GUIDANCE DOCUMENT

Guidance for Evaluation and Implementation of Black Carbon-amended Engineered Media Filtration for Passive Treatment of Stormwater Runoff

Richard Luthy
YeoMyoung Cho
Stanford University

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SERDP Project ER18-1145

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14. ABSTRACT

The purpose of this guidance is to support DoD site managers and Remedial Project Managers in evaluating, designing, and implementing stormwater black carbon-amended media filtration control measures. This guidance addresses the chemicals of concern covered in this study, ER18-1145, namely the representative PFASs perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), and the pesticides atrazine, imidacloprid, and fipronil. While ER18-1145 evaluated more CoCs than this, these compounds were selected because they are representative of the range of studied PFASs and pesticide mobility within BC-amended filter media. PFOS and PFOA were selected among the PFASs because of their regulatory relevance, with PFOS being indicative of less mobile PFASs and PFOA being representative of more mobile PFASs. Atrazine, imidacloprid, and fipronil were chosen because they are indicative of the range in mobility of the studied pesticides, with atrazine and imidacloprid representing moderate relative mobility and fipronil representing high relative mobility. Contaminant mobility within media filters is indicative of the rate at which the filter media is exhausted, with more mobile contaminants causing filter media exhaustion sooner. The report describes a design tool, "Treatment Engineered Media Performance and Sizing Tool," (TEMPEST) to inform the selection and design of black carbon-amended stormwater control measures.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

µg/L	microgram per liter
AFCEC	Air Force Civil Engineer Center
AFFF	aqueous film forming foam
ASTM	American Society of Testing and Materials
BC	Black carbon-based
BCSMFs	BC-amended stormwater runoff media filters
BET	Brunauer Emmete Teller
CEC	cation exchange capacity
BMP	best management practice
BSM	bioretention soil media
CoCs	constituents of concern
CWA	Clean Water Act
DOC	dissolved organic carbon
DoD	Department of Defense
EBV	empty bed volume
EISA	Energy Independence and Security Act
FOP	Field Operating Procedure
GAC	granular activated carbon
HQUSACE	Headquarters, U.S. Army Corps of Engineers
IBMPDB	International Stormwater BMP Database
ng/L	nanograms per liter
MDD	maximum dry density
NAVFAC	Naval Facilities Engineering Systems Command
NPDES	National Pollutant Discharge Elimination System
O&M	Operations and Maintenance
PAHs	polycyclic aromatic hydrocarbons
PCBs	polychlorinated biphenyls
PFAS	per- and polyfluoroalkyl substances
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanesulfonic acid
RAC	regenerated activated carbon
RPMs	Remedial Project Managers
SCMs	stormwater control measures
SCS	Soil Conservation Service

SERDP	Strategic Environmental Research and Development Program
SMFs	stormwater media filters
SOP	Standard Operating Procedure
TCLP	toxicity characteristic leaching procedure
TEMPEST	Treatment Engineered Media Performance and Sizing Tool
TMDL	Total Maximum Daily Load
TrOCs	trace organic contaminants
TSS	total suspended solids
UFC	unified facilities criteria
USEPA	United States Environmental Protection Agency
WET	Waste Extraction Test

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1. INTRODUCTION

1.1 Background and Project Context

This Strategic Environmental Research and Development Program (SERDP) project, ER18-1145, Prevention of Sediment Recontamination by Improved SCMs to Remove Organic and Metal Contaminants from Stormwater Runoff, is in response to the SERDP Statement of Need (ERSON-18-C3) to understand the impacts and control of stormwater on sediment recontamination and recovery. Stormwater runoff is a major pollution source (EPA 2007) that contains a highly variable mixture of particulate-bound and dissolved constituents of concern (CoCs), such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), per- and polyfluoroalkyl substances (PFAS), pesticides, corrosion inhibitors, and metals, as well as other dissolved organics, salts, and turbidity that can interfere with the removal of these CoCs in structural treatment controls. Several of these CoCs—notably current-use pesticides (including insecticides and herbicides), corrosion inhibitors, and PFAS—are understudied in published stormwater control measures (SCMs) and best management practice (BMP) performance studies and databases. Some of these stormwater CoCs can be sources of recontamination of receiving water sediments and a threat to receiving water quality (surface water and groundwater), and therefore they are a concern for Department of Defense (DoD) facilities (SERDP/ESTCP 2012). Additionally, changes in runoff patterns due to expected increases in the frequency and intensity of storms create increased unreliability in controlling sediment recontamination. Novel systems may be needed to prevent sediment recontamination and/or receiving water quality impacts.

The overall goal of SERDP Project ER18-1145 is to evaluate the efficacy and longevity of black-carbon (BC) and/or zeolite-amended engineered stormwater media filters (abbreviated to BCSMFs) for treating stormwater runoff at DoD facilities. While traditional sedimentation-based SCMs (e.g., retention and detention ponds) generally remove larger, settleable particles, these SCMs are limited in their ability to remove finer particulates and dissolved contaminants, posing risks for transporting these contaminants offsite. BC media amendments (i.e., biochar, granular activated carbon [GAC] and regenerated activated carbon [RAC]), and zeolite amendments have the potential to improve the removal of dissolved metals and trace organic contaminants (TrOCs) such as PCBs, PAHs, PFAS, pesticides, and corrosion inhibitors. This is particularly true when contact time controls are incorporated into the design.

Project objectives and tasks were designed to develop and build knowledge on performance and design tradeoffs for BCSMFs to maximize CoC removal performance and longevity. Specific objectives included: 1) assessment of BCSMF media mixtures for removal of dissolved contaminants; 2) development of performance curves with kinetic and flow rate design parameters typical of SCM designs; 3) evaluation of engineered media filters under intermittent wetting/drying periods and saturation levels; 4) long-term contaminant transport and performance modeling of engineered media filters based on typical stormwater media filter design criteria; and 5) development of a technical design document for improved stormwater SCMs and recommended field demonstration testing for future studies.

This document serves as a product of the final objective, a technical design document to assist in selection and specification of media amendments to treat stormwater runoff for the CoCs studied. The document is accompanied by a design spreadsheet tool (attached to pdf) to assist in understanding the estimated reductions and longevity (time to exhaustion) for the studied CoCs based on BC amendments to engineered stormwater filtration media and target CoC removal.

A separate project, also completed for the SERDP Statement of Need, is also described in this guidance, which focused on control of separate CoCs normally bound to settleable particulates.

1.2 Purpose of this Guidance

The purpose of this guidance is to support DoD site managers and Remedial Project Managers (RPMs) in evaluating, designing, and implementing BCSMFs to address the CoCs covered in this study, namely the representative PFAS perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), and pesticides atrazine, imidacloprid, and fipronil. While ER18-1145 evaluated more CoCs than this, these compounds were selected because they are representative of the range of studied PFAS and pesticide mobility within BC-amended filter media. Specifically, PFOS and PFOA were selected of the PFAS because of their regulatory relevance, with PFOS being indicative of less mobile PFAS and PFOA being representative of more mobile PFAS. Atrazine, imidacloprid, and fipronil were chosen because they are indicative of the range in mobility of the studied pesticides, with atrazine and imidacloprid representing moderate relative mobility and fipronil representing high relative mobility. Contaminant mobility within media filters is indicative of the rate at which the filter media is exhausted, with more mobile contaminants causing filter media exhaustion sooner.

This guidance is intended to distill key findings from ER18-1145 to help site managers and RPMs make key practical decisions about using BCSMFs as a stormwater treatment alternative, including: (1) whether BCSMFs should be considered for a site; (2) whether BCSMFs can meet their regulatory and/or treatment objectives with acceptable maintenance cycles, and if so; (3) how systems should be designed, constructed, and operated/maintained.

1.3 Limitations and Supporting References

This document is intended to provide guidance for how the findings of ER18-1145 can be included in BCSMF system planning, design, and implementation as a singular stormwater control measure or as part of a treatment train of measures to improve water quality through a reduction in CoC discharges. Testing as part of ER18-1145 was specifically conducted on selected biochar products and RAC. Therefore, the use of the term BC, henceforth specifically refers to the specifications of the evaluated biochar and RAC. These specifications are provided in Section 4.

Note that this document is not intended to be a comprehensive stormwater design manual. There are numerous existing guidance documents available for DoD site managers and their contractors related to stormwater management and SCM or BMP design. This guidance document is not intended to replace those comprehensive stormwater design guidance manuals but, rather, to be used as a companion, with guidance specifically focused on BCSMF treatment systems for target CoCs.

The following references may be used as the primary basis for stormwater system design, including conveyance, pre-treatment, SCM design, and construction:

- Unified Facilities Criteria (UFC) [for Stormwater] Low Impact Development; https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc/ufc-3-210-10.

  The UFC provides technical criteria for military construction. Headquarters, U.S. Army Corps of Engineers (HQUSACE), Naval Facilities Engineering Command (NAVFAC), and Air Force Civil Engineer Center (AFCEC) are responsible for administration of the UFC system. The UFC is prescribed by MIL-STD 3007 and provides planning, design, construction, sustainment, restoration, and modernization criteria, and applies to the Military Departments, the Defense Agencies, and the DoD Field Activities in accordance with USD Memorandum dated 29 May 2002. UFC will be used for all domestic DoD projects and work for other customers where appropriate.

- United States Environmental Protection Agency (USEPA) Guidance for Implementing Section 438 of the Energy Independence and Security Act; https://www.wbdg.org/ffc/epa/criteria/epa-841-B-09-001

  The purpose of this document is to provide technical guidance and background information to assist federal agencies in implementing Energy Independence and Security Act (EISA) Section 438. Each agency or department is responsible for ensuring compliance with EISA Section 438. The document contains guidance on how compliance with Section 438 can be achieved, measured, and evaluated. In addition, information detailing the rationale for the stormwater management approach contained herein has been included. This document is intended solely as guidance.

- State and local guidance; (See state and local stormwater criteria and guidance).

- Applicable Clean Water Act (CWA) waste discharge permits governing stormwater discharges for the site (including construction, industrial, and municipal stormwater National Pollutant Discharge Elimination System (NPDES) permits, and where applicable, Total Maximum Daily Load (TMDL requirements incorporated therein); https://www.epa.gov/cwa-404/clean-water-act-section-402-national-pollutant-discharge-elimination-system.

1.4 Organization

This document is organized into five sections.

- Section 1 provides an orientation to the overall project and the intended purpose of this guidance document.

- Section 2 includes an orientation to passive BCSMFs for stormwater treatment, including when they should be considered and what key questions need to be asked and addressed in evaluating potential project designs.
- Section 3 includes guidance for evaluating BCSMF system application and designs and introduces a design and performance estimation tool that can be used to support design variables to successfully construct and treat CoCs.
- Section 4 includes additional guidance, specifications, and considerations related to the design, construction, and Operation and Maintenance (O&M) of BCSMFs, as a subset of traditional biofiltration SCMs.
- Section 5 summarizes the findings of companion research [ER18-1371: Development of Tools to Inform the Selection of Stormwater Controls at DoD Bases to Limit Potential Sediment Recontamination] that were in progress at the time of publication.

2. ORIENTATION TO BLACK CARBON-AMENDED ENGINEERED MEDIA FILTRATION FOR PASSIVE STORMWATER TREATMENT

Traditional media-based stormwater filtration systems have been widely used to treat stormwater runoff and are generally documented as a standard SCM type in stormwater technical guidance manuals nationwide, such as those used for post-construction (or new and re-development) SCM selection and design. The most basic stormwater media filters (SMFs) are sand filters, which rely primarily on physical filtration, followed by mixed media SMFs that typically involve sand mixed with an organic amendment such as compost or other organically rich soils containing humus (loam), typically ranging from 5 to 40% by volume (although other alternative organic amendments may be allowed). This mixture is often referred to as a bioretention soil media (BSM). Media amendments are also often sought when low numeric limits (e.g., for heavy metals such as copper, lead, and zinc) must be met in stormwater discharges, such as under NPDES permits for industrial stormwater discharges. Caution should be exercised when using these organic amendments as discharge of higher nutrient (nitrates and phosphates) concentrations have been documented with the first three to five years in use.

Where SMFs are unvegetated, these are typically referred to as media filters. Where SMFs are vegetated, these are often referred to as bioretention. More recently, bioretention has been further refined to bioretention without underdrains (i.e., no treated surface discharge) or bioretention with underdrains (also known as biofiltration), acknowledging whether volume losses through infiltration are included in the design. Depending on the underlying soil type and infiltration capability, bioretention with underdrains may also provide substantial infiltration, especially when the underdrain is raised within the system profile to allow accumulation of volume in the pore space beneath the underdrain. The baseline performance of bioretention systems for conventional pollutants is summarized as part of the International Stormwater BMP Database (IBMPDB)[1]. The performance data in the IBMPDB represents the discharge from the underdrains of bioretention (aka biofiltration). Readers are referred to the IBMPDB for comprehensive statistical evaluations of removal performance for “standard” or “typical” SMFs for a wide range of CoCs, although limited to no data may be available for many of the CoCs studied here.

DoD site managers and RPMs may encounter various site conditions and regulatory settings that require enhanced treatment of target CoCs. Some insecticides, herbicides, corrosion inhibitors, and PFAS can be challenging to treat because they are hydrophilic, meaning they readily dissolve in water, including stormwater runoff and groundwater, and are not particle-associated. Dissolved forms of pollutants in stormwater are difficult to remove through common or traditional treatment processes such as settling and physical filtration alone (i.e., without use of adsorption or cation exchange processes). Successful treatment options for these compounds can include passive engineered media treatment systems with amendments specifically selected to adsorb or absorb (together called sorption) the target CoCs. Other treatment approaches can include active media treatment systems and advanced treatment such as chemical oxidation. These treatment approaches

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[1] https://bmpdatabase.org/performance-summary-reports

are effective because they are capable of either retaining or destroying the CoCs that often pass through a typically designed SCM.

Where treatment of the target CoCs requires enhanced levels of treatment beyond what is provided by standard SMFs, the use of passive BCSMF treatment systems (with or without vegetation) can be a desirable treatment option due to their simplicity, improved sustainability, and potential cost effectiveness compared to active treatment approaches, which typically require a power supply and containerized treatment unit operations.

When designing a BCSMF, adequate sorptive material (e.g., black carbon and/or other amendments) and contact time (often achieved through passive flow controls as part of the design) are needed to meet treatment objectives and provide acceptable longevity between maintenance cycles. The concentrations of CoCs must also be within a range that is treatable for passive BCSMF systems. For sites with a higher contaminant loading (e.g., those that are directly impacted with aqueous film forming foam [AFFF]), media breakthrough and exhaustion may be relatively rapid. Therefore, there is a range of hydrologic and constituent conditions where BCSMF treatment systems can be most effective. Beyond this range, an active or other treatment systems may be necessary and more cost effective.

This guidance is intended to support key decisions that site managers face when evaluating and designing BCSMFs, including:

Evaluation and Design of BCSMFs:

- Can BCSMFs meet a site's stormwater treatment objectives (e.g., necessary CoC removal rates)?
- Can BCSMFs perform sufficiently over maintenance intervals that are acceptable (e.g., reasonable time until media replacement)?

Key design parameters include the target CoCs, the amount and type of BC included in the media bed to treat those constituents, the footprint or area of the media bed, the depth of the media bed, a flow control such as pipe or orifice size to limit flow-through rate and to better calculate contact time, and the desired effluent concentration (and desired margin of safety) before media performance deterioration.

Other Considerations:

- What differences need to be considered in design and specifications of BCSMFs compared to traditional SCMs, especially bioretention?
- What differences should be considered in construction and operation of BCSMFs compared to traditional SCMs?

3. EVALUATION AND DESIGN OF BCSMFs

SCMs exist on a spectrum of design based on drainage area, dominant hydrologic processes, water quality (regulatory) goals, operational and capital cost, availability of construction materials, and the co-benefits that they offer. Therefore, design should consider many of these factors during the evaluation process. BCSMFs are one management tool in the suite of practices that can be used to manage stormwater runoff. These SCMs focus specifically on providing a high level of sorption capacity for target CoCs found substantially in a dissolved or colloidal form.

This section details the applicable constituents for which the design tools were developed, along with a description of the treatment mechanisms/unit processes on which BCSMFs depend, relevant design variables, modeling efforts and tools supporting design, and estimated longevity of treatment based on various influent and design characteristics.

3.1 Applicable Constituents of Concern

The laboratory study performed in ER18-1145 included the following CoCs:

- Metals: nickel, copper, zinc, cadmium, and lead.
- Legacy hydrophobic contaminants and pythrethroids: PCBs, PAHs, bifenthrin, and permethrin.
- Pesticides and corrosion inhibitor: atrazine, benzotriazole, diuron, fipronil, imidacloprid, and mecoprop.
- PFAS derived from AFFF: PFOS and PFOA, as well as other PFAS.

Full-scale columns (24-inch depth, 3-inch diameter), operated in gravity driven downflow configuration, with sample ports at 6-inch intervals, were used to investigate the performance of BC- and zeolite-amended media. The laboratory-based experiments were designed to be representative of field conditions by using catch basin material obtained from Naval Weapons Station, Seal Beach, CA, dissolved organic carbon (DOC) concentrate derived from straw, and salts to provide realistic synthetic stormwater quality. Additionally, columns were conditioned with synthetic stormwater before challenge testing with added contaminants to allow for growth of biofilms and initial media fouling. Column study and contaminant transport modeling results for selected CoCs (PFOS, PFOA, atrazine, imidacloprid, and fipronil) were then used to develop the design and performance information to support this guidance document.

Contaminant transport was modeled using an advection-dispersion model with retardation due to intraparticle pore diffusion-limited sorption using Freundlich sorption parameters. These parameters, along with effective tortuosity, were then fit by minimizing the normalized mean squared error of the difference between the model prediction and observed values greater than the limit of quantification using a multi-parameter solver. Additional long-term column experiments validated the modeling approach for predicting contaminant transport at higher flow rates, different influent concentration levels, and at different BC contents. Experimental results are included in the ER18-1145 Final Report and are also published in peer-reviewed journal articles, such as Pritchard et al. (2022). BCSMF system performance tables were then constructed using the contaminant transport model to determine the effects of:

- Flow rate (related to contact time; governed by ponding depth and pipe or orifice controls on discharge).
- Inflow CoC concentration(s).
- Type and percent of BC by volume.
- Media depth.
- Desired effluent concentration (to determine target removal percentage).

These parameters can be used to predict the removal performance and, therefore, the effluent concentration from a BCSMF for the selected CoCs. Additionally, annual volume treated and filter lifetime (or time until actual removal is anticipated to drop below target removal) are also calculated. Filter lifetime is particularly important to evaluate for these lesser-studied hydrophilic trace organics and PFAS. With some hydrophobic organics and heavy metals, studies have shown in the lab and field that solid loading can lead to clogging prior to exhaustion of filter lifetime. However, with the hydrophilic trace organics and PFAS, media exhaustion (actual discharge concentration exceeds discharge limit) can precede clogging. Moreover, even with inclusion of BC materials, removal of hydrophilic organics and PFAS is governed by the rate of contaminant sorption rather than the media sorption capacity. Therefore, a tool that can estimate the contaminant removal level and lifetime of performance for specific SCM designs and scenarios is useful to better achieve water quality discharge goals. This guidance assists SCM designers in creating effective designs and in writing an informed SCM operations and maintenance plan (i.e., to understand lifecycle costs and anticipate media replacement). A lifecycle cost analysis can be useful to budget projects as well as to compare treatment alternatives and identify a lowest cost solution.

The results of this effort were included in a design tool called the Treatment Engineered Media Performance and Sizing Tool (TEMPEST). This tool assists BCSMF system designers to calculate the various treatment lifetimes for specific BCSMF designs based on site runoff characteristics (average annual rainfall, 85th and 95th percentile rainfall volumetric or flow capture, impervious area, inflow concentration) using the filter performance tables and a desired treatment objective expressed as ratio of effluent concentration to modeled concentration of full exhaustion. For example, a value of 1.0 is where effluent concentration is equal to influent concentrations representing complete exhaustion, while a value of 0.5 is where effluent concentration is 50% of the influent concentration. Specifying a specific CoC treatment objective permits users to select a BCSMF design that represents a reasonable estimated media lifetime for a defined (but predicted) CoC removal or discharge concentration.

TEMPEST does not include predicted results for all the above CoCs. The included compounds were selected because they are representative of the range of studied PFAS and pesticides.

Specifically, PFOS and PFOA were selected of the PFAS because of their regulatory relevance, with PFOS being indicative of less mobile PFAS and PFOA being indicative of more mobile PFAS. Atrazine, imidacloprid, and fipronil were chosen because they are indicative of the range in mobility of the studied pesticides, with atrazine and imidacloprid representing moderate relative mobility and fipronil representing high relative mobility. Contaminant mobility within media filters is indicative of the rate at which the filters are exhausted, with more mobile contaminants causing filter exhaustion sooner.

3.2 Hydrologic Considerations

The primary considerations in the drainage area of an SCM are the size and imperviousness of the area, which strongly affect the flow and volume of stormwater runoff entering the system. The drainage area, CoCs, and impervious area may impact which type of SCM is best suited or how many units or sizes of the practice are needed. Consideration of the drainage area is crucial for ensuring that the system is functional and will maximize the lifespan. Media in undersized practices can become exhausted much quicker, while oversized practices are less cost efficient.

Due to the typical size of an engineered media biofiltration system, they are applied in drainages that have a relatively small contributing area (less than 5 to 10 acres). The engineered media biofiltration system surface area may range between 2% to 12% of the contributing area depending on the imperviousness of the contributing drainage area, depth of media, and discharge rate. The TEMPEST tool can help determine the combination of media depth and footprint to size the BCSMF that can achieve a defined and desired target reduction in CoC concentration.

Clogging is always a concern in filtration-based systems. While much of the BCSMF treatment is based on sorption capacity, clogging due to particulate matter and other solids in the influent often controls maintenance cycles in traditional SCMs. For hydrophilic and dissolved compounds, solids management may be more challenging. Pretreatment to reduce solids loading should always be included in the design treatment train to reduce the time to surface clogging due to solids deposition, allowing increased treatment of the targeted hydrophilic and dissolved CoCs. Pretreatment system maintenance should consider the potential rate and type of accumulated solids, associated CoCs, and proper disposal. While clogging was not the focus of this research, typical solids loading and pretreatment settling were included in the column study design. Maintenance of the surface media was completed several times during the experiment.

3.3 Treatment Unit Processes in BCSMFs

Sorption is the primary design parameter and most influential removal mechanism for BCSMF treatment systems. In addition, sedimentation and physical filtration play a part in the overall treatment. Each unit process is provided in this section with more detail.

3.3.1 Settling and Sedimentation

Settling and sedimentation are not the primary unit treatment processes within BCSMF treatment systems, although some settling does occur. Sedimentation includes deposition or settling of particles within an SCM system. The sedimentation rate can vary based on factors such as the particle size, density and diameter, water temperature, and the balance between settling and mixing. The sedimentation rate increases as density and size of particles increases. The mass of particles that settle on the media surface are dependent upon the inflow mass loading. Drainages with high mass loading will require maintenance sooner than those with lower mass loading. Pretreatment systems that have good observability to inspect maintenance needs, have relatively easy access, and require simple equipment to maintain are recommended prior to all SCMs to reduce the frequency of maintenance and extend the lifetime of operation between maintenance cycles.

3.3.2 Physical Filtration

SCMs that include granular or sand-based media as part of their design use filtration as a physical process to remove suspended solids and sediment-bound pollutants. As stormwater infiltrates the granular media (typically by way of gravity in passive systems), solids and pollutants are trapped between the media particles of the system, removing them from the stormwater.

Filtration efficiency of an SCM is expressed as a ratio between the concentrations of pollutants in the stormwater at the top of the filter bed (influent concentration: Co) to the concentration at the discharge locations (effluent concentration: C). Factors such as particle size, media type, media filter design/depth, and infiltration rate strongly impact the filtration efficiency.

The trapped solids and pollutants accumulate within the media particles over time, eventually clogging the filter and reducing the flow rate of the SCM. Sediment should be removed by backwashing, surface scraping, or media replacement to ensure the functionality of the SCM in maintained.

3.3.3 Adsorption/Absorption (Sorption)

Adsorption is a process in which the pollutant adheres to the surface of media, while absorption is the mechanism where the pollutant is completely dissolved or diffused in the media particle. These processes often happen together, collectively resulting in the term sorption.

The speed at which CoCs undergo sorption to the media is dependent upon many factors, including the constituent chemical characteristics and concentration, temperature, pH, water hardness, sodium, or other competing ions, for example. The bench study supporting this guidance evaluated various rates of flow and media depth that correlate to media contact times to understand the influence of this design parameter. Figure 1 shows an example of how a longer contact time results in lower outflow concentrations. In this example, if the BCSMF treatment system was designed for 240 minutes of contact time (using an orifice control), then the media would treat decades worth of volume before reaching an effluent concentration requiring media replacement.

The percentage of black carbon is also a primary design variable to determine the amount of sorption that can occur within BCSMF treatment systems. Figure 2 demonstrates how the percentage of biochar can affect the treated volume (as represented by empty bed volumes, the total volume of the media bed).

For these performance estimations to be consistent with the modeling effort, biochar and RAC that have nearly the same specifications as that used in the study, should be used. See Section 4 for media specifications to develop media to achieve modeled treatment goals.

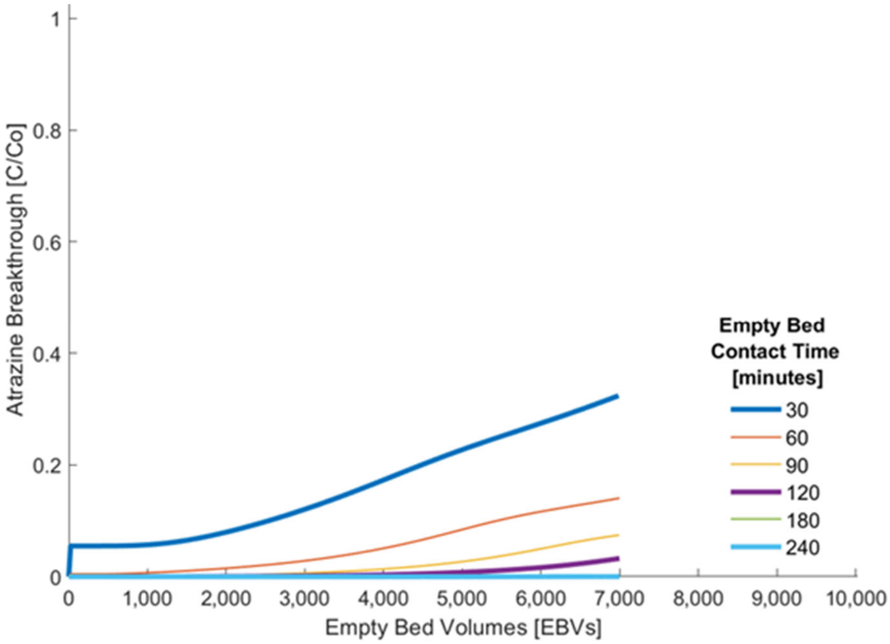

Figure 1. Example from the empirically developed model demonstrating how contact time impacts the ratio of outflow concentration versus inflow concentration for atrazine with an influent concentration of 1 µg/L and 30% biochar (by volume).

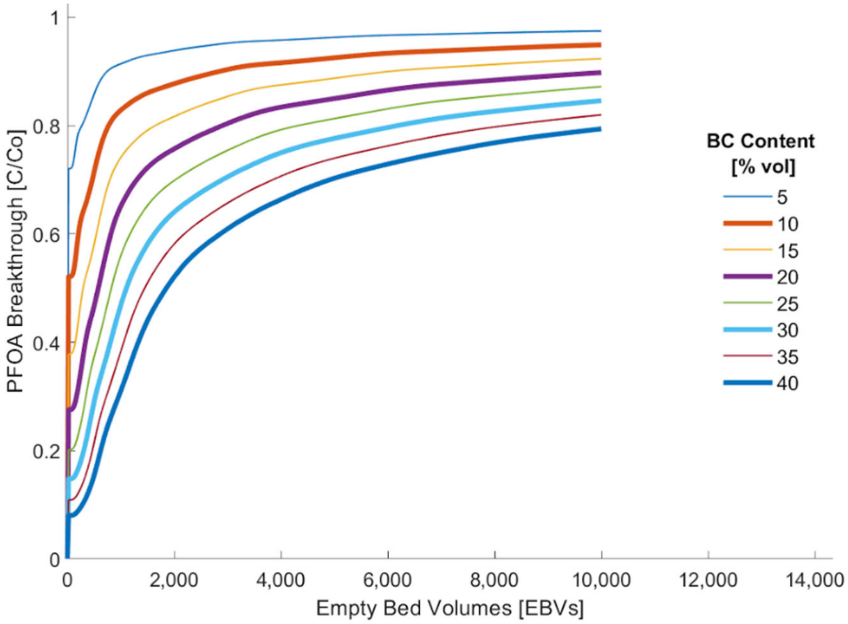

Figure 2. Example from the empirically developed model demonstrating how percent of black carbon (BC; in this case biochar) impacts the ratio of outflow concentration versus inflow concentration for PFOA with an influent concentration of 100 ng/L and 30% biochar (by volume).

3.3.4 Ion exchange

Black carbon and natural zeolites are also used in industrial processes for their ion exchange properties. While also related to sorption, the internal structure, including interconnected cavities and channels of molecular dimensions, allow for reactive surface functional groups to readily contribute to ionic exchange and transfer and distribution of solutes between a fluid phase and the media particles. Thus, the media can reduce CoCs through cation exchange similar to water purification and wastewater treatment.

3.3.5 Phytoremediation and Biodegradation

Many traditional SCMs include vegetation in their design, such as aquatic plants in wetlands and ponds, grasses and native vegetation in rain gardens, bioretention systems, and biofiltration systems, as plants often add beneficial treatment characteristics. Although vegetation is known to uptake and transform TrOCs, the contact time or hydraulic residence time to achieve phytoremediation may be much longer than the time required for other treatment unit processes (e.g., sorption and ion exchange). As such, the role of phytoremediation and biodegradation of CoCs was not studied in as part of ER18-1145.

3.3.6 Summary

The unit operations and process that can treat CoCs are primarily adsorption/absorption (sorption), ion exchange (for cationic CoCs only), and possible biodegradation and/or phytoremediation as shown in Table 1.

Table 1. Summary table of the unit processes that may occur within a BCSMF treatment system, including vegetated systems.

Processes	Description in the context of stormwater treatment	Potential CoCs Targeted	Media Parameters to Evaluate
Filtration/ Straining	Straining/entrapment of particles into the interstitial spaces	Particulate-bound CoCs	Particle size distribution
Sorption	Adsorption/absorption of dissolved pollutants to the media grains	Heavy metal, and trace organics	Absorption/absorption capacities, contact time, particle size, surface area
Ion Exchange	Exchange of deleterious ions for ions with no adverse environmental impacts	Heavy metals	Cation exchange capacity
Biodegradation	Degradation of contaminants through microbial action	Organics, nutrients, trace organics	Active biomass/g of media; pH
Phytoremediation	Plant uptake and transformation of contaminants	Trace organics, heavy metals	Plant health/species; plant toxicity

It is important to keep these processes in mind when considering media development, design, and implementation of BCSMFs.

3.4 Evaluation of BCSMF Performance and Longevity

3.4.1 Column Study BCSMF Performance Tables

Data from column studies were used to fit and calibrate an advection-dispersion model with sorption retarded intraparticle pore diffusion. The Freundlich isotherm was used to describe sorption of TrOCs to the BC materials. Sorption and effective tortuosity parameters were fit by minimizing the normalized mean squared error of the difference between the model prediction and observed values greater than the limit of quantification. The model-derived parameters were then validated in additional laboratory-based column experiments using different flow rates, influent concentrations, and BC contents. Results from the experiments are reported in the ER18-1145 Final Report and peer-reviewed journal articles such as Pritchard et al. (2022). BCSMF system performance tables were constructed using the contaminant transport model to determine the effects of flow rate and media depth (related to contact time), inflow concentration, and percent of black carbon on removal performance, as these are primary SCM design variables. This process was completed for selected hydrophilic trace organics: atrazine, imidacloprid, fipronil, PFOS, and PFOA.

3.4.2 Treatment Engineered Media Performance and Sizing Tool (TEMPEST)

The filter performance tables were included in a BCSMF design tool called TEMPEST to assist BCSMF system designers in making decisions on filter design and engineered media based on their specific site conditions and treatment objectives. TEMPEST integrates the filter performance tables generated from the contaminant transport modeling with hydrologic modeling and SCM sizing for design storm events, to estimate BCSMF performance and filter media lifetimes (the time at which predicted effluent concentration is greater than the target effluent concentration defined by the target removal) and filter media costs. By allowing users the flexibility of inputting watershed and SCM specific inputs to evaluate the impact on filter lifetime and media cost, the preliminary design and decision-making process is streamlined.

TEMPEST, included in APPENDIX D of the ER18-1145 Final Report is a Microsoft Excel based tool. Users should follow instructions outlined in the "Read Me" and "Instructions" tabs. The "Instructions" tab describes in detail each sheet of the tool that requires user input, provides a step-by-step process for inputting data into the tool, lists data that are either required, provided, or optional, and summarizes author notes and key assumptions. See below section for the key subwatershed characteristics and SCM design parameters users are required to obtain.

3.4.3 TEMPEST Components

The Soil Conservation Service (SCS) curve number method is used to calculate runoff volume based on rainfall design storm event and drainage area physical properties. Two options exist for DoD facilities for estimating the required volume of runoff that needs to be retained on-site using low impact development BMPs to comply with EISA Section 438. One option is to retain runoff from the 95th percentile rainfall event (EPA 2007, United States Army 2013). The tool offers default 85th and 95th percentile 24-hour event rainfall depths and mean annual rainfall depths (1981 to 2010) for 206 cities across the contiguous United States (Shresthra et al. 2013, NOAA 2022, and US Climate Data 2022). Users may also input their own design storm and mean annual rainfall depths. The minimum required data for the hydrologic components of the tool include drainage area, land use breakdown of the drainage area, and watershed surface area flow properties (flow length and slope). The hydrologic component of the tool determines SCM size and the total volume of runoff that will move through the media filter over the course of a year. Both values impact filter lifetime and cost.

While SCM design parameters and sizing are based on volume-capture only, users have the flexibility to design the SCM to either fully capture the specified design storm runoff volume within the ponding layer or insert specific SCM dimensions, regardless of the design storm runoff volume. TEMPEST assumes outlet-controlled SCMs where water flows into the SCM at a faster rate than it does through and out of the SCMs. Flow is controlled at the outlet of the SCM using either orifice design parameters (preferred design due to better long-term control) or a user-specified SCM media outflow rate. The minimum required data for the SCM design component of the tool include ponding depth, media filter depth, and orifice width. SCM design parameters are used to estimate the empty filter flow through rate and empty filter contact time, which is a design variable in the BCSMF performance tables and a parameter that impacts total empty bed volumes until media exhaustion. Media filter volume is used to estimate empty bed volumes per year and thus filter lifetime and cost. While TEMPEST includes several flags/suggestions and specific ranges of design parameters to assist in designing an SCM with respect to common design practices, users should refer to local and state requirements.

SCM performance parameters include all the parameters necessary to utilize the BCSMF performance tables. TEMPEST allows the user to select from five CoCs (atrazine, fipronil, imidacloprid, PFOA, and PFOS) and two media filter materials (Biochar and RAC) for SCM media performance design. Required data for the SCM performance table include CoC influent concentration. Every SCM performance parameter impacts media filter lifetime and media cost.

3.4.4 TEMPEST Outputs

TEMPEST generates key outputs to assist users in assessing the effectiveness of their SCM design parameters and evaluate the filter lifetime-cost tradeoffs.

Target effluent concentration. The target effluent concentration is calculated using CoC influent concentration and target removal and can be used to confirm that target removal is possible with the user-specified SCM design (sizing and performance). If the mean predicted empty bed volume (EBV) is 0, the target removal is not possible. Users may either decrease target removal, increase material content, increase media flow through time, or try a different media material to increase EBVs and thus, media filter lifetime.

Mean Filter Lifetime (in EBVs). Mean EBV represents the mean number of empty bed volumes treated until media exhaustion (until effluent concentration is greater than user-defined target effluent concentration given the SCM design parameters). The BCSMF lookup tables report mean EBV for 14 media flow-through time values (empty filter flowthrough time) ranging from 30 minutes to 360 minutes and 8 BC volume contents ranging from 5% to 40%. TEMPEST assumes a linear interpolation for cases when the media flow through time falls between two of the lookup table values.

Mean Filter Lifetime (in years). The mean EBVs until exhaustion and the estimated SCM EBV/year are used to estimate the mean filter lifetime in years. If a filter lifetime is projected to last greater than 25 years, required media replacement will likely be governed by clogging and not sorption capacity.

Filter Lifetime Uncertainty. BCSMF performance tables report mean EBV standard deviations. The standard deviation represents the portion of the uncertainty stemming from the contaminant transport modeling of the estimated mean filter media lifetime. The mean filter media lifetime is found by averaging the estimated lifetimes of three independent column replicate-derived models. Instances of low relative standard deviation (<25%) indicate a higher degree of confidence in the estimated filter media lifetime. Instances of larger relative standard deviation (>50%) indicate higher degrees of uncertainty in the estimated filter media lifetime. Uncertainty can be decreased by decreasing the flow through rate or increasing the BC content. Instances when the mean estimated filter lifetime minus the standard deviation is greater than 25 years are noted specifically in the TEMPEST results table. The filter lifetime standard deviation does not account for uncertainty related to background DOC or other discrepancies of laboratory versus real world conditions.

Media purchase cost. Finally, media purchase cost[2] was included to assess the tradeoffs between filter media performance and filter material. RAC generally outperforms biochar on a percent volume basis as RAC is five times denser than biochar, thus equivalent volumes of RAC and biochar would contain five times more RAC by mass (sorption is typically on a per mass basis). However, biochar is 1/3 the price of RAC on a volume basis and so depending on cost, biochar may outperform RAC on a cost basis. See Table 2 for cost estimates for BC amendment used in the column test study. Default costs are based on manufacturer data reported in the column studies and does not include shipping. Costs will depend on the quality and sources of BC. Additionally, transport and mixing are variable and may be a substantial component of the costs. Users may input their own cost data for BC and sand.

Table 2. Media purchase costs used as default values in TEMPEST. Biochar and RAC costs (in 2022 USD) are specific to the manufacturers used for lab column tests. Users are encouraged to manually enter costs in TEMPEST for the three materials based on their specific manufacturers/suppliers.

Parameter		**Biochar**[a]	**RAC**[b]	**Sand**
Cost by Mass	$ kg^{-1}	2.54	1.50	0.05
Density	kg m^{-3}	103	510	1,600
Cost by Volume	$ m^{-3}	262	763	85.11
Cost by Volume	$ ft^{-3}	7.42	21.61	2.41

[a] Biochar Supreme Environmental Ultra, WA; [b] Norit GAC 830R.

3.4.5 TEMPEST Scenario Example

Two scenarios are provided as an example to compare biochar and RAC performance with identical hydrologic, SCM sizing, and target removal inputs. The example is for treatment of PFOS at an influent concentration of 0.1 micrograms per liter (µg/L) (or 100 nanograms per liter [ng/L]) with a target removal of 95% (i.e., target effluent concentration of 0.005 µg/L (or 5 ng/L). The results for predicted media filter lifetime and cost are compared. Table 3 lists the input values used to set up the scenarios.

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[2] Default media purchase costs in TEMPEST are specific to the manufacturer used for lab column tests. Biochar Manufacturer: Biochar Supreme Environmental Ultra, WA. RAC Manufacturer: Norit GAC 830R.

Table 3. TEMPEST Input Parameters for the Two Provided Scenario Examples.

TEMPEST Parameter	Value Inputted
State (For default rainfall depth values)	California
City (For default rainfall depth values)	Los Angeles
Recurrence Interval for Default Design Storm	95th Percentile 24-hr Event
95th Percentile Rainfall depth (in)	2
Dominant Hydrologic Soil Type	C
Drainage area (acres)	1
Area of Streets and Roads (acres)	0.2
Industrial Area (acres)	0.8
95th Percentile Rainfall volume (ac-ft)	0.10
Mean Annual Volume of Runoff (ac-ft)	0.64
Design SCM to capture full 95th percentile storm event runoff?	Yes
Ponding Depth (ft)	1.5
Media Filter Depth (in)	18
BMP Footprint (ft^2)	2,994
Orifice Diameter (in)	3.25
Orifice Coefficient	0.61
CoC	PFOS
BC Media Content (% Volume)	20
Influent Concentration (µg/L)	0.1
Target Removal (%)	95%
Default Cost values for Sand and BC?	Yes

Table 4 displays the TEMPEST outputs considering the parameter inputs specified above. Scenario 1 (Biochar) has a shorter predicted filter lifetime (12 years) but lower initial media purchase cost ($15,000); whereas, Scenario 2 (RAC) has a longer lifetime (>25 years) but higher media cost ($28,000). While there exists uncertainty in the RAC filter lifetime, the lower bound of the standard deviation still predicts a filter lifetime of +25 years.

Table 4. TEMPEST outputs for the two provided scenario examples looking at the difference between Biochar and RAC.

	Empty Filter Flow Through Time (min)	**Target Effluent Concentration (ng/L)**	**Mean Filter Lifetime (EBVs)**	**Mean Filter Lifetime (years)**	**Filter Lifetime Uncertainty**	**Media Purchase Cost (Sand and BC)**
Scenario 1 (Biochar)	112	5	73	12	> +/- 50%	$15,000
Scenario 2 (RAC)	112	5	9045	+ 25 Years	Entire Range Still + 25 Years	$28,000

3.4.6 Key Assumptions and Limitations of TEMPEST

While TEMPEST assists BCSMF designers to estimate effluent concentrations and filter media lifetimes based on pollutant, site, and BCSMF design parameters, users should be aware of local regulations, recognize TEMPEST's limitations and assumptions, and use TEMPEST at their own risk. A list of key assumptions is included below:

- TEMPEST performs volume-based SCM sizing of the BCSMF using a runoff volume produced for a selected design event. Flow-based SCM sizing is not fully supported. However, a user can do a flow-based design outside the tool and then enter the SCM footprint, depth, and flowrate in the tool to simulate this scenario in order to estimate CoC removal and filter lifetime performance.
- TEMPEST assumes outlet- (or orifice-) controlled SCMs by default, no media-flow-controlled SCM calculations are used in this tool.
- Solids pretreatment is recommended for any filtration-type SCM, including BCSMFs. TEMPEST's media lifetime estimates are based on modeling calibrated to results of lab column experiments, which used pretreated influent total suspended solids (TSS). Therefore, the contaminant transport modeling and TEMPEST assume that the CoCs are primarily dissolved and/or colloid-associated. This tool does not predict the estimated time to clogging from solids accumulation.
- TEMPEST assumes 100% of the design volume of runoff is treated through the SCM and media filter. Note that this volume is different from the mean annual runoff volume. As defined in the UFC design manual, this volume achieves the requirements defined as the "maximum extent technically feasible" criterion.
    - To estimate EBV/year, TEMPEST uses the total mean annual volume of runoff. In practice, a portion of the mean annual runoff volume is anticipated to bypass the treatment system during large and/or back-to-back storms. These bypass flows will remain untreated. The EBV/year used in calculating the lifetime of the media is an

overestimate of actual treatment volume, resulting in this estimate as a conservative value.

- TEMPEST includes five CoCs for evaluation: atrazine; fipronil; imidacloprid; PFOS; and PFOA. Future work could expand this to incorporate other CoC types.
- Increased DOC may result in faster contaminant transport and reduced sorption capacity. The lab column experiments used DOC concentration of 5 to 9 mg carbon per liter. Thus, the assumed DOC for the modeling, and used in TEMPEST, is 5 mg carbon per liter. Caution should be used when using the tool in watersheds where DOC concentrations are much greater than this value. The impact of background DOC on estimated filter lifetime is still a topic of academic study, and thus safety factors are encouraged for instances in which background DOC is significantly higher than 9 mg carbon per liter.
- The BCSMF performance table standard deviation represents the uncertainty in the model-estimated mean filter media lifetime. The mean filter media lifetime is found by averaging the estimated lifetimes of three independent replicate-derived models. Uncertainty can be decreased by decreasing the flow through rate or increasing the BC content. This does not account for uncertainty related to DOC.
- The contaminant transport modeling results are specific to the BC media studied in the laboratory experiments. The TEMPEST tool should only be used when using BC material of similar specifications, as reported in section 4.1. Use of larger sized BC media than is recommended below will reduce the CoC removal performance and is not supported by TEMPEST. Additionally, the contaminant transport modeling assumed saturated conditions with continuous flow. Unsaturated conditions and intermittent flow are not expected to affect metal or pesticide and corrosion inhibitor removal performance and may even improve PFAS removal performance.

As with any model, estimated performance is just that and there is an associated uncertainty with the estimates. While the reported standard deviation quantifies the uncertainty resulting from the contaminant transport modeling, including experimental and sampling error and error associated with conducting the parameter fitting, other sources of uncertainty are possible. Laboratory-based experiments, regardless how representative of field conditions, are inherently laboratory based, and may deviate when transferred to the field. To account for this, standard engineering practice for SCM design is to incorporate safety factors such as using a higher target removal percent (which determines desired effluent concentration) and/or to monitor effluent concentration. The same is recommended here with BCSMF design. Therefore, when applying information from TEMPEST for the purpose of BCSMF design, the ability to apply a safety factor has been included and should be used. For example, it is recommended that BCSMF designers understand how either a change in the % carbon used or change in media contact time affects the reported lifetime values provided by TEMPEST. As with any estimated result, the best way to assure that target effluent concentration is achieved is to monitor the effluent to determine whether media replacement may be nearing.

4. OTHER DESIGN, CONSTRUCTION, AND OPERATION CONSIDERATIONS FOR BCSMFS

The focus of this section is on differential guidance compared to traditional biofiltration or media filtration SCMs.

4.1 Specifications for BCSMF media

Specifications for media amendment materials are necessary to obtain a product that performs as expected, as well as to populate notes in for-construction design plan sets (which are needed to support construction bidding, accurate cost estimation, and proper construction). Additionally, there are important testing and rinsing aspects that are either necessary or are helpful to get the longest life from the media. The following are example media specifications and testing guidance that are recommended for BCSMFs.

4.1.1 Filter Media Mixing and Delivery

One of the most important aspects to creating a functional treatment media blend is to determine a qualified supplier. A supplier, typically a landscaping company that provides media for other applications, should be able to mix up to four media amendments. The supplier should also be capable of washing materials at the site of storage or mixing. It is recommended that filter media components be thoroughly mixed off site prior to delivery. Mixing should be performed using a drum mixer or another approved blending method. Proportions of individual components in filter media should be controlled using individual hopper feeds to a continuous mixing system. Batch blending methods may be approved by the Engineer or Engineer's designated representative. Filter media should not be mixed using a bucket loader.

Blended filter media should be delivered to the Site and should either be immediately placed in the treatment facility or should be properly stored on site. If the duration until placement is longer than one week, the media should be properly covered and contained to prevent dispersion or separation from wind or rain. Filter media should be delivered to the Site for infiltration rate testing.

4.1.2 General Filter Media Requirements

The BCSMF filter media should consist of the following components by volume:

- Clean fairway top dressing filter sand or any other sand meeting requirements specified below.
- Biochar or RAC.
- Zeolite (optional, effective for heavy metals).

Blended filter media should conform to the specifications shown in Table 5.

Table 5. Blended Filter Media Specifications and Test Methods.

Parameter	Test Method	Requirement
Total porosity	American Society of Testing and Materials (ASTM) D1557	> 35% @ 85% of maximum dry density (MDD)
Maximum dry density	ASTM D1557	< 105 lb/ft^3 @ 85% MDD
Permeability	ASTM D2434	> 8 in/hr @ 85% MDD
Percent Passing 200 sieve	ASTM D422	< 3%; all materials passing the 200 sieve should be non-plastic
Coefficient of Uniformity (D60/D10)	ASTM D422	< 4
pH		6.0 to 8.0
Chloride		< 300 ppm
Salinity		< 3.0 mmho/cm (<3.0 mS/cm) as electrical conductivity

Quantities of biochar should be determined using the companion TEMPEST. Translating between percent volume and weight can be accomplished using bulk density information. Quantities by weight are not included in this specification guidance.

Prior to or after placement (in situ), the media should be rinsed until turbidity is reduced and stabilizes. Wash water from this activity should be monitored for turbidity and other CoCs. Discharge of wash water should conform with regulatory guidelines for waste discharge.

4.1.3 Filter Sand

Filter sand should consist of clean, washed silica sand, similar to golf course top-dressing sand. It should conform to Table 6 as determined by an accredited laboratory. In general, materials passing #12 x #40 mesh sieves are acceptable.

Table 6. Sieve Size Analysis Results for Filter Sand.

Sieve Size	Percent Passing
No. 4	100
No. 10	95-100
No. 18	80-100
No. 35	20-70
No. 60	5-25
No. 100	0-5
No. 200	0-2

4.1.4 Biochar

Biochar should consist of material that is made via 1) slow-pyrolysis with temperature greater than 700° C for 2 hours, or 2) fast-pyrolysis with temperature greater than 900 ° C in an air-fed updraft gasifier and uses a wood feedstock (ideally pine wood). It may be advantageous to search for a local manufacturer that can make the product to the specifications below.

Biochar should be rinsed and/or sieved material conforming to the requirements in Table 7. In general, materials passing #12 x #40 mesh sieves are acceptable.

Table 7. Biochar Specifications.

Parameter	Requirement
Feedstock	Should be produced from a wood feedstock (preferably a soft wood such as pine). May not be produced from grass or other friable feedstocks
Production Temperature Regime	Should be produced under 1) slow-pyrolysis with oxygen limited conditions at least 700 °C for at least 2 hours, or 2) fast-pyrolysis at 900-1000 °C in an air-fed updraft gasifier
Post-production treatment	May be treated after production to upgrade or otherwise alter material. All other required parameters must still be met.
Post-production processing	Should be either rinsed or sieved to remove very fine and coarse particles
Brunauer Emmete Teller (BET) Specific Surface Area	>500 m^2/g
pH	< 10
Total Ash	<10%; dry weight basis
Organic Carbon	> 70%; dry weight basis
Percent passing #12 mesh sieve	> 95%
Percent passing #40 sieve	< 5%

4.1.5 Regenerated Activated Carbon

RAC should consist of GAC that has been regenerated and is designated for high performance water treatment, such as for industrial or municipal wastewaters. RAC should be sieved to confirm to the requirements in Table 8 below. Materials passing #8 x #30 mesh sieves are acceptable. Cabot Norit 830R regenerated granular activated carbon was used in the column studies and contaminant transport modeling. Similar RAC products meeting the specifications of Table 8 are acceptable.

Table 8. RAC Specifications.

Parameter	Requirement
Use purpose	Designed to provide high level of treatment for industrial and municipal wastewater
Density	31.2 - 38.0 lb/ft^3
Brunauer Emmete Teller (BET) Specific Surface Area	>900 m^2/g
Percent passing #12 mesh sieve	> 95%
Percent passing #40 sieve	< 5%

4.1.6 Other Media Amendments

Other alternative organic and ion exchange amendments may be added in place of biochar, regenerated activated carbon, and/or standard zeolite; however, their performance has not been evaluated here, and their performance should not be estimated with TEMPEST. While the added benefits of these may be limited, some have proven promising in other studies at removing other CoCs; therefore, they may offer potential improved treatment capability for a broader suite of CoCs. There is no requirement to include these alternative amendments. The additional costs of these materials should also be recognized.

4.1.6.1 Coconut Coir

Coconut coir is made of brown coconut fibers with high lignin and phenolic content. Coconut coir can provide additional water holding capacity and some organic carbon to support microbial and vegetation growth. There are many suppliers of coconut coir, but in general it should have the properties shown in Table 9.

Table 9. Coconut coir specifications.

Parameter	Requirement
Moisture	Up to 8%
Impurities	<3%
Length	50-200 mm
Diameter	50 to 300 µm

4.1.6.2 Clinoptilolite Zeolite

Clinoptilolite zeolite is a mineral-based additive. Zeolite has a high internal and external surface area that results in a high ion holding capacity. This large surface area and ion holding capacity also helps to retains heavy metal cations, including zinc (Zn), copper (Cu), silver (Ag), lead (Pb), cobalt (Co) and nickel (Ni). It can also enhance nutrients removal (especially ammonia) through precipitation and ion exchange. Because zeolite is a mineral material, its presence also can help to maintain water permeability/hydraulic conductivity.

Many suppliers are available in the western U.S. Zeolite should be sieved to a size fraction that aids in the above benefits and should conform to the requirements in Table 10. It is best if zeolites can be rinsed prior to media mixing to remove very fine particles.

Table 10. Recommended Zeolite Specifications.

Parameter	Requirement
Percent passing #8 sieve (2.38 mm)	98%–100%
Percent passing #20 sieve (0.84 mm)	0%–2%
Cation exchange capacity (CEC)	> 1.3 mg eqv./ (full exchange >1.8 mg eqv./g)
Surface area	> 20 m^2/g
Pore diameter	> 5 nm
Chemical Composition SiO_2	>70%
Al_2O_3	> 9.0%
Si:Al ratio	> 5.5:1
Elemental Analysis Cd	< 1 ppm
Cr	< 10 ppm
Cu	< 4 ppm
Pb	< 18 ppm
Hg	< 1 ppm

4.1.7 Test Methods

Sieves for Testing Purposes Test sieves should be made of either: 1) woven wire cloth conforming to ASTM E11; or 2) square-hole, perforated plates conforming to ASTM E323.

Field test procedures may be either a Standard Operating Procedure (SOP) or a Field Operating Procedure (FOP) for an American Association of Highway and Transportation Officials (AASHTO) or ASTM test procedure. A Field Operating Procedure is a technically equivalent abridged version of an AASHTO or ASTM test procedure for use in field conditions.

4.1.8 On-Site Infiltration Rate Testing

Filter media should be tested following delivery to site and prior to placement for verification of infiltration rate compliance.

i. For every 30 cubic yards of media to be installed, a filtration rate test should be performed on a representative media sample by the Engineer or Engineer's designated representative.

ii. The final media installed should be from the same batch as the representative sample tested.

iii. The constant head infiltration rate should be a minimum of <u>8 inches per hour</u>, field measured. If the infiltration rate is less than <u>8 inches per hour</u>, the contractor should not install the media and should contact the Engineer for a remedy.

4.1.9 Media Acceptance

Filter media should be tested according to these specifications prior to placement. If the media does not meet the requirements as outlined in these specifications, the contractor should contact the Engineer.

Media may be rejected if in non-compliance with the specifications and removed from the Site by the Contractor.

4.1.10 Media Placement

Media should be placed in the treatment facility via any method that does not generate unnecessary compaction, pulverization, or excessive dust. Use of a conveyor belt system with as short a drop as possible is recommended. A front-end loader, with operation to avoid excessive dump height, is also acceptable.

No equipment should be placed on the media after it has been placed in the treatment facility.

4.2 Outlet Control

Separate from traditional design approaches for bioretention, the BCSMF system media flow-through rate is not limited by the media, but rather using underdrain and orifice flow controls to achieve system design hydraulics and target contact time. Minimum media hydraulics should be satisfied through use of the specified materials. As such, underdrain linear open area, pipe flow, or orifice restrictions are recommended for controlling outlet flow rate. TEMPEST applies the orifice flow equation to outflow rate and allows for orifice sizes between 0.375 inches (3/8 inch) to 4 inches.

4.3 Vegetation

Vegetation can be beneficial to BCSMFs, mostly for providing resistance to clogging and maintaining hydraulic throughput through root growth. The roots may add organic matter and provide increased microbiological or mycorrhizal growth that may add to treatment capabilities. However, a full life cycle assessment should be done to understand irrigation and fertilization requirements or other vegetation operation and maintenance needs prior to selecting and planting vegetation. Some aspects of establishing and maintaining vegetation may lead to nutrient export such as fertilization and use of compost.

4.4 Media Testing and Disposal

When media exhaustion is nearing, the media can be tested for proper disposal methods. Media material should be properly disposed of or salvaged. Follow local/state requirements for solid waste characterization, transport, and disposal.

Typically, testing can be completed using standard toxicity characteristic leaching procedure methods (SW-846 Test Method 1311) and/or Waste Extraction Test (WET) methods to determine the proper disposal methods for media materials. A solid waste profile report should be provided based on toxicity characteristic leaching procedure (TCLP) results.

If materials do not require hazardous disposal, materials may be salvaged and used for other beneficial uses or disposed of in a standard solid waste disposal facility. Caution should be used if materials are salvaged and used again.

4.5 Additional Factors Not Specific to BCSMFs

Much of the BCSMF design is independent of whether BC is present. For example, pre-treatment should be included whether BC is present, as clogging dynamics are the same. To maximize time until clogging and to make maximal use of the chemical removal performance of the media, pretreatment should be included in the design.

Regular maintenance should also occur. This can include solids removal, surface scarification, and vegetation maintenance at the minimum. Inspections for clogging assessment should be done regularly (typically after rainfall events larger than 0.5 inches and quarterly). Any accumulation of solids should be addressed in a regular maintenance cycle.

As influent velocity can scour any filtration SCM, energy dissipation should be included to protect the filtration layer and prevent scouring within the surface of the treatment system.

Underdrain design is similar, although using an underdrain with known discharge per linear foot is useful in design. Also, it is best practice to avoid filter fabrics between media types as this can lead to premature clogging. Instead, use gravel (e.g., pea gravel or squeegee) as a bridging/choking layer to limit media movement between layers and into the underdrain.

As BCSMFs are anticipated to treat stormwater runoff with CoCs, a liner is recommended between the base of the system and surrounding native soil.

As with any SCM, the way to understand performance and whether discharge requirements are met is to monitor the effluent (for discharge requirements) and influent (for system performance). In this way, an owner can demonstrate and be assured that they know whether regulatory limits are achieved. This may also inform necessary operation and maintenance such as media replacement.

5. COMPANION RESEARCH: ER18-1371 - DEVELOPMENT OF TOOLS TO INFORM THE SELECTION OF STORMWATER CONTROLS AT DOD BASES TO LIMIT POTENTIAL SEDIMENT RECONTAMINATION

5.1 Application

An associated study (SERDP ER18-1371) led by Texas Tech University with Geosyntec (in progress) is currently developing a set of tools to inform the selection of stormwater controls at DoD bases to reduce recontamination of bed sediment cleanup sites in receiving waters. Multiple SCMs currently in place at DoD facilities are being evaluated based on their performance to reduce pollutant loads and prevent sediment recontamination across a range of particle sizes for a suite of pollutants including metals, PAHs, PCBs, and PFAS. SCMs being evaluated include:

1. Retention Pond—At the Reese Technology Center in Lubbock, TX
2. Biofilter (hardwood mulch over proprietary engineered media) and media filter (bone char + ferrous-coated activated aluminum) hybrid—At Naval Base Point Loma
3. Vegetated Bioswale—At Naval Base San Diego
4. Vegetated Biofilter—At Naval Based San Diego
5. Hydrodynamic separator—At Puget Sound Naval Shipyard
6. Two Hydrodynamic separator + cartridge filters (zeolite, perlite, and GAC)—At Puget Sound Naval Shipyard

For sediment recontamination to occur, two criteria must be satisfied: 1) the mass loading of settleable solids (i.e., particles sizes that may settle in the near field zone, where receiving water bed sediment cleanup sites are more likely to be susceptible to long-term impacts of ongoing stormwater discharges) must be high enough to result in appreciable deposition of sediment (e.g., > 1mm per year); and 2) the concentration of the sediment cleanup CoCs per mass of settleable suspended solids (i.e., pollutant "particulate strength") must be above relevant sediment screening or cleanup criteria. The study focuses on heavy metals, hydrophobic trace organics commonly associated with contaminated bed sediment sites (e.g., PCBs, PAHs), and PFAS.

5.2 Results to date

Preliminary results demonstrate that coarse solids are effectively being removed in the tested stormwater management systems. Thus, stormwater contaminants that are associated with coarse silts and sand particles are effectively removed by most SCM types, including basic pretreatment devices that rely primarily on sedimentation processes and exclude filtration or chemical adsorption or cation exchange processes. This is critical in evaluating sediment recontamination potential because in the SCMs evaluated in this study, large particles have been shown to be the primary contributor to sediment loading near stormwater outfalls.

5.3 Relation to ER18-1145

A framework is currently being developed to quantify the sediment recontamination risk for various stormwater contaminants based on loading and pollutant particulate strength of settleable solids. This framework will inform the design and selection of SCMs at DoD facilities to target pollutants that are or may be capable of driving sediment recontamination. Thus, the framework will assist with evaluating the sediment recontamination reduction benefit of SCM implementation scenario alternatives, so that when paired with costs, a reproducible, data-based cost-benefit comparison is enabled for RPMs to support stormwater management decision making. Because this associated study focused on particle-associated pollutants and their pollutant strengths, it is non-duplicative with the studies described in this document, which focused primarily on the removal of hydrophilic pollutants, or those that are able to pass through standard lab filters.

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