	5	use peat/sand equations	20
	PSM (enter values directly for specific material)**									
	biochar (highly variable; enter values directly for specific material)									
Tested Mixtures	R-SMZ	0	5	0	low	43	4	0	64	38
	R-SMZ-GAC	0	5	0	low	41	4	0	64	53
	R-SMZ-GAC-PM	5	8	0	low	43	10	0.5	64	55
Biofilter Media Mixtures	Kansas City	15	10	41	very high	40	12	10	1.4 (hand compaction)	15
	Wisconsin 1	4	10	10	low	40	10	5	64 (hand compaction)	35
	Wisconsin 2	11	10	0	low	40	10	5	52 (hand compaction)	35
	North Carolina	1.5	9	10	low	40	7	5	47 (hand compaction)	35

* if P high in soil, 0.25 mg/L filtered P effluent

**PSM amendments (phosphorus sorption materials) are not included on above list of amendments as they are highly variable; these characteristics can be added by the user for specific product in WinSLAMM

Table 2 Example of removals for rhyolite sand–surface modified zeolite–granular activated carbon mixture (R-SMZ-GAC) for full depth column tests (X is the influent concentration and Y is the calculated effluent concentration).

Constituent, mg/L unless noted otherwise	p that effluent = influent*	Regression equation (or Y = constant, and COV also shown)**	Mean influent concentration (approximate range)***	Mean effluent concentration***	Reduction (%)***
< 0.45 µm particles	0.25	Y = X	199 (80–250)	225	0*
0.45–3 µm particles	0.16	Y = X	9.9 (3–22)	7.2	0*
3 µm–12 µm particles	0.009	Y = 4.0 (0.5)	54.9 (22–90)	2.9	95
12 µm–30 µm particles	0.009	Y = 0.68 (0.76)	54.5 (18–90)	0.67	99
30 µm–60 µm particles	0.009	Y = 1.1 (0.70)	37.4 (3–80)	1	97
60 µm–120 µm particles	0.009	Y = 0.85 (0.77)	20.0 (2–58)	0.76	96
120 µm–250 µm particles	0.009	Y = 0.08 (1.4)	5.1 (0–17)	0.08	98
250 µm–1180 µm particles (no particles found >1180 µm)	0.075	Y = 5.0 (0.66)	13.9 (3–45)	4.1	71
SSC	0.009	Y = 10.2 (0.24)	206 (50–400)	13.6	93
TSS (0.45 µm–75 µm)	0.009	Y = 10.2 (0.37)	171 (50–310)	10.2	94

* calculated using the sign test, ties ignored in the count; “no data” is when no samples were analyzed.

** <LOD (limit of detection) substituted with half of the detection limits for these calculations; if predicted effluent > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column).

*** <LOD substituted with half of the detection limits for these calculations.

Table 3 Kansas City biofilter tests (Seattle biofilter mix; x is the influent concentration and y is the calculated effluent concentration).

	Min influent conc. mg/L	Max influent conc. mg/L	Median reduction (%)	Count	Influent COV	Effluent COV	p of regression equation	p of intercept	p of slope term	Final equation
0.45–3	0.51	2.86	–56.2	6	0.45	0.31	0.012	n/a	0.007	y = 1.09x
3–12	18.8	94.04	55.5	6	0.66	0.5	0.086	n/a	0.072	y = 0.23x
12–30	12.1	202.9	62.6	6	1.12	0.8	0.0068	n/a	0.0036	y = 0.21x
30–60	9.44	175.3	65.3	6	1.44	0.86	0.0042	n/a	0.002	y = 0.20x
60–120	5.6	104.7	73.7	6	1.38	0.67	0.18	n/a	0.17	y = 4.9 mg/L (COV = 0.66)
120–250	0	21.9	81.3	6	1.14	1.06	0.0062	n/a	0.0033	y = 0.20x
250–1180	13.7	112.9	72.3	6	0.69	0.56	0.098	n/a	0.085	y = 12.6 mg/L (COV = 0.56)
>1180	0	0	n/a	6						y = 0
Total SSC	61	595	62.4	6	0.81	0.51	0.011	n/a	0.0067	y = 0.22x

Table 4 Wisconsin media 2 Neenah biofilter tests (mix 2 only available) (x is the influent concentration and y is the calculated effluent concentration).

	Min influent conc. mg/L	Max influent conc. mg/L	Median reduction (%)	Count	Influent COV	Effluent COV	p of regression equation	p of intercept	p of slope term	Final equation
0.45–2	0.56	60	56	44	1.3	0.72	2.10×10^{-5}	n/a	2.00×10^{-5}	log effluent = 0.35 (log influent)
2–4	0.07	86	86	44	2.4	0.81	0.017	2.20×10^{-11}	0.017	log effluent = $-0.74 + 0.32$ (log influent)
4–8	0.03	36	89	44	1.8	0.88	0.0086	1.30×10^{-17}	0.0086	log effluent = $-1.04 + 0.32$ (log influent)
8–16	0.04	29	90	44	1.5	0.91	0.011	5.40×10^{-15}	0.011	log effluent = $-0.99 + 0.33$ (log influent)
16–31	0.08	23	93	44	1.3	0.85	0.046	1.70×10^{-12}	0.046	log effluent = $-0.97 + 0.33$ (log influent)
31–63	0.96	52	88	44	1.2	1.2	0.00014	n/a	0.00014	effluent = 0.48 mg/L; COV = 1.2
63–125	0.8	52	90	44	1	0.92	0.0027	n/a	0.0027	effluent = 0.65 mg/L; COV = 0.92
125–250	0.27	41	88	44	0.95	1.2	0.6	0.00081	0.6	effluent = 0.40 mg/L; COV = 1.2
250–500	0.02	33	87	40	1.8	1.4	0.31	2.30×10^{-7}	0.31	effluent = 0.34 mg/L; COV = 1.4
>500	0.14	54	86	43	1.8	1.2	0.76	0.00027	0.76	effluent = 0.32 mg/L; COV = 1.2
SSC	4	262	82	44	1	0.65	0.13	0.0011	0.13	effluent = 6 mg/L; COV = 0.65

Table 5 Example of filterable pollutant removals for rhyolite sand–surface modified zeolite–granular activated carbon mixture (R-SMZ-GAC) for full depth column tests (x is the influent concentration and y is the calculated effluent concentration).

Constituent, mg/L unless noted otherwise	p that effluent = influent*	Regression equation (or Y = constant, and COV also shown)**	Mean influent concentration (approximate range)
Chloride	0.063	$Y = 30$ (0.18)	18 (1–34)
Fluoride	0.063	$Y = 2.2$ (0.25)	2.6 (1.7–3.1)
Sulfate, as SO_4	0.063	$Y = 37$ (0.29)	45 (39–51)
Boron	0.031	almost all effluent < LOD	170 (< LOD–509)
Ammonia, as N	0.008	$Y = 0.013$ (1.4)	2.7 (0.3–3.9)
Nitrite + nitrate as N	0.063	$Y = 3.0$ (0.84)	6.0 (4.9–7.1)
Gross alpha radioactivity, pCi/L	0.125	all effluent < LOD	5.3 (3.9–6.8)
Uranium, pCi/L	0.125	all effluent < LOD	1.2 (1.1–1.5)
Radium 226 + 228, pCi/L	0.125	$Y = 0.31$ (1.2)	0.92 (0.67–1.2)
Arsenic, filtered	0.109	$Y = 14$ (0.34)	33 (< LOD–109)
Aluminum, filtered	0.008	$Y = 45$ (0.39)	73 (< LOD–121)
Boron, filtered	0.031	all effluent < LOD	177 (< LOD–472)
Cadmium, filtered	0.008	almost all effluent < LOD	28 (1–54)
Copper, filtered	0.004	$Y = 13$ (0.40)	42 (23–69)
Iron, filtered	0.008	$Y = 0.37 X$	63 (44–109)
Magnesium, filtered	0.004	$Y = 4300$ (0.39)	2480 (2140–3520)
Manganese, filtered	0.125	almost all effluent < LOD	3.4 (< LOD–13)
Nickel, filtered	0.004	$Y = 0.3 X$	27 (7–68)
Potassium, filtered	0.004	$Y = 8000$ (0.23)	2410 (1960–3250)
Chromium, filtered	0.004	$Y = 0.27 X$	14 (7–19)
Thallium, filtered	0.004	almost all effluent < LOD	64 (27–94)
Antimony, filtered	0.035	$Y = 34$ (0.39)	56 (39–86)
Nitrate, mg/L	0.063	$Y = 3.0$ (0.88)	6.0 (4.9–7.1)

*values < 0.05 are statistically significant, while slightly larger values shown indicate marginal significance

**if the slope term is not significant, the effluent concentration is assumed to be not related to the influent concentration and the average effluent value is shown, along with the COV to indicate the variability

Table 6 Summary of filtered pollutant retention in Wisconsin media 2 biofilters (Wisconsin Neenah mix: 86% sand, 11% peat moss, and 3% Imbrium) (x is the influent concentration and y is the calculated effluent concentration, both in $\log_{10}$ space).

	% of influent values ND	% of effluent values ND	Min influent conc	Max influent conc	Median reduction (%)	Count (including ND)	Influent COV	p of regression equation	p of intercept	p of slope term	Final equation
TDS (mg/L)	69%	0%	<50	152	–320	48	0.8	5.00×10^{-16}	n/a	6.00×10^{-17}	$\log \text{effluent} = 1.187(\log \text{influent})$
Filtered phosphorus (mg/L)	0%	0%	0.008	0.06	7.5	44	0.5	0.013	0.046	0.013	$\log \text{effluent} = 0.548(\log \text{influent}) - 0.7297$
Filtered copper ($\mu\text{g/L}$)	7%	57%	<2	6	58	14	0.4	0.65 (few data)	0.030	0.66	$\text{effluent} = 3 \mu\text{g/L}$ (COV = 0.24)
Filtered zinc ($\mu\text{g/L}$)	0%	44%	3	27	70	25	0.8	8.60×10^{-6}	n/a	5.40×10^{-6}	$\log \text{effluent} = 0.467(\log \text{influent})$
Ammonia (mg/L)	2%	39%	0.15	1.7	90	41	0.6	0.026	8.10×10^{-6}	0.026	$\log \text{effluent} = 1.049(\log \text{influent}) - 1.0028$
Nitrate plus nitrite (mg/L)	0%	4%	0.061	0.59	17	23	0.7	0.008 98	0.0226	0.0089	$\log \text{effluent} = 0.557(\log \text{influent}) - 0.358$
Chloride (mg/L)	42%	4%	<1	11	–140	24	1.3	3.70×10^{-7}	n/a	1.90×10^7	$\log \text{effluent} = 1.728(\log \text{influent})$
Fecal coliforms (#/100 mL)	5%	16%	1	17 000	71	19	2.9	0.004 18	0.03	0.0042	$\log \text{effluent} = 0.446(\log \text{influent}) + 0.801$
E. coli (#/100 mL)	17%	9%	1	1842	–29	23	3.6	0.042	0.015	0.042	$\log \text{effluent} = 0.442(\log \text{influent}) + 0.799$
Enterococci (#/100 mL)	0%	0%	4	4200	11	27	1.6	3.40×10^{-8}	0.000 35	3.40×10^{-8}	$\log \text{effluent} = 0.596(\log \text{influent}) + 0.70$

Table 7 Media capacities for filtered pollutants for biofilter media components and mixtures.

	GAC	Peat moss	Rhyolite sand	Site sand	Site zeolite	SMZ	R-SMZ	R-SMZ-GAC	R-SMZ-GAC-PM	Site sand– GAC–site zeolite layered mg pol/gm
	mg pol/gm media	mg pol/gm media**	mg pol/gm media	mg pol/gm media	mg pol/gm media	mg pol/gm media	mg pol/gm media	mg pol/gm media	mg pol/gm media	mg pol/gm media
Sulfate	0.64	–0.000 01	0.030	>0.016	0.067	0.091	0.047	>0.27	0.055	>0.31
Calcium, Filtered	0.37	>6.3	0.12	0.017	0.25	0.082	0.056	0.072	0.14	0.081
Chloride	0.010	–0.000 01	0.00	0.00	0.00	0.00	0.00	0.00	0.0066	0.00
Fluoride	0.026	>0.30	0.016	0.0025	0.031	0.012	0.0063	0.0078	0.0096	0.0079
Potassium, Filtered	0.00	0.0021	0.00	0.000 05	0.00	0.00	0.00	0.00	0.00	0.00
Sodium, Filtered	0.033	–0.000 01	0.00	0.0079	0.00	0.024	0.00	0.00	0.00	0.00
Ammonia	>0.23*	0.056	>0.12	>0.000 73	>0.22	>0.17	>0.066	>0.089	>0.10	>0.067
Nitrate	>0.52	0.011	0.012	>0.0033	0.0034	0.0087	0.0044	0.10	0.10	>0.12
Nitrite	0.000 19	0.00	0.00	0.00	0.000 18	0.000 11	0.00	0.000 15	0.000 08	0.000 28
Phosphate	0.0	–0.000 01	0.00	>0.0020	>0.050	0.000 89	0.000 12	0.00	0.00	0.00
Aluminum, Filtered	>0.0037	–0.000 01	0.000 25	0.000 11	0.000 08	0.000 18	0.000 04	>0.0011	0.000 10	0.000 03
Antimony, Filtered	>0.0027	>0.016	0.000 60	0.000 17	0.0011	0.000 53	0.000 34	0.000 36	>0.0010	>0.000 63
Arsenic, Filtered	>0.0021	0.00	0.000 68	0.000 14	>0.0017	>0.000 77	0.000 20	>0.000 61	0.000 59	>0.000 50
Boron, Filtered	>0.011	0.011	0.00	0.000 25	0.000 55	0.00	0.000 71	>0.0036	>0.0042	>0.0029
Cadmium, Filtered	>0.0025	>0.0089	>0.0013	>0.000 17	>0.0021	>0.0016	>0.000 63	>0.000 85	>0.000 99	>0.000 68
Chromium, Filtered	>0.0012	>0.0035	0.000 05	0.000 01	0.000 01	0.000 03	0.00	>0.000 36	>0.000 31	0.000 31
Copper, Filtered	>0.0036	>0.0082	0.000 19	0.000 05	>0.000 98	0.00	0.00	>0.0011	>0.000 90	>0.000 84
Iron, Filtered	>0.0051	0.00	0.00	0.000 15	0.00	0.00	0.00	>0.0014	0.00	>0.0012
Magnesium, Filtered	0.0011	0.0080	0.00	0.00	>0.092	0.0	0.00	0.00	0.00	0.000 00
Manganese, Filtered	>0.000 27	–0.000 01	0.00	0.00	>0.000 09	0.00	0.00	>0.000 09	0.00	>0.000 07
Nickel, Filtered	>0.0023	>0.0078	>0.0011	0.000 11	>0.0014	>0.0015	>0.000 48	>0.000 65	>0.000 86	>0.000 57
Thallium, Filtered	>0.0056	>0.018	>0.0031	>0.000 33	>0.0048	>0.0037	>0.0014	>0.0019	>0.0021	>0.0016
Zinc, Filtered	0.00	–0.000 01	0.00	0.00	0.00	0.00	0.000	0.00	0.00	>0.000 05

*the > values shown represent constituents where breakthrough was not observed during the tests

**the negative values for peat moss reflect ion exchanged constituents

Table 8 Media mixture capacities for radioactive stormwater constituents.

	R–SMZ	R–SMZ–GAC	R–SMZ–GAC–PM	Site sand–GAC– site zeolite layered
	pCi pol/gm media	pCi pol/gm media	pCi pol/gm media	pCi pol/gm media
Gross alpha	>0.097	>0.14	>0.16	>0.11
Gross beta	>0.037	0.015	0.079	>0.063
Radium-226	>0.0041	0.00	>0.0067	>0.0047
Radium-228	0.00	0.0051	>0.0075	0.00
Alpha radium	>0.017	>0.016	>0.024	0.017
Strontium-90 (very low influent)	0.00	0.00	0.00	0.00
Tritium (very low influent)	0.00	0.00	0.00	0.00
Uranium	>0.024	>0.035	>0.041	0.00

Table 9 Example particle size distribution of stormwater particulates.

Stormwater PSD size range (μm)	Percentage of particulates in each stormwater influent PSD range
<3	10
3–12	10
13–30	15
31–60	25
61–150	25
151–300	10
301–2000	5
Total:	100

Table 10 Calculations to obtain media mixture PSD.

Media size range (µm)	Fine sand		GAC		Peat		Weighted sum for mixture		Cumulative percentage
	% in range	X0.4	% in range	X0.3	% in range	X0.3	% in range	Size µm	
<3	0	0	0	0	0	0	0	3	0
3–12	0	0	0	0	0	0	0	12	0
13–30	0	0	0	0	1	0.3	0.3	30	0.3
31–60	1	0.4	0	0	2	0.6	1	60	1.3
61–150	21	8.4	0	0	12	3.6	12	150	13.3
151–300	33	13.2	1	0.3	17	5.1	18.6	300	31.9
301–1000	37	14.8	9	2.7	28	8.4	25.9	1000	57.8
1001–2000	4	1.6	36	10.8	10	3	15.4	2000	73.2
2001–3000	2	0.8	36	10.8	5	1.5	13.1	3000	86.3
3001–4000	2	0.8	13	3.9	7	2.1	6.8	4000	93.1
4001–6000	0	0	5	1.5	9	2.7	4.2	6000	97.3
6001–8000	0	0	0	0	2	0.6	0.6	8000	97.9
>8000	0	0	0	0	7	2.1	2.1		
Sum	100	40	100	30	100	30	100		

Table 11 Particulate solids removal calculations.

Stormwater size range (µm)	Fraction of material in each storm- water influent size range	Inf part solids conc. Total SSC = 300 mg/L; conc in size range	Effluent for intermediate media mixture (for low to high SSC concentrations and intermediate sized media, from on-line Appendix tables)	Effluent % PSD	Effluent cumulative %
<3	10	30	30.0*	36.9	36.9
3–12	10	30	26.8	33.0	69.9
13–30	15	45	17.1	21.0	90.9
31–60	25	75	3.33	4.1	95.0
61–150	25	75	3.33	4.1	99.1
151–300	10	30	0.7	0.9	100.0
301–2000	5	15	0	0.0	100.0
	100	300 mg/L	81.3 mg/L	100	

*effluent concentration cannot be greater than influent concentration for each particle size range, except for <3 µm where increased concentrations can be associated with fines being washed from media.

Table 12 Treatment flow rate for media components.

	cm/h
Fine sand	33
GAC	100
Peat	use peat/sand equations

Table 13 Maximum sediment load before clogging for mixture.

	Maximum sediment load, from Table 1 (kg/m ²)	% in mixture	Weighted capacity
Fine sand	10	40	4
GAC	38 (coarse material)	30	11.4
Peat	20	30	6
Total			21.4 kg/m ²

Table 14 Filtered pollutant removal equations for example.

	Influent concentration	GAC removal equation*	Peat removal equation*	Sand removal equation*
Copper (filtered), µg/L	15	Y = 6.8 (0.64)	Y = 12.3 (0.26)	Y = X
Ammonia, mg/L	0.9	Y = 0.27 (2.1)	Y = X	Y = 0.54X
Nitrate, mg/L	20	Y = 46 (0.63)	Y = X	Y = X
Phosphate, mg/L	2.3	Y = 3.7 (0.62)	Y = X	Y = 0.48X

*effluent median concentration and coefficient of variation, if no regression equation shown

Table 15 Filtered pollutant removal calculations.

	Effluent for media component			Weighted calculation			Sum (final conc.)	% reductions for filtered form
	GAC	Peat	Sand	GAC × 0.3	Peat × 0.3	Sand × 0.4		
Copper (filtered)	6.8	12	15	2.0	3.7	6.0	12	21.8
Ammonia	0.27	0.9	0.49	0.081	0.27	0.20	0.55	39.4
Nitrate	46	20	20	13.8	6.0	8.0	28	–39.0
Phosphate	3.7	2.3	1.1	1.1	0.69	0.44	2.2	2.5

Table 16 Effects of contact times on filtered pollutant removals for example.

	GAC		R-sand		PM	
	Minimum time (min)	%/min (after minimum time)	Minimum time (min)	%/min (after minimum time)	Minimum time (min)	%/min (after minimum time)
Ammonia	200	0.025	20	0.012	2000	0.017
Nitrate	20	0.061	n/a	n/a	n/a	n/a
Phosphate	1	−0.04	1	0.006	1000	0.015
Copper	1	0.08	100	0.044	1	0.08

Table 17 Media pollutant retention capacities of example.

	mg pollutant/kg media		
	GAC	Peat	Sand
Copper (filtered)	0.0036	0.0083	0.00
Ammonia	0.24	0.00	0.000 73
Nitrate	0.53	0.00	0.0034
Phosphate	0.00	0.00	0.0021

Table 18 Total media filtered pollutant retention capacity of example.

	Weighted capacity (fraction)			mg pollutant/g media	mg pollutant capacity for biofilter
	GAC 0.3	Peat 0.3	Sand 0.4	Total capacity	
Copper (filtered)	0.0011	0.0025	0	0.0036	390 000
Ammonia	0.071	0	0.000 29	0.071	7 900.000
Nitrate	0.16	0	0.0014	0.16	18 000 000
Phosphate	0	0	0.000 82	0.000 82	91 000

Table 19 Total media capacity of example.

Pollutant	Influent concentration	Effluent concentration	Retained concentration	Retained mass	Retained mass (mg)
Copper (filtered), µg/L	15	12	3.3	290 000 µg	290
Ammonia, mg/L	0.9	0.55	0.35	31 000 mg	31 000
Nitrate, mg/L	20	28	−7.8	n/a	n/a
Phosphate, mg/L	2.3	2.2	0.058	5100 mg	5100

Table 20 Expected run times before breakthrough.

Pollutant	Pollutant capacity for biofilter (mg)	Fraction of total consumed by example 25 mm rain (mg retained/mg capacity ratio)	Approx. meters of rain before breakthrough
Copper (filtered)	390 000	0.000 73	35
Ammonia	7 900 000	0.0039	6.5
Nitrate	18 000 000	n/a	n/a
Phosphate	91 000	0.056	0.45