Hydrologic Performance of Vegetated Compost Blankets for Highway Stormwater Management

Erica R. Forgione, A.M.ASCE[1]; Gary K. Felton[2]; Ahmet H. Aydilek, F.ASCE[3]; and Allen P. Davis, F.ASCE[4]

Abstract: In an attempt to reduce the impacts of stormwater, stakeholders are exploring ways to improve the performance of existing stormwater control measures adjacent to highways, including vegetated filter strips (VFSs). This study assesses the hydrologic performance of a VFS amended with a vegetated compost blanket (VCB) through evaluation of dynamic flow modification, event volume storage, and cumulative performance. Over 2.25 years, 278 rainfall events were observed at a highway median in Maryland for two VCBs of 7.6-cm depth and 30-m width along the highway, one at 3-m length and one at 6-m length. Supplemental greenhouse mesocosm experiments provided supporting information on stormwater storage and slope impacts. VCBs were found to significantly reduce both stormwater flow and volume. Peak flows were significantly reduced by 39% for the 3-m and 72% for the 6-m VCB in comparison to highway runoff. At the highest flowrates, both VCBs were unable to significantly reduce flow, and instead acted as conveyance. Total influent stormwater volume capture over the entire study period was found to be 44% and 55% for the 3-m and 6-m VCBs, respectively. A useful design estimate for representative storage capacity, using saturated moisture content and wilting point of the media, was determined through use of a hockey-stick fit for inflow-outflow curves. Improvements in VFS soil hydraulic properties and vegetative cover over the course of the experiment were observed, indicating additional mechanisms for hydrologic improvement. **DOI: 10.1061/JSWBAY.SWENG-537.** © *2024 American Society of Civil Engineers.*

Practical Applications: To reduce and manage excess stormwater, engineers have designed green systems called stormwater control measures to absorb and filter stormwater. One of these systems is a vegetated filter strip (VFS), a thin layer of soil on the sides of highways often planted with grasses. To test whether a layer of compost placed on top would significantly absorb more stormwater, two large vegetated compost blankets (VCBs) were studied on a highway median in Maryland, and small test setups that simulate a highway median topped with a VCB were studied in a greenhouse. It was found that the VCBs lowered the highest peak flows during storms by 39%–72%, with longer flow path VCBs having a better performance. The systems were also able to store 44%–55% of the total volume of stormwater over a 2.25-year study period. An equation was created to estimate the volume of stormwater a VFS with VCB should be able to store; the equation uses the compost and soil volumes and standard compost and soil properties. The VCBs laid over a VFS in this study were effective in reducing the amount of highway stormwater more than a VFS alone.

Author keywords: Stormwater; Runoff; Compost; Green infrastructure; Highway; Compost blanket.

Introduction

Stormwater caused by rapid urbanization coupled with reliance on traditional "gray" stormwater infrastructure has become a major challenge to the resiliency and safety of urban areas (National Research Council 2009). Increase in impervious surfaces produces greater volumes of stormwater runoff that cause an array of environmental and public safety risks (Konrad 2003; O'Driscoll et al. 2010; Copeland 2016). Low-income communities and communities of color are often the most vulnerable to these risks due to structural/historical inadequacies in critical infrastructure (Hendricks and Van Zandt 2021). Additionally, as climate change continues to exacerbate these impacts, rapid adaptation of reliable stormwater infrastructure becomes even more critical (Moore et al. 2016). Green stormwater infrastructure systems, sustainable engineered alternatives to "gray" infrastructure, have become increasingly utilized in recent decades in an attempt to address the challenges presented by excess stormwater (National Research Council 2009). These systems retain, infiltrate, and evapotranspire stormwater on or near-site, effectively returning the water balance closer to a pre-urbanization state.

In order to address highway stormwater challenges, state Departments of Transportation (DOTs) are minimizing highway stormwater impacts through improvement of existing stormwater control measures (SCMs) such as vegetated filter strips (VFSs) and vegetated swales (TRB 2006). Use of a vegetated compost blanket (VCB) has been proposed as a sustainable amendment to the VFS systems currently used on highways, as compost was identified as an inexpensive, available, and renewable material that could help DOTs meet both stormwater and sustainability requirements.

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VCBs consist of loosely applied layers of compost that would be placed directly over an existing VFS system, followed by seeding and vegetation growth, making it an easy retrofit. VCBs have been used successfully as an erosion control method on bare (without a VFS) steep slopes (Faucette and Risse 2002; Mukhtar 2005; Faucette et al. 2007, 2009; Faucette 2008; AASHTO 2010; Bhattarai et al. 2011; Bakr et al. 2012; National Academies of Sciences, Engineering, and Medicine 2012). VFS systems have shown limited performance in stormwater volume retention when applied to highly compacted soils (Higgins et al. 2016), such as those on highway medians. As a blanket evaluated for erosion control, compost has been shown to increase infiltration and reduce runoff volume (Glanville et al. 2003; Persyn et al. 2004; Beighley et al. 2010; Caltrans 2012; Bakr et al. 2012) and increase vegetative cover (Faucette and Risse 2002; Persyn et al. 2007; Mukhtar et al. 2008), due to its ability to increase infiltration and water holding capacity, improve soil structure, and increase vegetative growth (USCC 2001b). Studies evaluating VCB performance for erosion control have focused on suspended solids (usually TSS) reduction (Bakr et al. 2012), rill erosion prevention (Glanville et al. 2003; Persyn et al. 2004), and runoff rate reduction (Beighley et al. 2010). However, an in-depth evaluation of a VCB used primarily as an SCM, specifically through evaluation of dynamic performance through real storm events, long-term functionality, or volumetric storage performance, has not been performed.

The goal of this study is to evaluate the hydraulic performance of VCBs through investigation of hydrograph characteristics and flow distributions as well as hydrologic performance through assessment of volumetric storage and compost/soil characteristics. A field study on the median of a four-lane highway in Maryland was conducted for 2.25 years on two VCB systems, a 3-m and a 6-m flow path, as well as a section of untreated highway for comparison. Field experiments were supplemented with a greenhouse mesocosm study to increase the range of tested variables and with compost/soil characterization studies to describe the observed hydrologic performance and develop design information. This is the first study to evaluate a VCB as a retrofit to a VFS system.

Materials and Methods

Field Site Layout and Sampling

A large-scale field study was conducted on a median on the eastbound side of Maryland Route 32 in Howard County, MD, near a junction with Interstate I-95 (Fig. S1). This site is the location of a previous VFS/grass swale stormwater study (Davis et al. 2012a; Stagge et al. 2012). Two VCBs were installed, both 7.6-cm deep and spanning 30.5-m along the highway directly adjacent to edge of pavement; yard waste compost was used for the VCB. A diagram describing the VCB/VFS system control volume is shown in Fig. S2. One VCB was 3-m wide perpendicular to the highway and the other 6-m wide, both receiving runoff as sheet flow from the eastbound two-lane highway. At the downstream end of each VCB, a 15-cm half PVC pipe was embedded flush with the soil surface to collect effluent flow. Installation was completed on February 27, 2019. In compliance with Maryland Department of the Environment (MDE) regulations, a straw matting was placed over the VCB areas after installation and seeded with Maryland Department of Transportation State Highway Administration (MDOT SHA) approved turfgrass mix [MDOT SHA 705.03.03 (MDOT SHA 2020)], 95% tall fescue and 5% Kentucky bluegrass. Influent highway runoff was monitored using a 30.5-m section of concrete channel adjacent to the same highway, just east of the VCBs. The highway runoff channel and the two VCBs are shown in Fig. 1.

A preconstruction soil survey classified the VFS media as sandy topsoil (silty sand per USCS Classification, silty or clayey sand per AASHTO Classification) of varied depth (mean = 6.35 cm) overlaying a clayey soil (sandy low plastic clay per USCS Classification, clayey soil per AASHTO Classification). The clayey soil had a mean hydraulic conductivity of 2.5×10^{-6} cm/s ($n = 30$), measured by constant head infiltrometer (van Es et al. 1999), which is within range of compacted clays (Coduto et al. 2011), likely due to compaction during the original construction of the highway. Because the effluent collection pipes were installed below grade into the compacted subsoil layer, VFS effluent flow can be considered as including both the VFS and VCB effluents. Although each site collected runoff from 30.5-m along the highway, the drainage areas differed (highway runoff 446-m^2, 3-m VCB 338-m^2, 6-m VCB 374-m^2) (Table S1). Highway runoff drainage area was back-calculated using the Soil Conservation Service (SCS) curve number method (Cronshey 1986) by assuming a curve number (CN) of 98 for pavement and calculating the drainage area needed to achieve this CN based on best fit with observed runoff volumes [Eqs. (S1)–(S3)]. The 3- and 6-m VCB highway drainage areas were found using mapping estimations from construction specifications.

The half 15-cm PVC pipes on the downstream edge of each VCB fed downward through manholes into subsurface pipes exiting at a concrete pad for monitoring. For the highway runoff channel, a custom stainless steel sheet metal weir insert was installed with a 15-cm PVC pipe to collect and measure flow (Fig. 1). For all three systems, flow data were collected using Teledyne ISCO 6712 autosamplers connected to 15-cm Thelmar weirs in each effluent pipe. Two-minute water level data were collected by Teledyne ISCO 730 bubbler flow meters connected to each effluent weir and converted to flowrate with the weir rating curve. In some instances, flowrates were observed that exceeded the Thelmar weir maximum, and data from a laboratory flume experiment were used to estimate overlimit values. Two-minute rainfall data were collected using a Teledyne ISCO 674 rain gauge connected to the highway runoff autosampler at the site.

Greenhouse Experiments

VCB/VFS mesocosm boxes were made of a sloped wooden base and lined with an inert (NSF-ANSI 61 certified drinking water safe) pond liner. A porous plastic insert was attached to the downslope end of the box for effluent collection. A 10-cm layer of engineered topsoil (loamy sand per USDA Classification obtained from Stancill's, Inc. in Perryville, MD) was placed as the VFS layer following MDOT SHA specifications for furnished topsoil [MDOT SHA 920.01.02 (MDOT SHA 2020)]. A turf grass seed mixture of 95% tall fescue and 5% Kentucky bluegrass was then applied according to MDOT SHA specifications at a rate of 224 kg/ha. Grasses were watered with the equivalent of a 0.254-cm rain event on a Mon/Wed/Fri schedule and allowed to establish for 2.5 months, emulating field conditions where a VCB would be applied to an already established VFS. After vegetation establishment, yard waste compost (Leafgro obtained from The Montgomery County Yard Trim Composting Facility near Dickerson, Maryland) was placed on top of the VFS layer and again seeded according to MDOT SHA specifications (VCB/VFS system is presented in Fig. S2).

Rainfall and runoff were both applied: for rainfall, a gentle flow watering can was used to apply deionized water over the top of the mesocosms at equal intervals over the course of the storm duration;

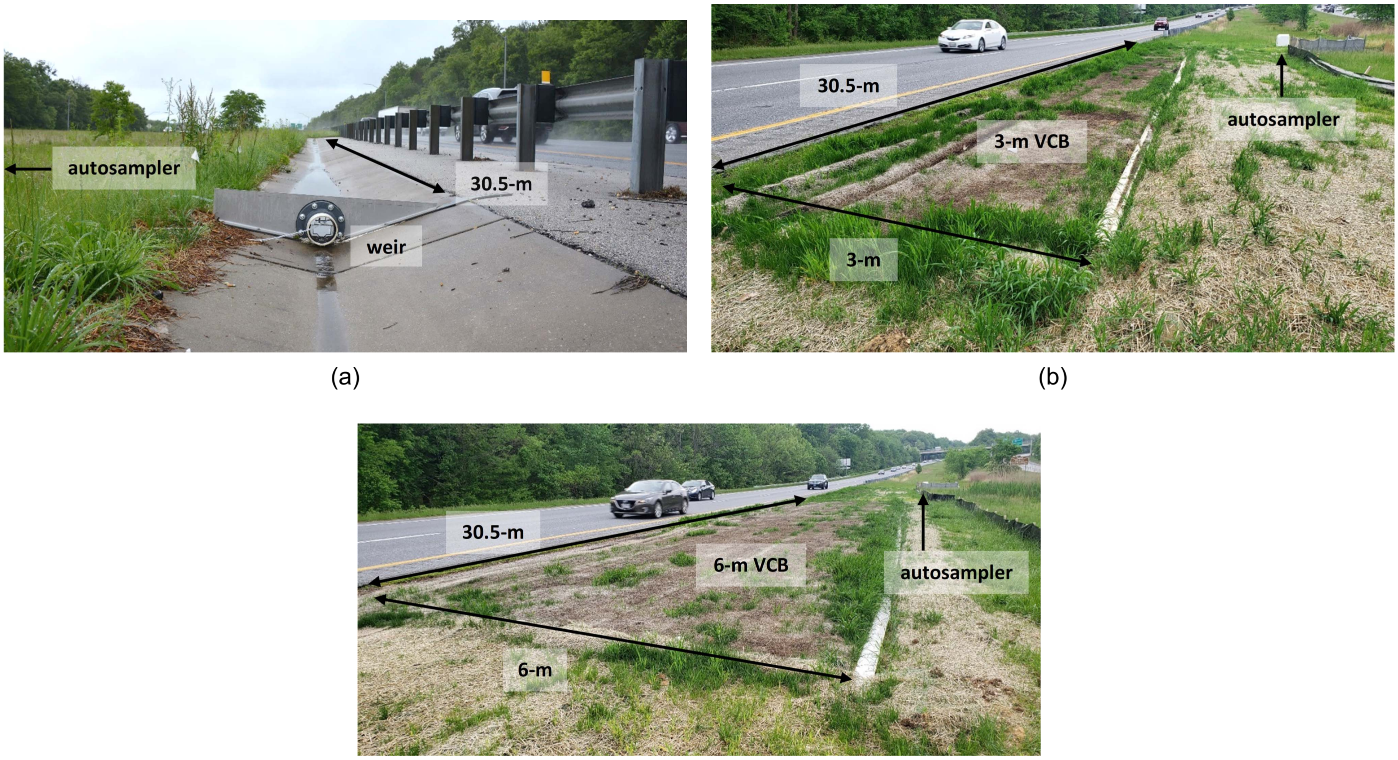


Fig. 1. Field site vegetated compost blankets: (a) highway runoff channel: 30.5 m along highway; (b) 3-m VCB: 30.5 m along highway, 3 m perpendicular to highway; and (c) 6-m VCB: 30.5 m along highway, 6 m perpendicular to highway; images of VCBs taken on May 4, 2019. (Images by authors.)

for runoff, a synthetic stormwater (with added chemical constituents) was pumped to the top of the box as sheet flow at a constant flow rate. The rainfall depth and drainage area ratio dictated the rainfall and runoff volumes and resulting flowrates that were applied. For example, mesocosms handling an assumed 3:1 drainage area ratio experiencing a 2.5-cm rainfall event received the equivalent volume of 2.5-cm of deionized water over the mesocosm surface area applied at equal time intervals, plus the equivalent volume of 7.6-cm of synthetic stormwater pumped to the top of the box to represent highway runoff. Synthetic stormwater was prepared in a 600-L polypropylene tank and pumped to the top of each mesocosm box. The applied storm event size and duration for each study are shown in Table S2. Mesocosms tested with each study are outlined in Table 1.

A custom inflow apparatus was built to evenly distribute synthetic stormwater to the top of the box from the pump tubing.

Table 1. Mesocosm parameters for greenhouse experiments Study 1 and Study 2; each contained loamy sand topsoil

Mesocosm	Study number	Slope	Compost depth (cm)	Drainage area ratio
Mesocosm A (standard)	1	5:1	7.6	3:1
Mesocosm A-2 (standard)	2	5:1	7.6	3:1
Mesocosm B	1	5:1	2.5	3:1
Mesocosm D	2	5:1	7.6	6:1
Mesocosm E	1	8:1	7.6	3:1
Mesocosm F	2	3:1	7.6	3:1
Mesocosm G	2	2:1	7.6	3:1

Note: Slope ratios refer to H (horizontal):V (vertical).

Images of mesocosm boxes and flow apparatuses are shown in Fig. 2. Several VCB operational parameters were tested in the greenhouse study, including a range of compost depths, slopes, and drainage area ratios. A summary of the tested mesocosms and variables is shown in Table 1.

Compost and Soil Testing

A preinstallation field soil survey was conducted in summer of 2018, and a postinstallation survey was conducted in summer 2021 to evaluate changes in media characteristics. Parameters and the methods used are shown in Table S3. Laboratory tests of dry bulk density, moisture content, and saturated moisture content were performed for soils and compost to evaluate changes in these properties. Infiltration tests were conducted in the field to determine saturated hydraulic conductivity and time to ponding but were limited by the underlying compacted subsoil layer. These tests were augmented with laboratory constant head hydraulic conductivity tests performed on collected soils and compost.

Vegetative Cover Methods

At the field site, in addition to the fully monitored VCBs, a third observational VCB was installed for monitoring of vegetative growth. Daily images were collected and analyzed for vegetative cover at both the field site and greenhouse experiments and processed using an image analysis code written in Matlab version 9.5.0 (R2018b) (Owen et al. 2020) as explained in detail in the Supplemental Materials section.

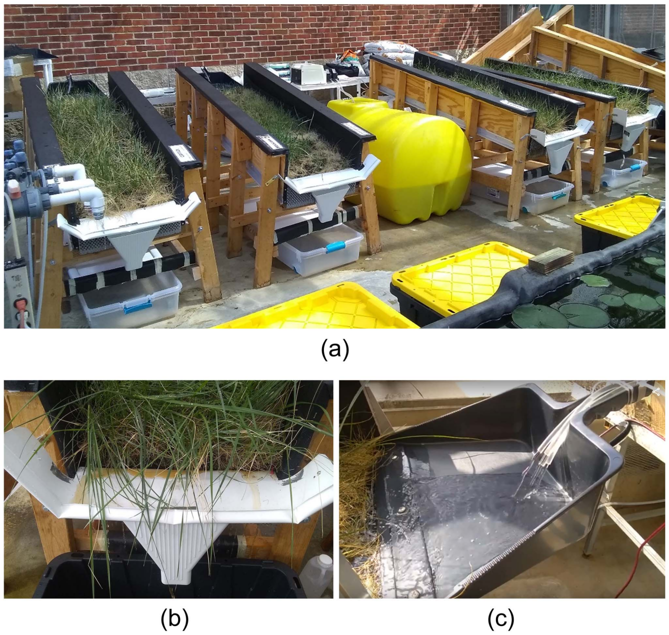


Fig. 2. Greenhouse Mesocosms and flow apparatuses: (a) mesocosm boxes prepared for a storm event; (b) runoff collection apparatus; and (c) influent synthetic stormwater flow distributor during a storm event. [Image (a) by authors; images (b and c) from Davis, A. P., A. Aydilek, G. K. Felton, and E. R. Forgione. NCHRP Research Report 1040: Achieving Highway Runoff Volume and Pollutant Reduction Using Vegetated Compost Blankets, Transportation Research Board, Washington, D.C., 2023, Figure 3-21 (left), p. 59, 3-22 (right), p. 59. Copyright, National Academy of Sciences. Reproduced with permission of the Transportation Research Board.]

Data Handling and Statistical Analysis

For field site data, the open-source programming software R was used to clean rainfall and flow datasets and conduct QA/QC. Observed field flowrates below the level of detection (0.009 m^3/h) were excluded from analysis, and any values above the maximum of 16 m^3/h were set as the maximum. During QA/QC, any storm events identified to exhibit evidence of equipment malfunction (e.g., missing data due to batteries dying) were excluded from the analysis. A code was created to separate datasets into individual storm events (defined by a 6-h break in rainfall) and calculate total storm event volumes for influent and effluent. Total volumes were found through taking the area under the curve for each hydrograph (multiplying the 2-min duration by flowrate at each timestep and summing per storm). The total volume (V) is calculated as

$$V = \int_0^{T_d} Q dt \quad (1)$$

where Q = measured stormwater flowrate at each 2-min interval; and T_d = event duration.

Influent volumes for the two field VCBs were not directly measured and were estimated by multiplying the rainfall depth with drainage area, which was found to be an acceptable method based on validation of estimations of drainage area based on lane widths (within 4%–12%). In storm events for which calculated outflow exceeded estimated inflow (4.6% of 3-m VCB storms and 2.0% of 6-m VCB storms), storage was assumed to be 0 and outflow was set equal to inflow. The storage volume for each storm event was calculated by subtracting the total effluent volume from the total estimated influent volume.

Peak flow, time-to-peak, and flow duration were collected from individual storm hydrographs. Peak flow was considered as the highest flowrate observed at a 2-min interval for each site location over the duration of each storm event. Time-to-peak was calculated as the time from the start of rainfall until the peak flow rate. Flow duration was considered as the time that flow began to the time that flow ended in each collection area. Flow-duration curves were created by ranking all measurable 2-min interval flow data for the study period in descending order and plotting against the cumulative duration (sequentially summing 2 min for every data point), allowing for comparison of the range of flowrates experienced by each treatment and the length of time they were observed to occur. For a better comparison of VCB performance, VCB values (including flowrates, peak flows, and volumes where indicated) were normalized by drainage area to the highway runoff by multiplying them by the ratio of highway runoff drainage area to the total VCB drainage area (highway + VCB).

Exceedance probability plots for comparisons of flow and volume data were created by ranking data in descending order, with exceedance probability for each datapoint calculated as

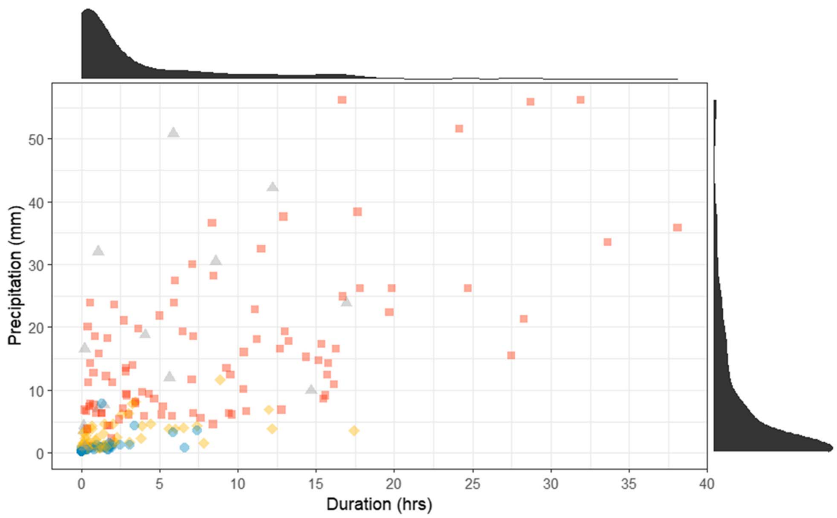
$$p = \frac{i - \alpha}{(n + 1 - 2\alpha)} \quad (2)$$

where i is rank and n is the total number of observations, with a value of $3/8$ used for α for a normal distribution, as has been used previously (Davis 2007). Where data were better described by a log-normal distribution, data were presented on a log scale and the geomean (lognormal mean) was presented along with the arithmetic mean for comparison. Student's t-test was used to make statistical comparisons based on mean and evaluated at a 5% significance level, although values of p are also given.

Results and Discussion

Observed Storm Event Characteristics

Between April 2019 and June 2021, 278 rainfall events, defined by a 6-h break in rainfall, were recorded at the site. Observed rainfall depth and duration are plotted in Fig. 3 and separated based on volume capture categories; precipitation and duration distributions are plotted on the edges of the plot as well for comparison. Rainfall depth over this period ranged from 0.25 to 56 mm with a median depth of 1.78 mm and a mean of 7.23 mm. Rainfall durations ranged from 0.03 to 38 h with a median of 1.1 h and mean of 4.0 h; 109 events had so little rainfall (most of these ~0.25 mm and ~2 min) that no measurable highway runoff was observed. This totals 39% of rainfall events, which is comparable to the 30% of rainfall events with depth between 0.254 and 2.54 mm and duration of 0–1 h as previously reported for Maryland (Kreeb 2003). An additional 22% of events were large enough to produce runoff and were completely absorbed by both VCBs, totaling 61% of events producing no effluent flow. Rainfall events that exceeded ~10-mm depth and ~15-h duration consistently produced VCB effluent, with only two storms just outside this range being fully captured. A total of 33% of rainfall events produced runoff exceeding the volumetric storage capacity of the VCBs, resulting in some amount of discharge volume. The 61% of fully captured storm events, many of which did not produce highway runoff, comprised only 11% of total rainfall depth, with storms exceeding the storage capacity totaling 75% of total rainfall depth (the remaining 13% is unknown due to missing data). While capture of the smallest storms



(a)

	Precipitation Event Type	# of Events	Event %	Rain Depth (mm)	Rain Depth (%)
	all storms	278	--	2010	--
●	storms not resulting in runoff	109	39%	62	3%
◆	storms resulting in runoff but not VCB/VFS effluent	61	22%	161	8%
■	storms resulting in VCB/VFS effluent	93	33%	1526	75%
▲	unknown due to missing effluent data	15	5.4%	261	13%

(b)

Fig. 3. Observed precipitation-duration distributions at field site: (a) precipitation duration correlation with individual frequency distributions shown on plot margins; and (b) legend and event statistics for Fig. 3(a); symbols shown next to precipitation event type align with data series in Fig. 3(a).

is still significant, emphasis on performance during larger rainfall events is considered to be more important in evaluating the VCB system performance.

Media Properties and Vegetative Growth

Soil testing done before VCB installation and at the end of the experiment (~2.25 years) provided evidence that compost properties as well as its effect on underlying soil structure influenced hydraulic performance (Table 2). The number of observations differs within tests due to safety limitations and inconsistencies at the field site associated with last-minute design changes; however, all samples were taken at specified locations consistently within ~1-m^2 area. At the end of the field experiment, topsoil bulk density decreased (26%), though not statistically significantly ($p \sim 0.075$); topsoil saturated moisture content significantly increased [29% ($p \sim 0.009$)]; and topsoil saturated hydraulic conductivity increased by approximately an order of magnitude ($p \sim 0.005$), all expected positive benefits of compost (USCC 2001a), as has been observed previously (Khaleel et al. 1981; Kirchhoff et al. 2003; Duzgun et al. 2021). However, subsoil characteristics were not changed except for saturated hydraulic conductivity, which significantly increased by an order of magnitude ($p < 0.001$). Despite this increase, hydraulic conductivity measurements should be assessed with caution due to the high spatial variability, and even for one order of magnitude difference, this still places the subsoil in the range of a

Table 2. Field soil hydraulic properties and statistics; bulk density, saturated moisture content, and saturated hydraulic conductivity

		Field precondition			Field postcondition		
Property	Parameter	Compost	Topsoil	Subsoil	Compost	Topsoil	Subsoil
Bulk density (g/cm^3)	Mean	0.286	1.226	1.654	0.360	0.977	1.636
	Stdev	0.0086	0.049	0.059	0.058	0.187	0.056
	n	3	3	3	10	4	9
Saturated moisture content, Θ (%)[a]	Mean	75.5	44.38	35.40	60.7	62.9	33.4
	Stdev	1.06	2.35	2.53	6.39	9.38	4.82
	n	3	3	3	11	4	9
Saturated hydraulic conductivity, K (cm/s)	Mean	7.87×10^{-2}	1.62×10^{-2}	2.53×10^{-6}	1.32×10^{-2}	2.04×10^{-1}	1.61×10^{-5}
	Stdev	1.57×10^{-2}	9.70×10^{-3}	3.10×10^{-6}	1.93×10^{-2}	8.25×10^{-2}	1.06×10^{-5}
	n	3	5	30	6	4	12

[a]Volume basis.

compacted clayey soil with low infiltration (Coduto et al. 2011). Improvements in topsoil properties over the course of the study including lower bulk density, increased porosity, and increased water holding capacity via migration of compost downward into the VFS allow for increased moisture retention in the VFS layer, in addition to the improvements offered by the VCB alone.

Hydrologic performance and soil media changes should also be attributable to a significant improvement in vegetative establishment by the compost, which offered increased rooting depth, added nutrients, and higher moisture retention, all contributing to improved growing conditions for turfgrasses. VCB treatments were observed to have statistically significantly improved establishment of MD DOT SHA turfgrasses over a VFS (topsoil) alone in greenhouse experiments through assessment of living grass cover ($p < 0.001$) and total cover (living grass and residue) ($p < 0.001$) over the study period (Table S4). Images of greenhouse and field turfgrass growth are shown in Figs. S7–S9. In all greenhouse mesocosm experiments, compost placed over vegetated topsoil increased living vegetative cover from ∼30%–90%, with compost treatments reaching 90% to >99% total cover (living and residue) by the end of the monitoring period (∼1 year) compared to 30%–75% for a VFS alone. Because all mesocosm variations showed improvement in vegetative cover over topsoil alone, VCBs should improve vegetative establishment for a range of site slopes (8:1 to 2:1), compost depths (2.5 to 7.6 cm), and drainage area ratios (3:1 to 6:1).

For both the greenhouse and field, 95% vegetative cover was achieved within the first 3 months, and rainfall depths to 95% cover were similar for all experiments with the exception of the 2.5-cm depth and the 2× drainage area ratio mesocosms (Fig. S6). Improved vegetative cover increases resistance to rainfall impact, improves infiltration, and slows flows through increased roughness (Abood et al. 2006; Pan and Shangguan 2006). The improvement of vegetative growth by compost treatments, which occurred over the first three months, therefore likely contributed to significantly improved hydraulic performance in VCB systems. The results from this study mirror those for VCBs as erosion control measures, which have shown them to be successful in volume retention, dissipation of rainfall impact, soil structure improvement, and improvement of vegetative growth (Faucette and Risse 2002; Mukhtar 2005; Faucette et al. 2007, 2009; Faucette 2008; AASHTO 2010; Bhattarai et al. 2011; Bakr et al. 2012; National Academies of Sciences, Engineering, and Medicine 2012).

Stormwater Flow and Volume Retention over Time

In the VCB systems, flow reduction and volume retention are expected to occur primarily through slowing of flow through the addition of roughness offered by the compost and vegetation as well as pore water storage. As stormwater enters the system as direct rainfall and highway runoff, available storage should be filled to some extent in both the VCB and VFS layers. Infiltration below these layers is assumed insignificant during the period of the storm event, given the compacted subsoil beneath. The retention of stormwater volume is also expected to be dependent on the antecedent moisture condition, rainfall intensity and duration, as well as seasonality.

The dynamic performance of VCB treatments over the course of a storm event is demonstrated through a select set of hydrographs, normalized by drainage area (Fig. 4). For a small event [Fig. 4(a)] (3.05 mm, 1.47 h), all incoming volume is totally stored, resulting in no effluent flow from either VCB system. During larger storms [Figs. 4(b and c)], storage in the system starts to fill, until some effluent flow begins. At this stage while stormwater is being released, the flashiness seen in the highway runoff hydrograph is considerably smoothed in the effluent hydrographs, and effluent flows are lower than influent, indicating some additional storage during conveyance. In Fig. 4(b), a 19.3-mm, 13.0-h storm, the VCB systems were able to dampen peaks and retain stormwater volume through the full event. Additionally, while peak flows for the 6-m VCB are lower than for the 3-m VCB at the highest intensity interval of the storm, they are similar for the rest of the event. This

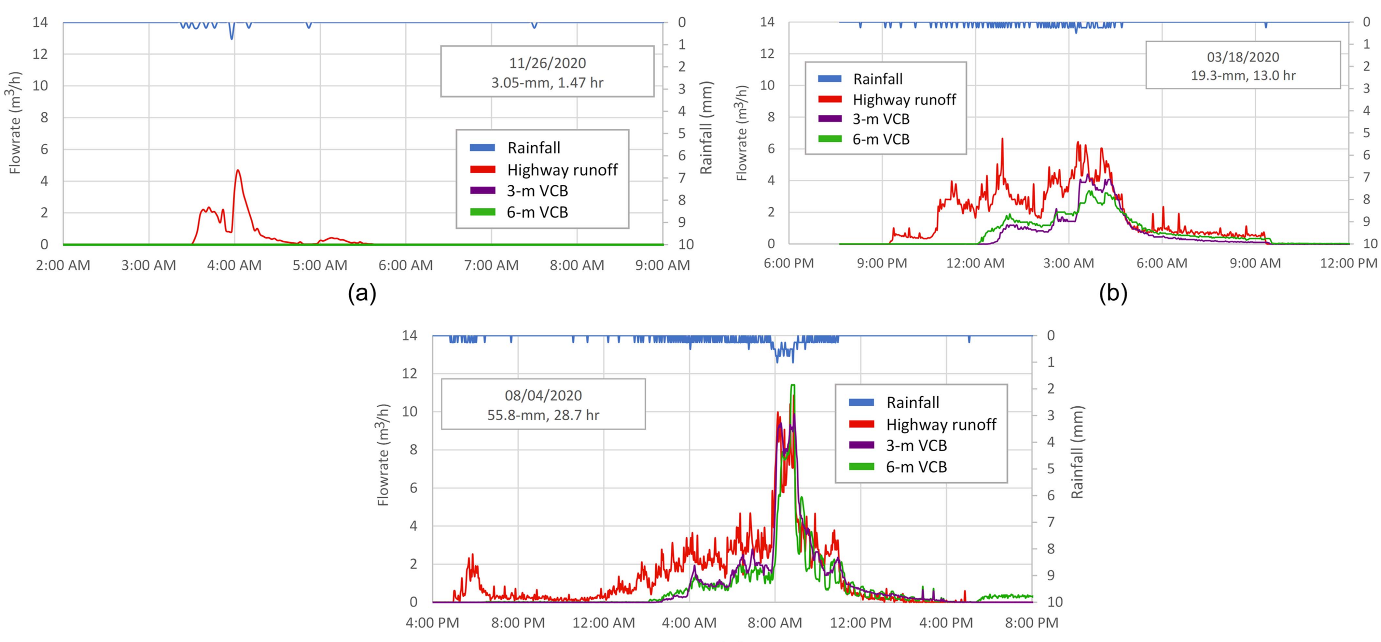


Fig. 4. Selection of field site hydrographs: (a) small storm event; (b) moderate storm event; and (c) large storm event. Flowrates are normalized by drainage area.

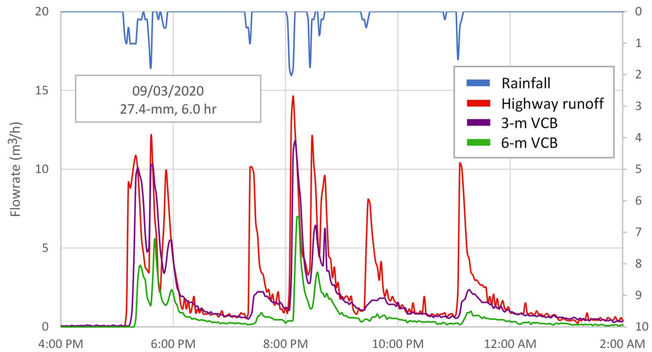


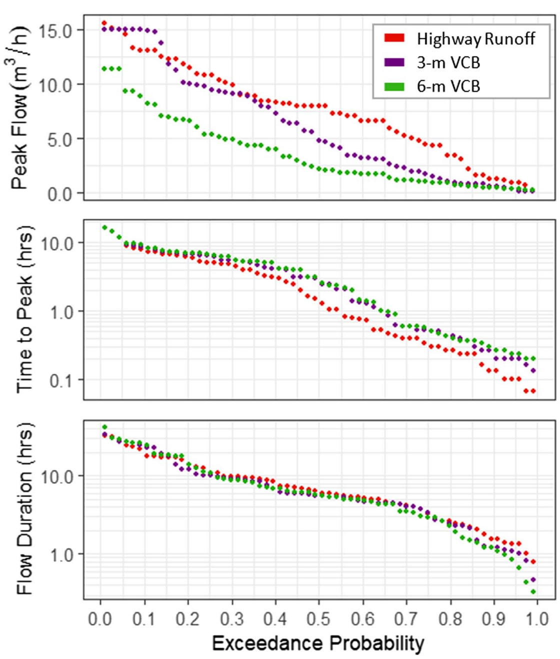
Fig. 5. Hydrographs from a high intensity multiple peak storm. Flowrates are normalized by drainage area.

indicates that the majority of storage was filled during the first part of the event, resulting in little difference between treatments later in the storm when conveyance became dominant.

In comparison, a large storm is shown in Fig. 4(c) at 55.8 mm and 28.7 h. Similar flowrate reductions and volume retention were observed throughout most of the event; however, during the highest intensity rainfall (∼8:00 AM to 9:00 AM) the hydrographs for highway runoff and both VCB systems are almost indistinguishable. At this point, the available VCB storage has been exceeded and the flowrates are no longer reduced through the treatments. One notable difference in the hydrographs is that the 6-m system was able to attenuate the first peak at 8:00 AM but not the one approximately an hour later, while the 3-m system was unable to mitigate either peak. Similar to Fig. 4(b), while some of the higher peaks are reduced by treatments after the high intensity period, significant volume retention no longer occurs. For all three storm events, retention at the start of the events shows that some storage was available in the system, while other hydrographs observed during the study period showed little to no volume retention, indicating a high antecedent moisture condition, and therefore little available storage.

It is important to note that storms with high intensity peaks resulted in different behavior than storms with consistent, long periods of precipitation. An example is shown in Fig. 5. At the start of the event, a large pulse of rain results in the first large flow peak for the highway runoff, which is largely reduced by the 6-m VCB but not the 3-m. Subsequent high intensity peaks show that the highest runoff peaks (generally above 10-m^3/h) are not greatly mitigated by the 3-m system, while the 6-m system was able to dampen all peaks. This demonstrates better performance of the 6-m system during high intensity rainfall events. However, the 3-m system does not appear to have filled all storage space during the highest pulses since later peaks are also reduced significantly by the 3-m system, indicating volume retention. Instead, this suggests that conveyance could be forced during high intensity pulses (for example, as surface flow over the VCB), which bypasses storage in the VCB/VFS. While some storage still occurs later in the 3-m system, this gives credit to longer flow paths as better protection against high intensity storm events.

Peak flows, time-to-peak, and flow duration were compared for those events where hydrographs were collected at all three sites (this biases toward larger storm events, median = 12.6 mm). Normalized peak flows were greatly reduced by VCBs, by 39% based on the median for the 3-m VCB, which is similar to the 43% peak runoff rate reduction previously found for a 3.75-cm-deep, 4.8-m-long compost blanket (Faucette et al. 2007), and 72% for the 6-m VCB (Fig. 6). Both systems reduced high probability flowrates (>50% exceedance), while the 6-m system greatly reduced peak flows over the full probability range. At higher peak flows, 3-m discharges exceed highway runoff flows, which may be attributable to inconsistencies in estimation of drainage areas used in normalizing datasets and/or unaccounted influent volume. Similar difficulty in accurately estimating the real contributing areas was previously experienced at the same location on an earlier research project (Davis et al. 2012a). The highest peak flows for the 3- and 6-m VCBs plateau at the maximum measurable



(m^3/h)	Highway Runoff	3-m	6-m
geomean	5.84	3.57	2.25
mean	7.58	6.16	3.59
median	7.94	4.82	2.23
stdev	4.17	4.97	4.43
n	61	61	61

(hrs)	Highway Runoff	3-m	6-m
geomean	1.24	1.83	1.99
mean	3.11	3.71	3.92
median	1.42	2.75	2.80
stdev	3.65	3.71	3.79
n	60	60	60

(hrs)	Highway Runoff	3-m	6-m
geomean	6.12	5.58	5.34
mean	8.85	8.57	8.84
median	6.12	5.48	5.57
stdev	7.66	8.16	8.89
n	62	62	62

Fig. 6. Peak flows, time-to-peak, and flow durations observed at field site. Peak flow (m^3/h) is normalized to highway runoff drainage area.

flowrate (15 and 11.4-m^3/h for the normalized 3- and 6-m systems, respectively), eliminating ability to make conclusions about system performance at the largest flowrates.

Time-to-peak was nearly doubled for VCB systems based on the median, increasing by 94% and 97% for the 3- and 6-m systems, respectively (Fig. 6). As the systems reach saturation during long storm events (~5-h peak delay and longer) any additional attenuation is minimized, and surface flow may also potentially occur. Flow duration, measured as the time from start of flow to the end of flow for each site, shows little difference between treatments. Although SCMs are generally expected to prolong event duration, median durations for the 3-m and the 6-m VCB instead decreased by 10% and 9% compared to the highway runoff (Fig. 6). Because the systems do not experience significant infiltration, they perform mainly as storage at the beginning of the storm event until reaching saturation, after which they primarily function as a conveyance. The most significant delay in flow occurs immediately after rainfall, with little delay in flow occurring late in the rainfall event as observed in Fig. 4. Because of this, flow duration was not significantly extended, but rather a small decrease was found for both systems.

Evaluation of hydraulic performance over the full study period can be done through a flow-duration curve, which was also normalized by drainage area (Fig. 7). As expected, the 6-m and 3-m systems have lower cumulative duration of flow than the highway runoff, mainly due to complete capture of 22% of storm events, which produced highway runoff but not VCB/VFS effluent. Both VCB/VFS systems have similar cumulative flow duration, echoed by similar observed storm event durations based on the geomean (Fig. 6). Also, both treatment systems had consistently lower flowrates than the highway runoff and a much steeper curve toward the highest flowrates, indicating good performance throughout the majority of operation. Only at the highest flowrates (~7-m^3/h and higher) is no difference found between the highway runoff and the VCB/VFS systems, indicating that flow is not appreciably reduced during the highest intensity periods of rainfall. This demonstrates the limits of VCB systems at the highest flows, as also noted in Fig. 4, where a period of high intensity rainfall resulted in no peak reduction by the treatments. For most of the duration, the 6-m system reduces flowrates more than the 3-m system, since the latter has a shorter flow path and reduced storage capacity, resulting in faster saturation and less flow attenuation in comparison to the 6-m system.

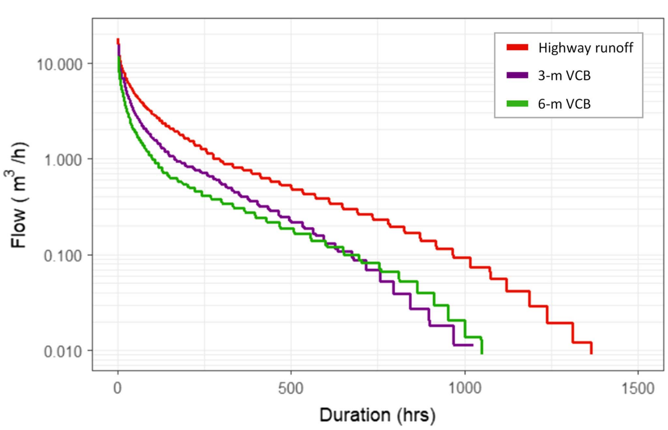


Fig. 7. Flow-duration curves for all flow data observed at field site. Flow is normalized by drainage area.

Impacts on flowrates can also be compared as specific discharge (equivalent rainfall per time over the entire drainage area). For the highway runoff, the maximum flowrate observed (16 m^3/h) is equivalent to 861 mm/day, which is similar to pavement drainage areas evaluated previously: 933 mm/day (Olszewski and Davis 2012) and 638 mm/day from the previous study site (Davis et al. 2012a). Maximum highway runoff discharge is ~10× higher than the maximum observed for a Maryland forested watershed stream (88 mm/day) (Olszewski and Davis 2012). Considering the median of all peak discharges observed for each site (427-mm/day highway runoff, 260-mm/day 3-m VCB, 120-mm/day 6-m VCB), VCB/VFS systems have a sizable impact on peak discharge reduction, with 39% and 72% reduction, respectively. Comparing the median flowrate using all flow data, highway runoff discharge is 18.5-mm/day, which is of the same magnitude of 10.6-mm/day found for this site during a previous study (Davis et al. 2012a). In comparison, median discharge for the 3- and 6-m VCB/VFS systems were 19.5 and 8.8 mm/day, respectively. While the 3-m VCB is not an improvement over highway runoff based on median flow (+6%), the 6-m VCB provided improvement (−52%). Median discharges for VCBs are also much closer to the range of values for a forested watershed stream near Baltimore, MD (1 to 5 mm/day) (Davis et al. 2012a). The longer flow path resulted in an improved performance for both peak discharge reduction (largest flows) and median discharge (overall performance) indicating better flow attenuation at the full range of storm sizes and a greater return to predevelopment hydrologic balance.

Volume Reduction

Normalized volumes for events where highway runoff, 3-m VCB, and 6-m VCB data were all collected are compared on an exceedance probability basis (Fig. 8 and Table 3). For comparison, the rainfall distribution for the same subset of data is also presented. Median rainfall for this dataset was 6 mm, near the point where effluent begins for both VCB treatments. The 3-m and 6-m treatments produced no discharge for a large portion of events (~45%),

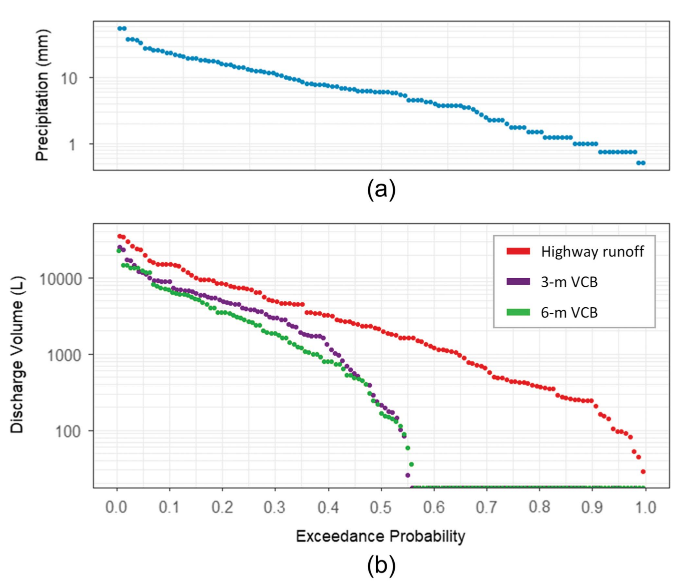


Fig. 8. Observed field stormwater discharge volumes: (a) observed precipitation exceedance probability plot; and (b) observed discharge volume exceedance probability plot. Discharge volume is normalized by drainage area.

Table 3. Field normalized stormwater discharge statistics observed for runoff inflow, 3-m VCB, and 6-m VCB

Parameter	Precipitation (mm)	Runoff volume (L)	3-m VCB volume (normalized) (L)	6-m VCB volume (normalized) (L)
Median	6.1	2,070	125	74
Mean	9.5	4,990	2,470	1,840
Min	0.51	28	0	0
1st quartile	1.8	435	0	0
3rd quartile	13	7,090	3,630	1,950
Max	56	35,700	25,000	22,600
n	124	124	124	124

Table 4. Field total volumes and storage over the full experiment

Category	Volume (m^3)	Rainfall (mm)
	3-m VCB	
Inflow	703	1,484
Outflow	392	827
Retained	311	656
	6-m VCB	
Inflow	952	1,524
Outflow	425	680
Retained	527	844

Note: Percentage retained for 3-m VCB: 44%; *n* for 3-m VCB: 248; percentage retained for 6-m VCB: 55%; *n* for 6-m VCB: 249.

and for those which produced effluent, a sizable difference was noted between VCB treatment volumes and highway runoff volume, indicating a benefit in volume reduction by both VCB treatments.

The 3- and 6-m systems converge at low and high volumes, while in the center, increased performance is noted for the 6-m system over the 3-m. For events where the VCBs have a high antecedent moisture content, it is expected that they have little remaining storage capacity (for example, with back-to-back storm events), and therefore less difference in volume retention is found between the two treatments. A gap between treatments is observed from ~10% to 45% exceedance; this indicates that for events producing effluent from the VCB systems, the 6-m system discharges less volume. By taking a subset of this data for only discharge volumes greater than 0, the 6-m system has a lower (~43%) median discharge volume than the 3-m (3,475 L for 3-m and 1,983 L for the 6-m).

Influent and effluent volumes for each event were compared to provide an overall summary of hydrologic performance (Fig. 9), excluding events where rainfall was so low that no influent highway runoff occurred. For each datapoint (individual storm event), storage is found as the vertical distance from the 1:1 correlation line. For additional comparison, the distributions for each variable are plotted at the edges of the main plot as well as an inset boxplot showing the storage values for the same dataset (found by subtracting outflow volume from inflow volume for each event). Because the highway drainage area for the 6-m system was only ~13% higher than for the 3-m, the data in these plots were not normalized.

The cumulative inflow and outflow volumes for each VCB were calculated over the entire study, including the events that did not produce highway runoff (Table 4). The 3-m VCB system captured 44% of influent stormwater volume and the 6-m captured 55%. These reductions are similar to those found previously for compost blankets of 3.75-cm depth and 4.8-m length (50%–60%) (Faucette et al. 2005, 2007). The addition of the VCB to the VFS improved volume capture performance, with larger volume reductions attained at shorter flow paths, as evidenced by total volume reductions observed previously for a VFS alone of 36% for an 8-m length and 59% for a 20-m length (Knight et al. 2013) and 20%–40% for a 2- to 5-m length and 62%–70% for a 8- to 15-m length (CVC and TRCA 2010).

For both VCB systems (Fig. 9) outflow volume frequency distributions (along the axes) have peaks much closer to 0 and are much narrower in comparison to the inflow volume distributions, indicating more frequent lower discharge volumes for the outflow over the inflow. Approximately 61% of the storm events were completely captured by the VCB system, evidenced by the points on the *x* axis, though many of these (39% of the total) did not produce highway runoff.

The volume data were described using a "hockey-stick" fit where a fixed storage capacity is reached, after which the outflow volume is equal to the inflow volume (slope = 1, indicating no additional losses other than pore space storage) (Davis et al. 2022),

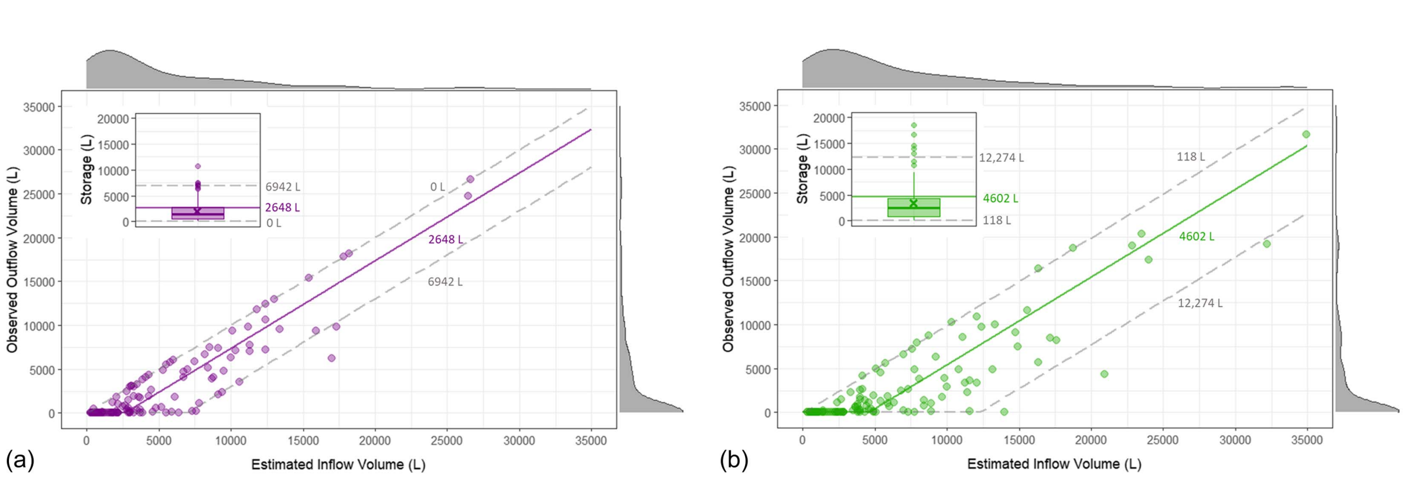


Fig. 9. Field inflow outflow curves for 3-m and 6-m VCBs: (a) 3-m VCB/VFS system; and (b) 6-m VCB/VFS system. Hockey-stick best fit shown in solid line; 95% confidence intervals shown in dotted gray lines; inset plot shows storage (inflow–outflow) with storage values labeled; frequency distributions for individual datasets shown on plot margins.

since infiltration was found to be insignificant due to compacted clay soils under the VCB/VFS system. This best fit was chosen considering that storage in the compost and soil layers was found to be the primary means of volume retention, and because this is a conservative estimation for sites where infiltration rates may not be known. The hockey-stick best fits are shown in the plots as solid, colored lines. Similar attempts utilizing an initial storage or abstraction volume to describe stormwater control measures have been done previously for bioretention (Davis et al. 2012b) and for green roofs (Fassman-Beck et al. 2016), though the slopes were not forced to 1 as they are here.

Linear best-fit was found through minimizing the sum of the squares of the residuals between the predicted data and the observed dataset. The average initial storage volume is 2,648 L for the 3-m system (RMSE = 1,964 L, $R^2 = 0.8012$) and 4,602 L for the 6-m system (RMSE = 3,215 L, $R^2 = 0.7128$). The 5th and 95th percentile storage values (dashed lines in Fig. 9) were also plotted to indicate the storage values within which 90% of events fall. Conceptually, this range accounts for the variability of available storage space prior to the rain event as well as the storm size, since many small storm events will be completely captured and will not fill all available storage space (approximately 45% from Fig. 8, as shown by the datapoints on the x axis above 55% exceedance). The RMSE (1,964 L for 3-m and 3,215 L for 6-m) is similar to the storage volume dataset standard deviations for the 3- and 6-m systems (2,071 L and 3,117 L, respectively). The volume retained for each particular storm event will depend on the storm size, duration, intensity, rainfall pattern, antecedent moisture content, and seasonal changes (vegetation, temperature, etc.), making this specific fit most appropriate for regions with conditions similar to this study. A comparison of the distribution of storage volumes along with summary statistics is shown in Fig. S5. The 6-m storage volume is 43% higher than the 3-m, based on the mean.

Greenhouse Storage Performance

The greenhouse mesocosm experiments were used to supplement field observations and to better understand VCB system performance over a range of possible site conditions. The inflow–outflow curves for these experiments are shown in Fig. 10 along with best fit statistics in Table 5. The hockey-stick best fit for mesocosms was also determined through minimizing the sum of the squares of the residuals between the predicted data and the observed dataset. Best fit storage is presented as volume (L) and also normalized as volume per VCB surface area (L/m^2) to account for differences in VCB length for comparison with field storage.

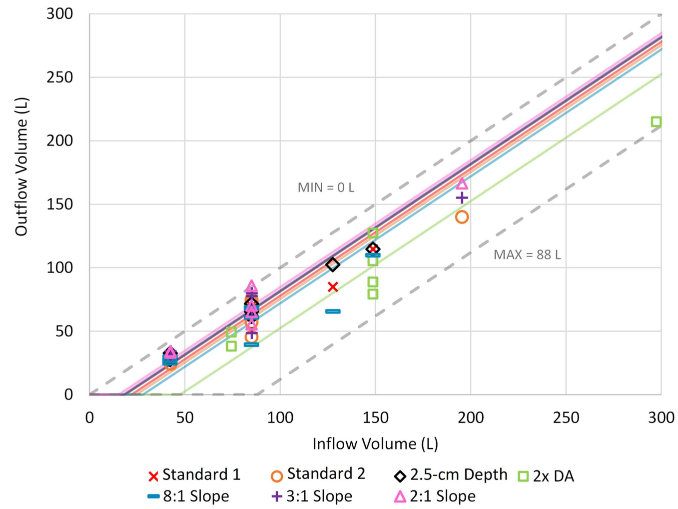


Fig. 10. Inflow–outflow curves for greenhouse experiments. Solid lines indicate hockey-stick best fit for each mesocosm; min and max storage based on porosity is shown in dotted gray lines; max storage for the 2.5-cm compost depth mesocosm is 54 L and for all others is 88 L.

Table 5. Inflow–outflow statistics for greenhouse experiments

Mesocosm	RMSE (L)	R^2	Best fit storage (L)	Best fit storage (L/m^2)
Standard 1	9.58	0.927	22.09	26.42
Standard 2	15.4	0.887	24.64	29.47
2.5-cm depth	7.11	0.960	18.69	22.35
2 × DA	21.31	0.904	47.57	56.89
8:1 slope	16.27	0.789	28.03	33.52
3:1 slope	13.41	0.920	17.84	21.34
2:1 slope	10.41	0.952	15.29	18.29
3-m VCB (field)	—	—	—	28.50
6-m VCB (field)	—	—	—	24.77
Hockey-stick design for 7.6-cm VCB depth [using Eq. (3)]	—	—	26.87	32.14

Note: All mesocosms have a 7.6-cm VCB depth except for the 2.5-cm depth variation. Max storage for the 2.5-cm compost depth mesocosm is 54 L and for all others is 88 L. Best fit storage refers to the x-axis intercept of the best-fit line, which can be considered an estimate of the average storage value. DA= drainage area ratio.

Predicting VCB Storage

Determining a storage volume for VCB/VFS design may be approached similarly to previous attempts utilizing a Bioretention Abstraction Volume (BAV) for bioretention SCMs (Davis et al. 2012b). However, unlike in bioretention, there is no bowl storage for a VCB/VFS system, nor is the lower media expected to remove a significant volume of stormwater due to the highly compacted subsoil; only the storage in the VCB and VFS layers is influential. The difference between saturated moisture content (w_{sat}) and wilting point moisture content ($w_{wilting}$) of the compost is considered as an average upper volumetric storage threshold since this defines the available storage after a long dry period and the VCB is shallow and vegetated. Based on antecedent moisture content behavior of the VCB/VFS storage, many storm events result in little to no storage, making 0 storage a conservative lower threshold. The VCB/VFS design storage volume (V_s) is therefore determined as the mean of the upper and lower (0 storage) threshold values, calculated as

$$V_s = \frac{[V_{VCB} * (w_{sat} - w_{wilting})_{VCB}] + [V_{VFS} * (w_{sat} - w_{wilting})_{VFS}]}{2} \quad (3)$$

where VCB = compost layer; and VFS = topsoil layer; and V = volume of each material.

Wilting point estimates were previously found for a leaf compost ($w_{wilting} = 44\%$) and a local topsoil ($w_{wilting} = 8\%$) (Duzgun et al. 2021); w_{sat} was found through a vacuum saturation test (compost $w_{sat} = 75\%$, topsoil $w_{sat} = 48\%$). Using these data and Eq. (3), design storage values of 2,018 L for the 3-m and 4,036 L for the 6-m VCB/VFS are obtained (using field media depths of 6.4-cm for topsoil and 7.6-cm for compost). These storage volumes are 23.8%

and 12.3% less than the average storage estimated by the hockey-stick method (3-m = 2,648 L, 6-m = 4,602 L), making this conservative but fairly accurate. To obtain the hockey-stick fit, the following two-part equation can be used:

$$1.\ \text{for } V_{\text{inflow}} \le V_s; \qquad V_{\text{outflow}} = 0$$
$$2.\ \text{for } V_{\text{inflow}} > V_s; \qquad V_{\text{outflow}} = V_{\text{inflow}} \tag{4}$$

where inflow volumes are calculated using some runoff model and the design volume (V_s) is calculated using Eq. (3). As compost decomposes and root depth changes over time, storage may also be expected to change, and estimations of storage volume can be considered most accurate during the first two years after application, as measured in this study.

Eq. (3) was used with the same values for w_{sat} and w_{wilting} to estimate the design storage volume for the mesocosm boxes (1.8-m length, 0.46-m width, 7.6-cm compost depth, 10-cm soil depth). A value of 26.87 L results, which is within the volume range found for the flattest slopes (22.09 to 28.69 L for 5:1 or less) in the greenhouse study.

The mean storage decreased with increasing slope, but was not found to be statistically significant, which shows that VCB systems can be effective for volume retention for slopes between 20:1 (field site) and 2:1. For variable compost depth, no significant difference was found in mean storage, suggesting that a thinner layer of compost (2.5 cm) may achieve similar results to a 7.6-cm layer. This also further supports evidence that for many storm events, all storage space is not utilized. This may in part be due to storm characteristics; however, observations in the greenhouse showed that compost was often not saturated over the full length of the mesocosm during low flow events. Because compost was installed above grade (over the existing VFS) and also because the system is sloped, larger volume attenuation for some storm events may be prevented, especially those producing lower highway runoff flows, as water is more likely to move downward to the VFS layer and be transported downslope.

Comparison of differing drainage area ratio mesocosms further supports the idea that all storage space may not be utilized. One system experienced twice the runoff (representing twice the highway drainage area at 6:1 DA ratio) and was the only mesocosm to be found statistically significantly improved ($p \sim 0.05$) by 94% increased storage over the standard (3:1 DA ratio) based on the mean. All other factors, including rainfall over the top of the mesocosm, remained the same, isolating the runoff flowrate as the driver for increased storage (this improvement can be seen in Table 5 and Fig. 10). Greater runoff flow rates from the highway should force a taller wetting front in the compost layer, which is above grade. This is further supported by the behavior observed in the high intensity hydrographs in Fig. 5. Both datasets give some credit to the theory that higher runoff flowrates (whether they are caused by a larger highway drainage area or a higher intensity storm event) result in greater contact of highway runoff flows with the compost layer (which has a much higher volumetric saturated moisture content than the topsoil: 76% versus 44%), resulting in increased total storage.

Even though water storage increases from 24.64 L to 47.57 L, the net result was not improved for the $2 \times \text{DA}$ (6:1 DA ratio) greenhouse system over the standard (3:1 DA ratio). The total outflow volume (over the full experiment) increased from 447 L to 703 L by increasing the drainage area, making the utilization of available storage more efficient, but the overall stormwater volumetric performance much less successful. Finding ways to increase stormwater runoff contact with the compost layer while still maintaining lower drainage area ratios could improve storage efficiency.

The Soil Conservation Service (SCS) curve number approach (Cronshey 1986) is often used for describing the hydrologic benefit of SCMs (Davis et al. 2012b; Olszewski and Davis 2012; Fassman-Beck et al. 2016), including an attempt previously on compost blankets used for erosion control (Beighley et al. 2010). A composite curve number (CN) that includes the surface area of the highway and each VCB was found through linear best fit of a curve number calculation for each system (described in more detail in the Supplemental Materials section). For the 3-m system, the composite CN was determined to be 97 (RMSE = 1,767 L, $R^2 = 0.8227$) and 95 for the 6-m system (RMSE = 2,533 L, $R^2 = 0.7667$). Separating the CN for the VCB areas alone resulted in a CN of 85 for the 3-m and 83 for the 6-m system, resulting in a mean CN of 84. This value is comparable to CNs found previously for compost blankets on steep slopes used in erosion control (Beighley et al. 2010), where blankets of depth 5.0-cm over a 4:1 slope resulted in a CN of 80–82 during rainfall simulation experiments (in this field study blankets were 7.6-cm depth and ~10:1 slope).

A CN is a widely used tool in stormwater design and implementation; however, it has drawbacks for use in this particular system. The NRCS method was intended for use at the watershed level, making it less accurate for small systems, and it does not account for the flow path of the system, rather estimating a percent runoff over the entire surface area. In reality, highway runoff flows into the VCB area before exiting, making a more complex system in series not accounted for by the CN. When possible, the hockey-stick method [Eq. (1)] with the representative volume storage value should be used.

Conclusions

Two field-scale VCBs within a highway median were monitored over 2.25 years to evaluate their hydraulic and hydrologic performance as SCMs. Performance was evaluated as a combined system of a VCB overlaying the preexisting VFS. Differing lengths from edge-of-pavement were evaluated to assess the influence of flow path and potential storage volume with both discharge flows (hydrographs) and total event volumes used in their evaluation. A range of greenhouse mesocosm studies were used to supplement field data through volumetric storage comparisons as well as evaluations of compost/soil hydraulic properties and vegetative cover.

Due to highly compacted subsoils, infiltration was not a significant removal pathway for stormwater volumes, with storage being the main stormwater removal pathway. VCB application improved the hydraulic properties of VFS soil but did not have a significant impact on the highly compacted subsoils over the period of study (2.25 years). VCBs were found to improve site hydrology in comparison to highway runoff alone for both runoff flows and volumes. A large portion of smaller storm events (22% producing highway runoff and 39% not producing highway runoff) were completely captured, and significant volume reductions were found for many larger storm events, resulting in 44% and 55% total volume removal over the full study period for the 3-m and 6-m VCBs, respectively. VCBs were shown to mainly function as storage for small storms, at the beginning of larger storms, and between high intensity peaks of rainfall. At the highest flowrates and after apparent saturation was reached, however, both VCBs transitioned to mainly conveyance.

Event hydrographs were improved by VCB treatments, with peak flows, time to peak, and event duration showing reductions of 39% and 43%, increases of 94% and 97%, and decreases of 10% and 9% for the 3-m and 6-m systems, respectively, in comparison to highway runoff based on the median. The 6-m VCB had an improved performance over the 3-m VCB for both high flows and for overall flow reduction compared to the highway runoff; however, both systems were unable to attenuate the highest flows. If found to also provide appropriate water quality benefits, a VCB/VFS system might be considered a pretreatment prior to a highway swale system. In this case, many smaller storm events could be mitigated by the VCB/VFS alone while for larger storms reductions in flows and stormwater discharge volumes could be attained before discharge to the swale system for further treatment.

Because infiltration was found to be negligible, the most appropriate description of VCB/VFS volume retention performance is a representative average storage capacity, after which no additional storage is provided by the system. Average storage capacity can be calculated using Eq. (3) with estimated or measured values for saturated moisture content and wilting point moisture content for both the VCB and VFS layer, since estimates of these parameters are widely available. Greenhouse experiments showed that volume retention was not significantly changed over 20:1 to 2:1 slopes. Volume retention by a thinner VCB layer (2.5 cm versus 7.6 cm) was not significantly different, indicating that not all available VCB storage was being utilized. These observations highlight a potential inefficiency in VCB implementation; since VCBs were applied above grade over the existing VFS, greater flowrates may be required to increase the highway runoff flow wetting front with the VCB layer. Opting for greater drainage area ratios over smaller is not recommended due to the higher net discharge, but future designs may consider addressing the potential for increased storage capacity. A curve number of 84 was estimated for a VCB overlaying a VFS, which should provide a fair estimate of hydrologic performance if needed but is not considered the best representation of VCB functionality.

Finally, it is important to note that compost has been shown to release large amounts of nutrients immediately after installation, making water quality performance of VCBs critical in decision making. Overall performance evaluation and recommendations given here considered hydrologic performance alone. Both hydrologic and pollutant removal improvements are important goals for SCMs, and further research on overall water quality performance of VCBs will be essential to making appropriate design and implementation recommendations.

Data Availability Statement

All data generated or used during the study appear in the published article.

Acknowledgments

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Supplemental Materials

There are supplemental materials associated with this paper online in the ASCE Library (www.ascelibrary.org).

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