Prepared in cooperation with ms consultants

Assessment of Runoff Volume Reduction Associated with Soil Amendments Added to Portions of Highway Median-Strip Catchments in Ohio, 2018–20

Scientific Investigations Report 2021–5114
Version 1.1, December 2021

U.S. Department of the Interior
U.S. Geological Survey

Cover— Photograph of view looking west (upstream) at flume in median at State Route 30 near Township Road 13 near Bucyrus, Ohio (site number 404755082550600), by the U.S. Geological Survey, June 2020

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Area	
acres	4046.85642	square meter (m^2)

Abbreviations

ASTM	American Society of Testing and Materials
BMPs	best management practices
CNT	control
EDF	empirical distribution function
IQR	interquartile range
MLR	multiple linear regression
ODOT	Ohio Department of Transportation
USGS	U.S. Geological Survey

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Abstract

The U.S. Geological Survey installed 10 rain gages and 12 calibrated H-flumes to measure rainfall and runoff volumes at 10 locations in Ohio Department of Transportation highway median-strip catchments. Data were collected to facilitate comparisons of rainfall and runoff volumes at study sites before and after stormwater best management practices (BMPs) were installed and between sites with different BMPs. The BMP treatments comprised removing the top layer of the existing soil, rototilling the remaining soil to a 6-inch depth, mixing the soils with one of two soil amendments (compost with sand or shale) at one of two thicknesses (4 inches or 6 inches), topping with a compost blanket, seeding, and installing erosion control matting. The overall treatment used at a given study site is referred to as "BMP." At two locations where soil amendments were installed, a second "control" site was installed to measure runoff from an adjacent catchment in the same median strip where no soil amendment was installed. This no-treatment option (no soil amendment) was considered its own class of BMP.

Rainfall and runoff data were collected during periods when air temperatures were above freezing (including all months except January, February, and parts of December and March) from 2018 to 2020. The data collection period for each study site was divided into "pre-BMP" and "post-BMP" periods. Equipment to measure rainfall and runoff was installed and data were collected from April to December 2018 before installation of soil amendments (the pre-BMP period). The post-BMP period started between April and May of 2019 at the first measured rainfall after soil amendments were installed. Rainfall and runoff monitoring continued through September 2020. For control sites, the post-BMP periods were assigned to start with the first measured rainfall in the 2019 data collection season.

A rainfall-runoff "event" was defined as beginning at the time of the first measured rainfall and ending when rainfall and runoff (if any) ceased and remained ceased for at least 3 hours. A value referred to as "event runoff percentage," defined as the total volume of runoff during an event expressed as a percentage of the total volume of rainfall falling over the catchment, was computed for each event. The distribution of rainfall totals associated with events was similar between the pre-BMP and post-BMP periods; however, there were appreciable between-site differences in the distribution of event runoff percentages during the pre-BMP and post-BMP periods.

Empirical distribution function (EDF) tests were performed with and without data from events that resulted in no runoff to determine whether the distribution of event runoff percentages changed from the pre-BMP period to the post-BMP period. The null hypothesis that the EDFs of event runoff percentages were equal in the pre-BMP and post-BMP periods was rejected ($\alpha=0.05$) in at least one of the two tests for four sites (one site with a shale amendment and three sites with sand amendments). Mean event runoff percentages at each of those four sites decreased from the pre-BMP period to the post-BMP period. The null hypothesis that the EDFs of event runoff percentages were equal was not rejected for the other six sites' draining catchments with soil amendments or the two control sites. EDF tests performed on event rainfall totals indicated no statistically significant changes between the pre-BMP and post-BMP period distributions for any of the sites.

Double-mass analyses of cumulative runoff were performed for two pairs of closely spaced sites (each pair located in a common median strip): one site in each pair drained a catchment where soil amendments were installed, and the other (a control) drained a catchment without soil amendments. Those double-mass analyses indicated a small reduction in runoff from the pre-BMP to post-BMP period at the site whose catchment received the sand and compost amendment, but no perceptible reduction in runoff at the site whose catchment received the shale and compost amendment.

Regression analyses indicated that (a) three rainfall factors (event rainfall totals, total rainfall for the previous 7 days, and a cross product of the factors) and the intercept term were the four most important factors explaining event runoff percentages, (b) the effect of amendment type on event runoff percentage was small in comparison to the rainfall and intercept terms, (c) event runoff percentages tended to be lower for sites with shale amendments than sites with sand amendments; however, event runoff percentages tended to be lower for control sites than for sites with shale or sand

amendments, and (d) event runoff percentages increased with increasing amendment thickness. The counterintuitive results that event runoff percentages increased with increasing amendment thickness and that control sites tended to have lower event runoff percentages than sites draining soil-amended catchments likely reflects unmeasured factors that existed at the sites before BMPs were installed rather than the effect of the BMP treatments.

Although not definitive, some support for the conclusion that the sand amendment was generally more effective at reducing runoff than the shale amendment was provided by results from the EDF tests, double-mass analyses, and runoff statistics.

Introduction

Although stormwater best management practices (BMPs) involving incorporation of soil amendments have been extensively studied (Bean and Dukes, 2015; Clary and others, 2020; Curtis and others, 2007; Kranz and others, 2020; Mechleb and others, 2014; Mohammadshirazi and others, 2016; Pitt and others, 1999; Rivers and others, 2021), little quantitative hydrologic data have been collected in Ohio to evaluate the effectiveness of soil amendments for reducing stormwater runoff. To help address these data gaps, the Ohio Department of Transportation (ODOT) issued a request for proposals to install soil amendments of various types and thicknesses at 10 pilot-scale study sites within ODOT rights-of-way to assess runoff volume reduction associated with those amendments. An engineering consulting firm, ms consultants, was selected by ODOT to manage the research project, and they subsequently entered into an agreement with the U.S. Geological Survey (USGS) to assist the research efforts. The USGS was tasked with collecting rainfall and runoff data at the study sites, analyzing those data to evaluate changes in runoff volumes from before to after the soil amendments were installed, and comparing runoff results between BMP treatments. If the amendments are effective at reducing stormwater-runoff volume, they may be considered for use by ODOT in future construction projects.

Purpose and Scope

The purpose of this report is to provide the results of an assessment of rainfall-runoff volume reduction associated with installation of selected soil amendments and soil-amendment depths. Runoff data were collected during 2018–20 at 10 sites that were draining small catchments on ODOT highway median strips located in north-central and northeast Ohio where soil amendments were installed. Runoff data also were collected at two unamended control sites that were each collocated in the same median strip as one of the soil-amended sites. Rainfall data were collected near each site to facilitate the rainfall-runoff assessments.

Site Description

Rainfall and runoff were monitored at 10 locations in Ohio, before and after installation of stormwater BMPs. The BMP treatments comprised removing the top layer of the existing soil, rototilling the remaining soil to a 6-inch depth, mixing the soils with one of two soil amendments (compost with sand or compost with shale) at one of two thicknesses (4 inches or 6 inches), topping with a compost blanket, seeding, and installing erosion control matting. At two locations where soil amendments were installed, a second "control" site was instrumented to measure runoff from an adjacent catchment in the same median strip where no soil amendment was installed. Note that the acronym "BMP" is used to refer to the overall treatment at a given study site. The no-treatment option (applicable to control sites) was considered its own class of BMP. The following criteria were used to select study sites:

1. sites have a typical grass median that drains to a well-defined outlet,
2. sites have safe access to install and maintain monitoring instrumentation,
3. sites have drainage areas less than 3 acres,
4. sites can accommodate an amended area that constitutes a substantial proportion (30–50 percent) of its drainage area.

The study sites were located in north-central and northeast Ohio in Crawford, Wayne, Stark, Muskingum, and Licking Counties (fig. 1). Catchments for sites whose designation begins with "BMP" received soil amendments and sites whose designation begins with "CNT" (control sites) did not.

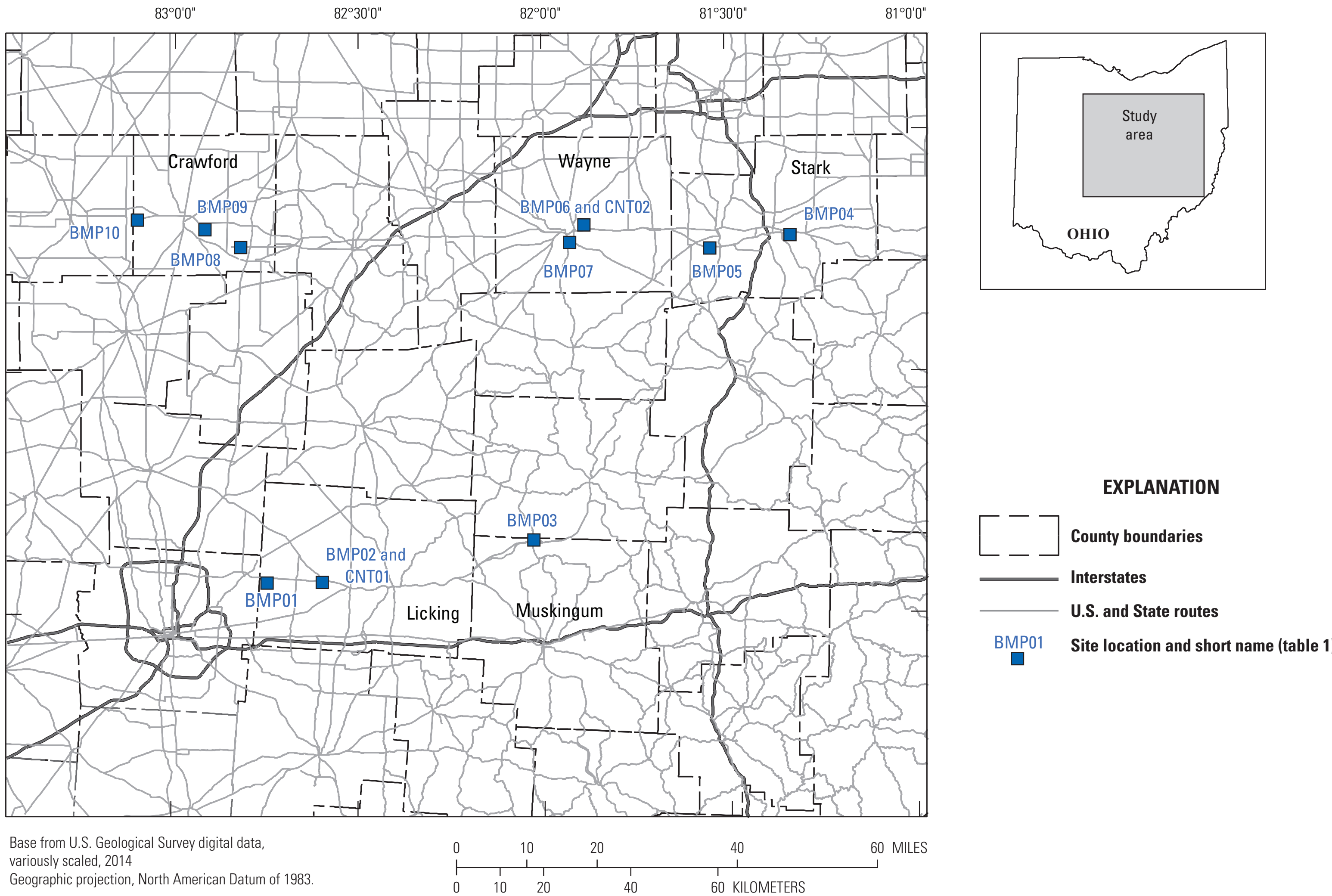

Figure 1. Map showing location of study sites in Ohio.

Table 1. Selected characteristics of study site catchments.

[Site locations are shown in figure 1. NWIS, National Water Information System; SR, State Route; nr, near; OH, Ohio; E, east; SW, southwest; TWP, Township; Rd, road; W, west]

Site	NWIS site identification number and link to data[1]	NWIS site name	Drainage area (acres)	Main-channel slope (percent)	Impervious/paved area (percent)
BMP01	400448082452500	Flume at SR 161 nr Beech Road nr New Albany OH	2.05	2.0	32
BMP02	400423082353500	Flume at SR 37 E of Moots Run nr Alexandria OH	1.03	1.2	33
BMP03	400918082012700	Flume at SR 16 nr SR 60 nr Dresden OH	0.51	2.3	25
BMP04	404702081193500	Flume at SR 30 nr Trump Avenue nr Canton OH	1.64	1.9	36
BMP05	404527081325100	Flume at SR 30 nr 17th Street SW nr Canton OH	1.88	1.0	37
BMP06	404755081531300	Flume at SR 30 E of Apple Creek nr Wooster OH	0.97	2.1	31
BMP07	404631081545100	Flume at SR 83 near Selby Road nr Wooster OH	1.89	2.5	45
BMP08	404543082490800	Flume at SR 30 nr Biddle Road nr Gallion OH	0.82	1.4	39
BMP09	404755082550600	Flume at SR 30 nr Twp Rd 13 nr Bucyrus OH	0.83	1.1	35
BMP10	404901083053600	Flume at SR 30 nr Twp Rd 1 nr Bucyrus OH	1.47	1.2	40
CNT01	400423082354100	Flume at SR 37 W of Moots Run nr Alexandria OH	2.42	1.9	35
CNT02	404755081531900	Flume at SR 30 W of Apple Creek nr Wooster OH	0.78	0.8	40

[1]U.S. Geological Survey, 2021.

Instrumentation and Data Collection

Rainfall and runoff were measured by USGS at 10 study sites (designated BMP01–BMP10) draining highway median-strip catchments where soil amendments were eventually installed. Control sites (designated CNT01 and CNT02) were established adjacent to 2 of the 10 BMP sites (fig. 1) to measure runoff from catchments where no soil amendment was installed. The drainage areas of the catchments for all 12 sites were small, ranging from 0.51 to 2.42 acres (table 1).

Results from the control sites were used to help distinguish changes in runoff attributable to temporal variation in rainfall conditions from changes in runoff attributable to the installation of soil amendments. CNT01 was located about 500 feet (ft) from BMP02, and CNT02 was located about 400 ft from BMP06. At locations with collocated BMP and control sites, a single rain gage was installed and assumed to provide rainfall data representative of the CNT and BMP catchments.

The study sites were established and instrumented in March of 2018, and data were collected until the beginning of December of 2018 when data collection was stopped due to the onset of freezing temperatures. Data collection was restarted in March of 2019, and the soil amendments were installed from April 1 through May 23, 2019 (table 2). Data were collected during periods when air temperatures were above freezing (including all months except January, February, and parts of December and March) through September 2020. The period before the soil amendments were installed will be referred to as the pre-BMP period, and the period after the soil amendments were installed will be referred to as the post-BMP period. For each BMP site, the post-BMP period was assigned to start on the date of the first event after the first day of the installation of the soil amendments. For control sites, the post-BMP periods were assigned to start with the first measured rainfall in 2019 (March 22, 2019, for site CNT01 and March 28, 2019, for site CNT02). The lengths of the pre-BMP and post-BMP periods varied among the sites with soil amendments because they were not all installed on the same date. The result is that some pre-BMP data were collected in 2019 at all BMP sites, but the pre-BMP and post-BMP periods varied by nearly 7 weeks, depending on the dates of amendment installation and on the first subsequent event (table 2).

The monitoring equipment comprised tipping-bucket rain gages that measure rainfall volumetrically in increments of 0.01 inch and H-type flumes (hereinafter referred to as H-flumes) with detached stilling wells equipped with submersible pressure transducers for measuring water levels with an accuracy of 0.01 ft. The detached stilling well was connected to the H-flume with a horizontal pipe (fig. 2). An example of a typical H-flume installation is shown in figure 3. H-flumes, originally developed by the U.S. Department of Agriculture's Soil Conservation Service to measure runoff from small catchments (Brakensiek and others, 1979), were chosen to measure runoff because their design provides accurate flow measurement over a wide range of flows.

Table 2. Soil amendment characteristics and dates of installation at study sites.

[Site locations are shown in figure 1. Dates shown as month/day/year. lb/ft^2, pound per square foot; NA, not applicable]

Site	Amendment, compost plus	Amendment thickness (inches)	Dates of amendment installation	Catchment area amended (percent)	Final amended soil composition				Application rate (lb/ft^2)		
					Percent native soil	Percent compost	Percent shale	Percent sand	Shale	Sand	Compost
BMP01	Shale	6	04/10/19 to 04/19/19	52	54	29	17	NA	38	NA	60
BMP02	Sand	6	04/04/19 to 04/10/19	54	54	29	NA	17	NA	109	61
BMP03	Sand	4	04/01/19 to 04/02/19	49	50	31	NA	19	NA	82	43
BMP04	Sand	6	05/20/19 to 05/23/19	44	54	29	NA	17	NA	109	61
BMP05	Sand	4	05/13/19 to 05/21/19	49	50	31	NA	19	NA	82	43
BMP06	Shale	4	05/08/19 to 05/13/19	55	50	31	19	NA	29	NA	43
BMP07	Shale	6	05/01/19 to 05/07/19	49	54	29	17	NA	38	NA	60
BMP08	Shale	4	04/25/19 to 04/30/19	49	50	31	19	NA	29	NA	43
BMP09	Shale	6	04/24/19 to 04/25/19	31	54	29	17	NA	38	NA	60
BMP10	Sand	6	04/22/19 to 04/24/19	24	54	29	NA	17	NA	109	61
CNT01	None	0	NA	0	100	NA	NA	NA	NA	NA	NA
CNT02	None	0	NA	0	100	NA	NA	NA	NA	NA	NA

Figure 2. Photograph showing H-flume and detached stilling well connected by horizontal pipe (photograph by the U.S.Geological Survey, April 2019).

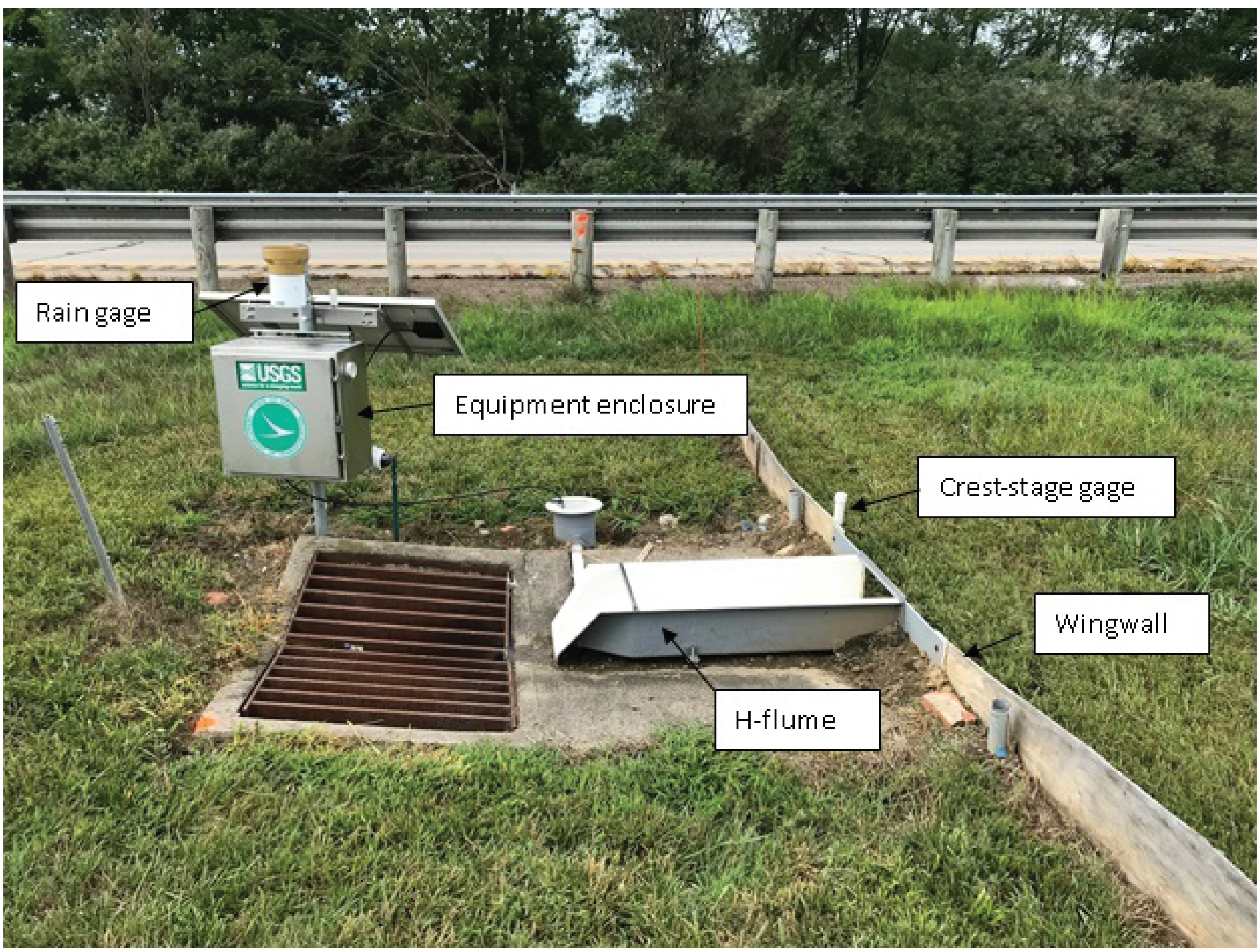

Figure 3. Photograph of typical study site showing H-flume, rain gage, equipment enclosure, crest-stage gage, and wingwall (photograph by the U.S. Geological Survey, June 2020).

H-flumes range in flow-measurement capacity because of the height of the H-flume (Gwinn and Parsons, 1976). The flow-measurement capacities of the flumes used in this study were selected to measure most of the flows that were anticipated during the study period with consideration for the tradeoff between sensitivity, accuracy, and measurable flow range. Three of the sites were equipped with 0.5-ft H-flumes and nine of the sites were equipped with 0.75-ft H-flumes. The 0.5-ft H-flumes have a maximum capacity of 0.331 cubic foot per second (ft^3/s) and the 0.75-ft H-flumes have a maximum capacity of 0.957 ft^3/s. The minimum rated flows for 0.5-ft and 0.75-ft H-flumes were 0.0004 ft^3/s and 0.006 ft^3/s, respectively. The flow was assumed to be zero any time the measured gage height (stage) was 0.01 ft or less. The H-flumes used in this study were precalibrated by the manufacturer who supplied their stage-discharge ratings.

Larger H-flumes were installed at two sites during the study to reduce periods when measurement capacity was exceeded. On August 10, 2018, the 0.75-ft H-flume at BMP07 was replaced with a 1.0-ft H-flume (with a maximum measurable flow rate of 1.92 ft^3/s) and on August 15, 2018, the 0.5-ft H-flume at BMP03 was replaced with a 0.75-ft H-flume (with a maximum measurable flow rate of 0.957 ft^3/s).

Additional equipment installed at each site include an electronic data logger to store rainfall and water-level information, a cellular modem to transmit the information, equipment (a battery, solar panel, and solar regulator) to power the instrumentation, a digital camera to facilitate remote visual checks of site conditions, and a crest-stage gage to field verify maximum water levels measured during events (Friday, 1965). Data, collected at 1-minute intervals, are available on the USGS National Water Information System (USGS, 2021) (table 1).

All sites were visited monthly by USGS personnel during periods of active data collection. During each site visit, the rain gage was inspected to ensure it was level, free of debris, and operational and then tested for calibration. The rain gage was recalibrated if out of calibration. Also, H-flumes were checked for level, wingwalls were inspected for evidence of undercutting, any accumulated debris was removed, crest-stage gages were checked (and cleaned if needed), a small area near the H-flume was mowed, and photographs were taken.

Soil Amendments

Two different soil amendments were installed by subcontractors hired by ms consultants at two different thicknesses and comprising a range of percentages of the catchments draining to the BMP sites (table 2). One soil amendment was a mixture of compost and sand (hereinafter referred to as the sand amendment), and the other soil amendment was a mixture of compost and expanded shale (hereinafter referred to as the shale amendment). These amendments were selected for use because they are readily available in Ohio, and both mixtures are thought to increase infiltration. The sand used meets ODOT Specification 703.02 for fine aggregate (Ohio Department of Transportation, 2021a). The expanded shale had been kiln fired causing it to expand, resulting in a very porous and lightweight material capable of retaining moisture. The shale met the American Society of Testing and Materials (ASTM) C330/C330M standard specification for lightweight aggregates for structural concrete (ASTM International, 2017), and the ASTM D5883 standard for use of rotary kiln produced expanded shale as a mineral amendment in topsoil for landscaping and related purposes (ASTM International, 2018). The compost originated from an Ohio Environmental Protection Agency class IV composting facility and met ODOT Construction and Material Specification 659.06 requirements (Ohio Department of Transportation, 2021b).

Soil amendments were installed at the edges of the roadways' grassed shoulders and extended to within about 2 ft on either side of the thalweg of the median strip, leaving a nearly 4-ft-wide swale undisturbed. An area extending about 10 ft upgradient from the concrete slab containing the storm drain was also left undisturbed.

The soil amendment process comprised removing the top layer of the existing soil, rototilling the remaining soil to a 6-inch depth, adding the amendment and rototilling it to a depth of 4 or 6 inches, topping with a 0.5-inch compost blanket, seeding, and installing the erosion control matting meeting ODOT Construction and Material Specification 671–Type A (Ohio Department of Transportation, 2021c). The seed was an ODOT Class 1 lawn mixture comprising bluegrass, fescue, and ryegrasses, which are hardy and provide quick coverage (Ohio Department of Transportation, 2021b). The final amended soil compositions are shown in table 2. Some fine grading and limited compaction was done to achieve the pre-amendment slope geometry and general elevations.

It was anticipated that the grass planted over the amended soils would grow sufficiently in a few weeks so that the BMP treatment could be considered complete. During the July 2019 field visit, USGS personnel noted that grass growth was sparse in five of the BMP site catchments (BMP04, BMP05, BMP06, BMP07, and BMP10). The sparse grass growth likely was caused by washout of grass seed because of heavy rains that fell over those areas shortly after the seeding. Those five catchments were re-seeded during the last week of July 2019 to improve grass cover.

Rainfall and Runoff Characteristics

A rainfall-runoff event (hereinafter referred to simply as an "event") was defined to begin at the time of the first measured rainfall and end when rainfall and runoff (if any) ceased and remained ceased for at least 3 hours. Consequently, multiple events could occur on the same day, with intervening periods of three or more hours having no measurable rainfall or runoff. The number of events measured at each study site during their pre-BMP periods ranged from 119 to 186 with a mean of 141 (table 3). The amount of rainfall measured during an event in the pre-BMP periods ranged from 0.01 to 4.25 inches, and the median rainfall amount was 0.10 inch. At BMP sites, only about one-third (34 percent) of the pre-BMP events had measurable runoff, whereas about one-quarter (28 percent) of the events at control sites had measurable runoff (table 3). A listing of all events included in the analyses throughout this report is in the accompanying data release (Whitehead and Koltun, 2021).

The number of events measured at each study site during the post-BMP period ranged from 166 to 266 with a mean of 209 (table 3). The amount of rainfall measured during an event in the post-BMP period ranged from 0.01 to 4.18 inches, and the median rainfall amount was 0.11 inch. About one-third (37.6 percent, a 2.5-percentage point increase from the pre-BMP result) of the post-BMP events at BMP sites had measurable runoff and nearly one-quarter (27.6 percent, about the same as the pre-BMP result) of the post-BMP events at control sites had measurable runoff (table 3). The distributions of pre-BMP and post-BMP rainfall amounts are illustrated in figure 4. The pre-BMP and post-BMP rainfall distributions were all positively skewed (most values are clustered around the left tail of the distribution). By definition, the top and bottom of the rectangles in the boxplots correspond to the 75th and 25th percentiles of observations, respectively, and 50 percent of the observations fall within the rectangles. The difference between the 75th and 25th percentiles (the length of the rectangle) is referred to as the interquartile range (IQR).

The total rainfalls in the pre-BMP and post-BMP periods at collocated sites BMP02 and CNT01 are not the same (table 3), even though they use rainfall data from a single collocated rain gage. This happened because the data logger at CNT01 (recording the water level in the H-flume) lost power during a few events. Because runoff data for those events were incomplete, the events (including the rainfall) associated with the periods of power loss were excluded from the analyses for CNT01. Similar problems happened at CNT02, resulting in a slightly different rainfall total than the rainfall total at BMP06 (the collocated BMP site).

The pre-BMP and post-BMP distributions of rainfall characteristics were examined by creating boxplots of the characteristics aggregated by amendment type (fig. 5). There were no remarkable differences between the pre-BMP and post-BMP distributions with the possible exception that the boxplot of pre-BMP event rainfall intensities for sites that received sand amendments (BMP02–BMP05 and BMP10) had a noticeably wider IQR and an upper whisker that extended appreciably higher than in the boxplot for the post-BMP period. Even though median intensities were about the same for the two periods, the 75th percentile (the top end of the IQR) of rainfall intensity was larger in the pre-BMP boxplot. This indicates that a greater proportion of the events at sites that received sand amendments had somewhat larger rainfall intensities during the pre-BMP period than during the post-BMP period. Because runoff frequently increases with increasing rainfall intensity, the higher intensity rainfalls associated with events during the pre-BMP period could (independent of other factors) translate into larger runoff per inch of rainfall than in the post-BMP period.

A measure that will be referred to as "event runoff percentage" was computed for each event. Event runoff percentage is defined as the total volume of runoff during an event expressed as a percentage of the total volume of rainfall falling over the catchment, assuming a spatially uniform distribution of rainfall. The assumption of spatially uniform rainfall is expected to apply because the catchments for the monitoring locations are small (less than 2.5 acres and half of the catchments less than or equal to 1.03 acres) (table 1). If you divide runoff percentage by 100, the result is equivalent to the "runoff coefficient" reported in some stormwater-runoff literature.

During some events, runoff rates exceeded the maximum capacity of the H-flumes. When that happened, some water would overtop the wingwalls and the sides of the H-flume, resulting in under measurement of the runoff volume. The part of the runoff hydrograph that was not directly measured was estimated by USGS personnel. The maximum water level immediately upstream from the wingwall was determined with a crest-stage gage (fig. 3), and gage-height records were used to determine water levels in the H-flume and the duration of overtopping. The maximum flow rate was determined by summing the maximum rated flow for the H-flume with estimates of the maximum flow overtopping the H-flume and wingwalls determined from weir-flow calculations. The number of times each H-flume's capacity was exceeded (necessitating hydrograph estimation) and the percentage of the total volumes of runoff that were estimated are shown in table 4. The mean percentage of total runoff that was estimated at the study sites was 3.6 percent during the pre-BMP and post-BMP periods. As previously mentioned, larger H-flumes were installed at sites BMP05 and BMP07 in August 2018 to reduce the occurrences of overtopping.

One way of looking at changes in runoff is to compare runoff percentages computed from the total rainfall and runoff volumes happening over all events during the pre-BMP and post-BMP periods (table 4). Runoff percentages ranged from 5.1 to 47.6 percent (median of 25.9 percent) during the pre-BMP period and from 3.0 to 45.6 percent (median of 24.1 percent) during the post-BMP period. During the pre-BMP period, three of the four largest runoff percentages happened at sites BMP01–BMP03. Runoff percentages decreased at these same three sites by the largest amounts (11.6 to 17.8 percent) in the post-BMP period. Runoff percentages at site BMP07 were high in the pre-BMP and post-BMP periods. Notably, site BMP07 also happened to have the largest percentage of impervious/paved area and the largest main-channel slope of any of the sites (table 1).

Table 3. Statistics of rainfall characteristics for the pre-best management practices and post-best management practices periods. [Data from Whitehead and Koltun, 2021.]

[Site locations are shown in figure 1. BMP, best management practices; Max., maximum; Min., minimum; CNT, control; NA, not applicable]

Site(s) or statistic	Pre-BMP rainfall, inches								Post-BMP rainfall, inches								Change in percentage of events with runoff
	Mean	Median	Max.	Min.	Sum	Number of events	Number of events with runoff	Percentage of events with runoff	Mean	Median	Max.	Min.	Sum	Number of events	Number of events with runoff	Percentage of events with runoff	
BMP01	0.36	0.11	3.53	0.01	46.57	129	55	42.6	0.31	0.11	3.99	0.01	59.48	195	77	39.5	−3.1
BMP02	0.36	0.12	4.25	0.01	48.87	136	54	39.7	0.36	0.14	4.18	0.01	61.71	172	69	40.1	0.4
BMP03	0.33	0.11	3.58	0.01	39.36	119	50	42.0	0.29	0.13	3.08	0.01	66.72	229	79	34.5	−7.5
BMP04	0.29	0.09	3.80	0.01	49.65	174	64	36.8	0.26	0.10	2.07	0.01	55.55	214	57	26.6	−10.1
BMP05	0.29	0.08	3.59	0.01	38.98	135	49	36.3	0.32	0.13	2.62	0.01	57.11	180	73	40.6	4.3
BMP06	0.23	0.07	3.15	0.01	43.52	186	42	22.6	0.25	0.10	2.66	0.01	58.00	231	62	26.8	4.3
BMP07	0.30	0.10	3.18	0.01	39.65	132	61	46.2	0.34	0.14	2.18	0.01	55.63	166	81	48.8	2.6
BMP08	0.25	0.13	2.69	0.01	35.32	144	24	16.7	0.29	0.10	3.11	0.01	64.76	227	54	23.8	7.1
BMP09	0.25	0.11	3.48	0.01	33.02	133	39	29.3	0.25	0.10	2.00	0.01	54.64	217	108	49.8	20.4
BMP10	0.25	0.11	3.08	0.01	32.90	132	61	46.2	0.28	0.12	2.06	0.01	52.93	187	98	52.4	6.2
CNT01	0.35	0.10	4.25	0.01	45.03	130	46	35.4	0.29	0.12	3.67	0.01	63.58	223	87	39.0	3.6
CNT02	0.25	0.06	3.14	0.01	36.17	146	30	20.5	0.24	0.10	2.66	0.01	64.28	266	48	18.0	−2.5
Max.	0.36	0.13	4.25	0.01	49.65	186	64	46.2	0.36	0.14	4.18	0.01	66.72	266	108	52.4	20.4
Min.	0.23	0.06	2.69	0.01	32.90	119	24	16.7	0.24	0.10	2.00	0.01	52.93	166	48	18.0	−10.1
Mean	0.29	0.10	3.48	0.01	40.75	141	48	34.5	0.29	0.11	2.86	0.01	59.53	209	74	36.7	2.1
All sites	NA	NA	NA	NA	NA	1,696	575	33.9	NA	NA	NA	NA	NA	2,507	893	35.6	1.7
BMP sites	NA	NA	NA	NA	NA	1,420	499	35.1	NA	NA	NA	NA	NA	2,018	758	37.6	2.4
CNT sites	NA	NA	NA	NA	NA	276	76	27.5	NA	NA	NA	NA	NA	489	135	27.6	0.1

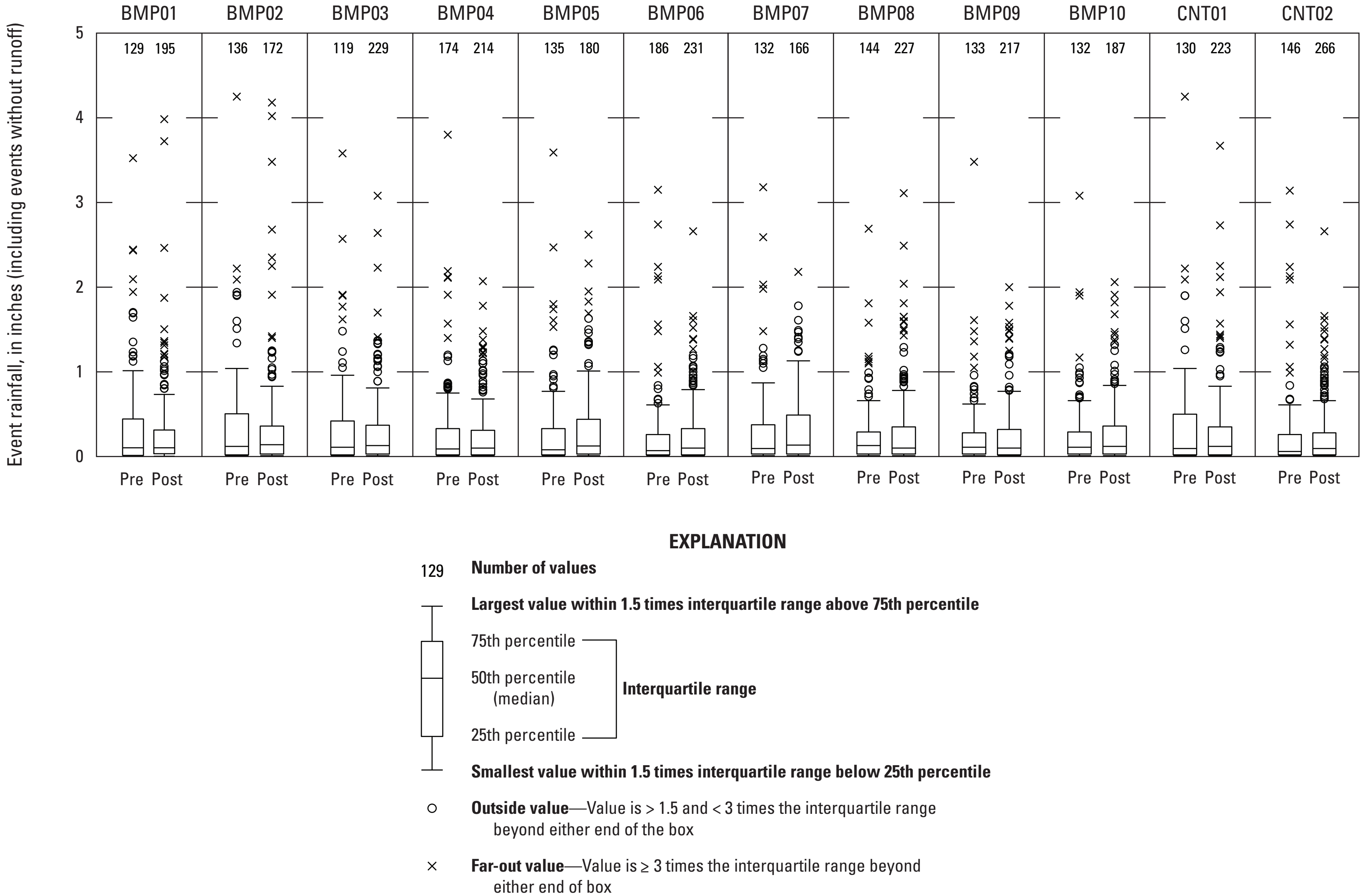

Figure 4. Boxplots showing distributions of event rainfall totals at study sites during periods before ("Pre") and after ("Post") soil amendments were installed. >, greater than; <, less than; ≥, greater than or equal to.

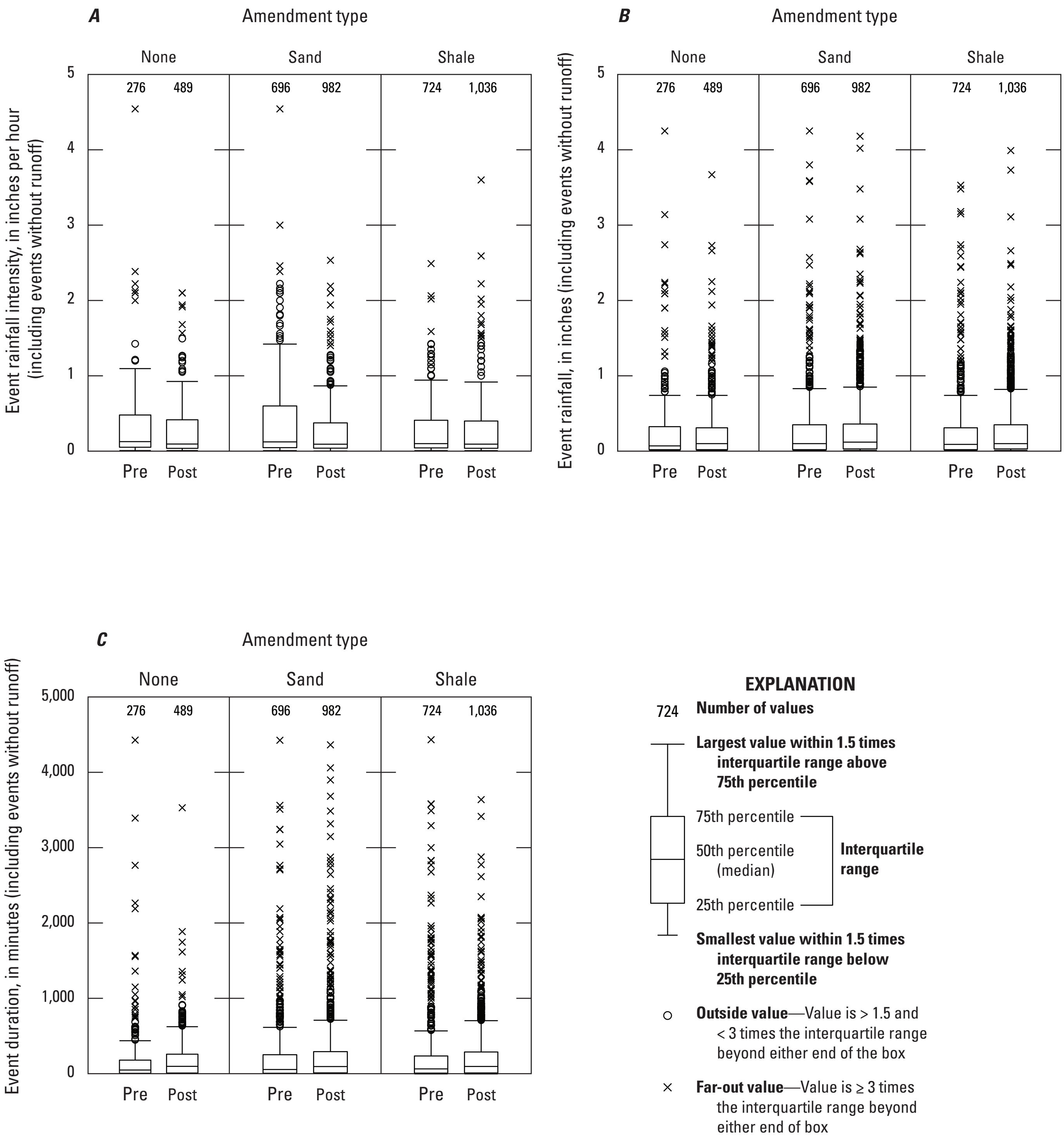

Figure 5. Boxplots showing distribution of *A*, event rainfall intensity; *B*, event rainfall; and *C*, event duration during pre- and post-BMP periods, aggregated by amendment type. BMP, best managment practice; >, greater than; <, less than; ≥, greater than or equal to.

Table 4. Summary of period-total rainfall and period-total runoff characteristics for the before best management practices (Pre-BMP) and after best management practices (Post-BMP) periods.

[BMP, best management practices; CNT, control; max., maximum; NA, not applicable; min., minimum]

Site or statistic	Amendment, compost plus	Amendment thickness (inches)	Pre-BMP period totals							Post-BMP period totals							Change in total runoff percentage from pre to post
			Rainfall (inches)	Rainfall (cubic feet)	Runoff (cubic feet)	Runoff percentage	Number of events with estimated flow	Total estimated volume (cubic feet)	Volume estimated (percent of total runoff)	Rainfall (inches)	Rainfall (cubic feet)	Runoff (cubic feet)	Runoff percentage	Number of events with estimated flow	Total estimated volume (cubic feet)	Volume estimated (percent of total runoff)	
BMP01	Shale	6	46.6	346,551	162,304	46.8	12	8,535	5.3	59.5	442,620	143,100	32.3	9	8,067	5.6	−14.5
BMP02	Sand	6	48.9	182,720	87,036	47.6	6	2,403	2.8	61.7	230,728	83,197	36.1	3	785	0.9	−11.6
BMP03	Sand	4	39.4	72,867	27,278	37.4	9	2,367	8.7	66.7	123,519	24,206	19.6	1	102	0.4	−17.8
BMP04	Sand	6	49.7	295,576	64,136	21.7	3	1,185	1.8	55.6	330,700	61,869	18.7	6	1,926	3.1	−3.0
BMP05	Sand	4	39.0	266,015	80,940	30.4	1	1,973	2.4	57.1	389,741	143,568	36.8	7	3,446	2.4	6.4
BMP06	Shale	4	43.5	153,238	13,746	9.0	1	496	3.6	58.0	204,224	13,255	6.5	1	45	0.3	−2.5
BMP07	Shale	6	39.7	272,027	129,373	47.6	6	2,625	2.0	55.6	381,661	173,975	45.6	10	4,500	2.6	−2.0
BMP08	Shale	4	35.3	105,134	8,622	8.2	1	6	0.1	64.8	192,765	25,340	13.1	6	4,158	16.4	4.9
BMP09	Shale	6	33.0	99,486	17,899	18.0	0	0	0.0	54.6	164,625	35,649	21.7	3	438	1.2	3.7
BMP10	Sand	6	32.9	175,558	41,824	23.8	0	0	0.0	52.9	282,440	84,972	30.1	4	602	0.7	6.3
CNT01	None	0	45.0	395,571	110,692	28.0	9	9,116	8.2	63.6	558,071	148,607	26.6	15	11,495	7.7	−1.4
CNT02	None	0	36.2	102,412	5,209	5.1	3	407	7.8	64.3	182,837	5,449	3.0	1	68	1.2	−2.1
Max.	NA	NA	49.7	395,571	162,304	47.6	12	9,116	8.7	66.7	558,071	173,975	45.6	15	11,495	16.4	6.4
Min.	NA	NA	32.9	72,867	5,209	5.1	0	0	0.0	52.9	123,519	5,449	3.0	1	45	0.3	−17.8
Median	NA	NA	39.5	179,139	52,980	25.9	3	1,579	2.6	58.7	256,584	72,533	24.1	5	1,356	1.8	−2.0
Mean	NA	NA	40.8	205,596	62,421	27.0	4.3	2,426	3.6	59.5	290,327	78,599	24.2	5.5	2,969	3.6	−2.8

Another way of looking at changes in runoff is to compare statistics of event runoff percentages (runoff percentages associated with individual events). Event runoff percentages at the study sites ranged from 0.0 percent to 99.2 percent for the pre-BMP period and from 0.0 percent to 91.5 percent for the post-BMP period (table 5). Figure 6 shows boxplots of event runoff percentage (including events where there was no runoff) for each site for the pre-BMP and post-BMP periods. Table 6 and figure 7 have the same formats as table 5 and figure 6; however, they exclude events without runoff. Figure 6 clearly shows that there were appreciable differences between sites in the distribution of event runoff percentages during the pre-BMP and post-BMP periods. At some sites, such as BMP06, BMP08, and CNT02, the IQRs for the pre-BMP and post-BMP periods are so compressed that the IQR rectangles are imperceptible. For those sites, at least 50 percent of the events had runoff percentages at or close to zero during both periods. The other sites (with visible boxes) had a larger proportion of events with larger runoff percentages. Even sites with the same BMP treatment showed marked differences in their distributions of event runoff percentages. For example, sites BMP02 and BMP04 had sand amendments at a thickness of 6 inches, yet site BMP02 tended to have larger event runoff percentages than site BMP04 in the pre-BMP and post-BMP periods.

The distributional differences in event runoff percentages are not as distinct when looking only at events that resulted in runoff (fig. 7). Still, it is obvious that the pre-BMP and post-BMP medians (represented by the horizontal line within the rectangles) and IQRs of event runoff percentages are much smaller at some sites (for example BMP06 and CNT02) than at others, including some with the same BMP treatments. These innate differences in runoff characteristics complicate the ability to meaningfully aggregate results as a function of BMP treatment.

Analyses

The following sections describe analyses done to (1) compare rainfall and runoff characteristics observed during the pre-BMP and post-BMP periods, (2) use runoff data from two locations where there were BMP and control catchments to test for changes in runoff characteristics that could be attributed to installation of soil amendments, and (3) identify factors related to the event runoff percentages and assess their relative importance.

Pre-BMP to Post-BMP Changes in the Distribution of Event Runoff Percentages

Assessing the effect of stormwater BMPs on the rainfall-runoff relation is complicated because many factors can affect the relation and cannot be controlled in an environmental setting. For example, one would expect that for a given rainfall amount and temporal distribution, the runoff as a percentage of the rainfall volume would be larger after a wet antecedent period than after a dry antecedent period because the infiltration capacity of the soils would be lower after the wet period. Because of the complicating factors, the first and simplest question to ask is, “Did the distribution of runoff as a percentage of the rainfall volume for events (event runoff percentages) at a given site change from the period before soil amendments were installed (pre-BMP) to after they were installed (post-BMP)?” That question was addressed when the empirical distribution function (EDF) test was implemented in the SAS NPAR1WAY procedure (SAS Institute Inc., 2018) that computed the Kolmogorov-Smirnov test statistic (D) as the maximum absolute deviation in the EDF of pre-BMP observations from the EDF of post-BMP observations. The EDF is the relation between observed event runoff percentages and their empirical nonexceedance probabilities (the proportion of observations less than or equal to the value). The null hypothesis for the EDF test is that there is no difference in the EDFs of the two classes (pre-BMP versus post-BMP event runoff percentages). A two-sided p-value was computed for the Kolmogorov-Smirnov test statistic and compared to an alpha (α) level of 0.05 for tests of significance. If the computed p-value was less than α, the null hypothesis was rejected, indicating that there was a statistically significant difference in the EDFs of the two classes. Exact tests, based on Monte Carlo estimation techniques, were used to compute the p-values because the distributions are heavily skewed.

The EDF tests were done two ways for each site. The first way included all events (including those where rainfall did not produce runoff), and the second way included only those events with runoff. When all events were included, the null hypothesis was rejected for sites BMP02, BMP03, and BMP04 (table 7), all of which had sand amendments. Figure 8 shows the EDFs of event runoff percentage, including non-runoff events for the pre-BMP and post-BMP periods at BMP03. For sites BMP02–BMP04, the post-BMP EDF curves lie above the pre-BMP curves throughout most of the range of runoff percentages. This indicates that the proportion of events with runoff percentages less than or equal to a given value tended to be larger during the post-BMP period. In other words, proportionally more events had lower runoff percentages during the post-BMP period than during the pre-BMP period. For example, about 75 percent of the pre-BMP events at site BMP03 had runoff percentages less than or equal to 20 percent; however, the percentage of events with runoff percentages less than or equal to 20 percent increased to 92 percent (an increase of 17 percentage points) in the post-BMP period (fig. 8). Also notable is the fact that a larger proportion of events had no runoff in the post-BMP period than in the pre-BMP period. Plots for sites BMP02 and BMP04 (not shown) looked similar to those for BMP03; however, the vertical spread between the pre-BMP and post-BMP curves were smaller. When only events with runoff were included in the EDF tests, the null hypothesis was rejected for sites BMP01–BMP03 (table 7), and in each case, the median runoff as a percentage of the rainfall volume was smaller in the

Table 5. Statistics of event runoff percentages (event runoff volumes expressed as percentages of rainfall volumes), including events without runoff.

[Event begins with the first tip of the rain gage and ends when rainfall and runoff (if any) ceased and remain ceased for at least 3 hours. Runoff percentage is the total volume of runoff during an event expressed as a percentage of the total volume of rainfall falling over the catchment, assuming a spatially uniform distribution of rainfall. BMP, best management practices; max., maximum; min., minimum; N, number of observations]

Site or statistic	Pre-BMP runoff percentage, including events with no runoff					Post-BMP runoff percentage, including events with no runoff					Change in mean runoff percentage	Change in median runoff percentage
	Max.	Min.	Mean	Median	N	Max.	Min.	Mean	Median	N		
BMP01	89.6	0.0	15.7	0.0	129	84.2	0.0	10.0	0.0	195	−5.8	0.0
BMP02	96.3	0.0	16.4	0.0	136	91.5	0.0	9.0	0.0	172	−7.4	0.0
BMP03	74.3	0.0	13.9	0.0	119	69.4	0.0	5.2	0.0	229	−8.7	0.0
BMP04	61.4	0.0	6.0	0.0	174	69.4	0.0	5.2	0.0	214	−0.8	0.0
BMP05	70.7	0.0	8.7	0.0	135	69.9	0.0	11.7	0.0	180	3.0	0.0
BMP06	42.2	0.0	1.7	0.0	186	38.4	0.0	1.3	0.0	231	−0.4	0.0
BMP07	99.2	0.0	16.1	0.0	132	87.1	0.0	17.9	0.0	166	1.8	0.0
BMP08	35.8	0.0	1.5	0.0	144	61.1	0.0	2.9	0.0	227	1.4	0.0
BMP09	77.7	0.0	5.7	0.0	133	62.8	0.0	6.1	0.0	217	0.4	0.0
BMP10	49.7	0.0	6.4	0.0	132	71.0	0.0	9.9	0.1	187	3.6	0.1
CNT01	73.4	0.0	8.6	0.0	130	76.7	0.0	7.5	0.0	223	−1.1	0.0
CNT02	25.1	0.0	1.0	0.0	146	20.4	0.0	0.6	0.0	266	−0.4	0.0
Max.	99.2	0.0	16.4	0.0	186	91.5	0.0	17.9	0.1	266	1.5	0.1
Min.	25.1	0.0	1.0	0.0	119	20.4	0.0	0.6	0.0	166	−0.4	0.0
Median	72.0	0.0	7.5	0.0	134	69.6	0.0	6.8	0.0	216	−0.7	0.0

Table 6. Statistics of event runoff percentages (event runoff volumes expressed as percentages of rainfall volumes), excluding events without runoff.

[Event begins with the first tip of the rain gage and ends when rainfall and runoff (if any) ceased and remain ceased for at least 3 hours. Runoff percentage is the total volume of runoff during an event expressed as a percentage of the total volume of rainfall falling over the catchment, assuming a spatially uniform distribution of rainfall. BMP, best management practices; max, maximum; min, minimum; N, number of observations]

Site or statistic	Pre-BMP runoff percentage, excluding events with no runoff					Post-BMP runoff percentage, excluding events with no runoff					Change in mean runoff percentage	Change in median runoff percentage
	Max.	Min.	Mean	Median	N	Max.	Min.	Mean	Median	N		
BMP01	89.6	0.030	36.9	34.0	55	84.2	0.593	25.2	21.4	77	−11.7	−12.6
BMP02	96.3	0.539	41.3	42.5	54	91.5	0.055	22.4	17.0	69	−18.9	−25.5
BMP03	74.3	0.058	33.0	34.9	50	69.4	0.004	15.0	7.7	79	−18.0	−27.1
BMP04	61.4	0.007	16.3	11.7	64	69.4	0.002	19.6	13.3	57	3.3	1.7
BMP05	70.7	0.008	24.0	25.2	49	69.9	0.014	28.9	26.0	73	4.9	0.8
BMP06	42.2	0.003	7.6	2.2	42	38.4	0.002	5.0	0.6	62	−2.7	−1.6
BMP07	99.2	0.070	34.8	32.6	61	87.1	0.022	36.7	34.3	81	1.9	1.6
BMP08	35.8	0.069	9.1	2.6	24	61.1	0.007	12.2	5.6	54	3.1	3.0
BMP09	77.7	0.033	19.5	12.2	39	62.8	0.004	19.6	15.3	68	0.1	3.1
BMP10	49.6	0.003	13.8	5.3	61	71.0	0.004	19.0	13.4	98	5.1	8.1
CNT01	73.4	0.179	24.4	16.5	46	76.7	0.018	19.2	13.2	87	−5.2	−3.3
CNT02	25.0	0.005	4.7	1.2	30	20.4	0.007	3.3	1.2	48	−1.3	0.0
Max.	99.2	0.539	41.3	42.5	64	91.5	0.593	36.7	34.3	98	−4.6	−8.3
Min.	25.0	0.003	4.7	1.2	24	20.4	0.002	3.3	0.6	48	−1.3	−0.6
Median	72.0	0.032	21.7	14.3	50	69.6	0.007	19.4	13.4	71	−2.3	−0.9

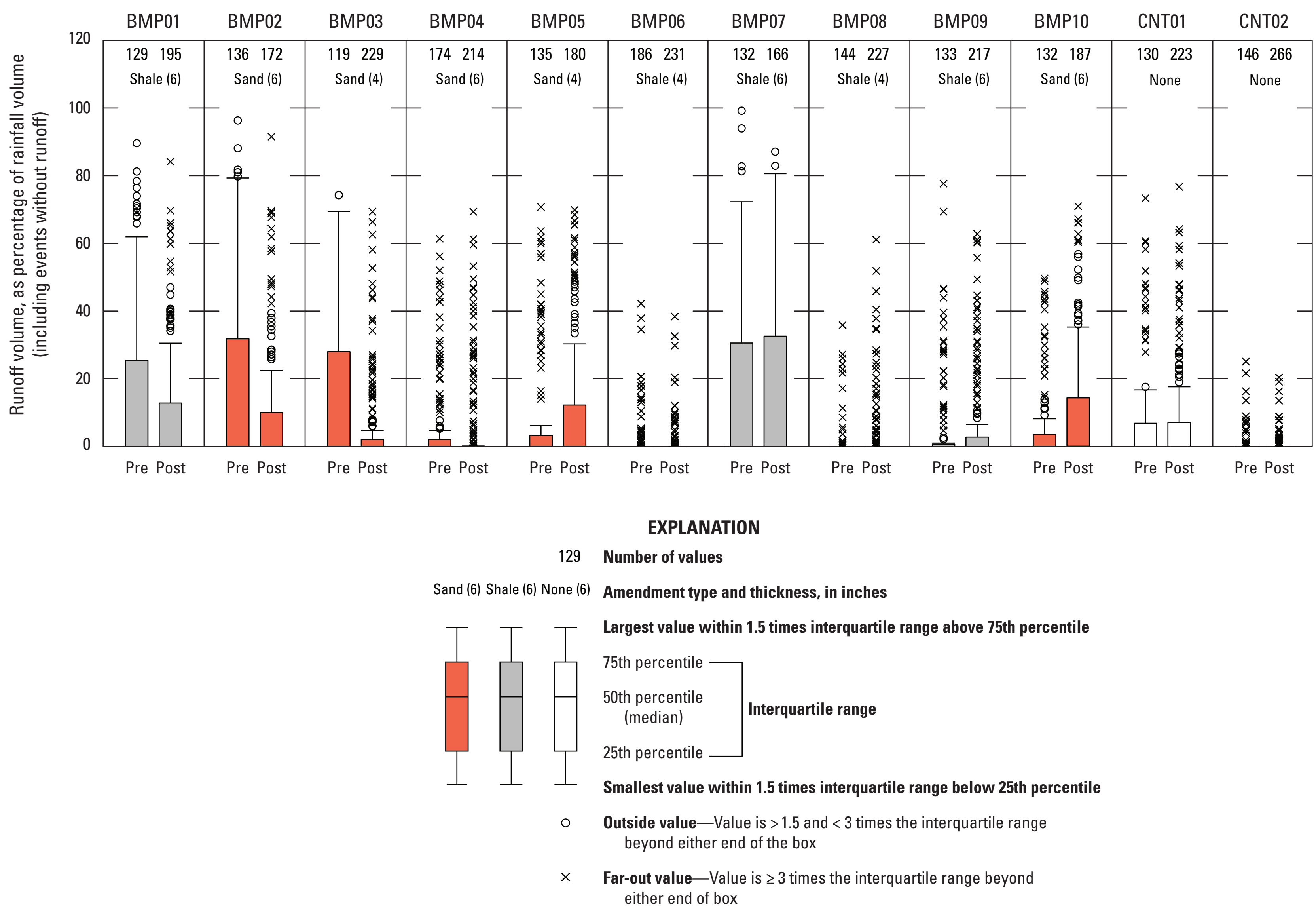

Figure 6. Boxplots showing site-specific distributions of runoff volume as a percentage of rainfall volume during periods before (“Pre”) and after (“Post”) soil amendments were installed, including events with zero runoff (color coding has been applied to boxes as an aid to help visually group results for sites with the same amendment type).>, greater than; <, less than; ≥, greater than or equal to.

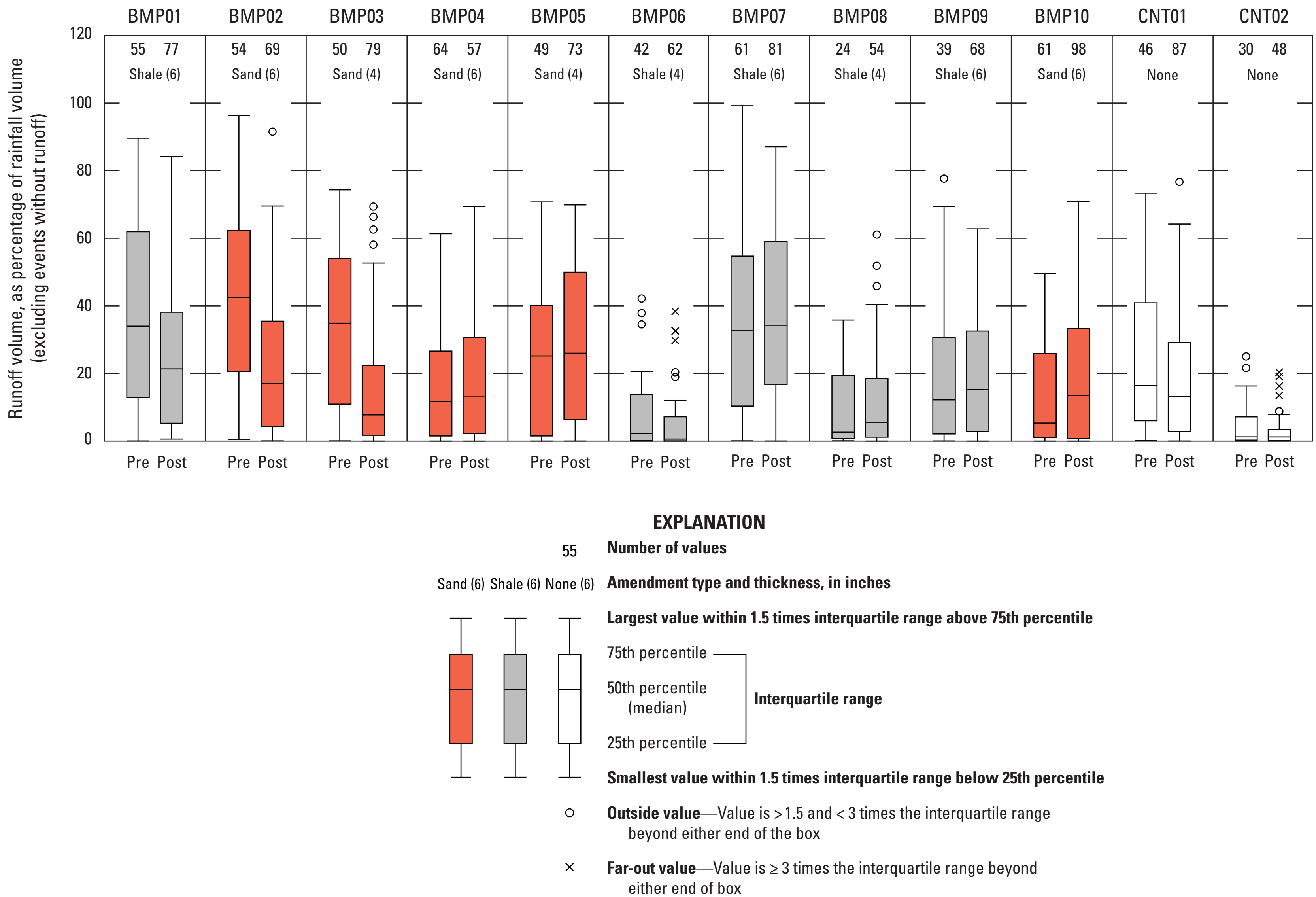

Figure 7. Boxplots showing site-specific distributions of runoff volume as a percentage of rainfall volume during periods before ("Pre") and after ("Post") soil amendments were installed, excluding events with zero runoff (color coding has been applied to boxes as an aid to help visually group results for sites with the same amendment type). >, greater than; <, less than; ≥, greater than or equal to.

Table 7. *D* statistic and *p*-values for Kolmogorov-Smirnov tests of differences in the empirical distribution functions of pre-best management practices versus post-best management practices event runoff percentages (event runoff volumes expressed as percentages of rainfall volumes) and event rainfall totals.

[Event begins with the first tip of the rain gage and ends when rainfall and runoff (if any) cease and remain ceased for at least 3 hours. Runoff percentage is the total volume of runoff during an event expressed as a percentage of the total volume of rainfall falling over the catchment, assuming a spatially uniform distribution of rainfall. Bolded values indicate statistically significant differences at a 5-percent level. EDF, empirical distribution function; BMP, best management practices; <, less than; CNT, control]

Site	Amendment, compost plus	Amendment thickness (inches)	*D* statistic (*p*-value) for Kolmogorov-Smirnov test of differences in EDFs of		
			Runoff percentage between pre-BMP and post-BMP periods, including events without runoff	Runoff percentage between pre-BMP and post-BMP periods, excluding events without runoff	Event rainfall totals between pre-BMP and post-BMP periods
BMP01	Shale	6	0.132 (0.054)	**0.299 (0.006)**	0.121 (0.144)
BMP02	Sand	6	**0.156 (0.016)**	**0.395 (<0.001)**	0.084 (0.532)
BMP03	Sand	4	**0.200 (0.001)**	**0.448 (<0.001)**	0.067 (0.747)
BMP04	Sand	6	**0.111 (0.047)**	0.103 (0.857)	0.040 (0.980)
BMP05	Sand	4	0.115 (0.114)	0.210 (0.120)	0.106 (0.265)
BMP06	Shale	4	0.040 (0.688)	0.189 (0.279)	0.083 (0.345)
BMP07	Shale	6	0.078 (0.529)	0.118 (0.655)	0.122 (0.162)
BMP08	Shale	4	0.080 (0.143)	0.185 (0.559)	0.060 (0.813)
BMP09	Shale	6	0.043 (0.823)	0.091 (0.971)	0.067 (0.715)
BMP10	Sand	6	0.109 (0.192)	0.153 (0.300)	0.070 (0.718)
CNT01	None	0	0.064 (0.570)	0.205 (0.136)	0.106 (0.241)
CNT02	None	0	0.048 (0.458)	0.204 (0.357)	0.100 (0.200)

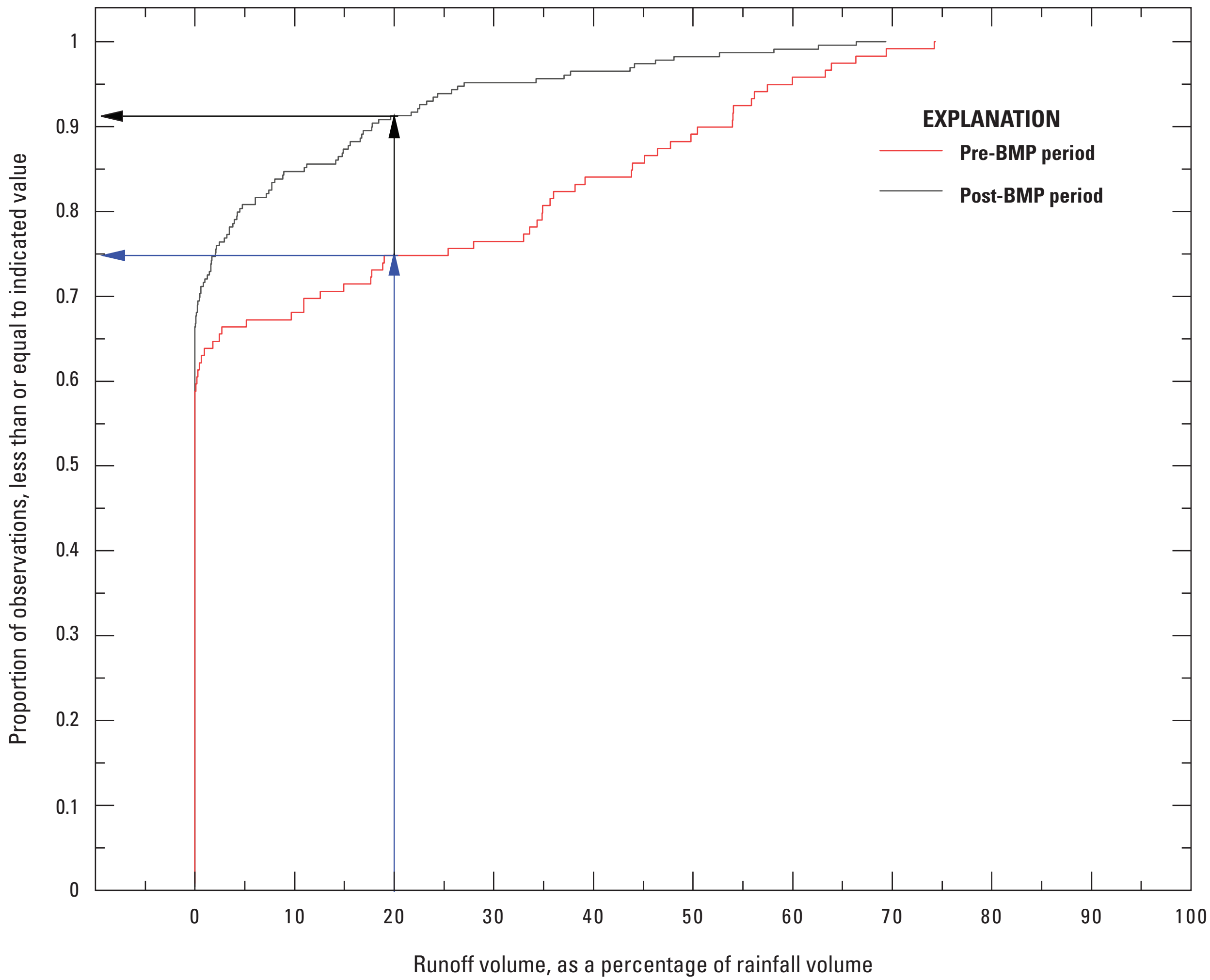

Figure 8. Graph showing empirical distribution function plots of runoff volume as a percentage of rainfall volume at site BMP03 for the periods before ("Pre") and after ("Post") soil amendments were installed. (BMP, best management practices).

post-BMP period than in the pre-BMP period (table 5). Site BMP01 had a shale amendment, whereas sites BMP02 and BMP03 had sand amendments. The EDFs of the other six sites with soil amendments (BMP05–BMP10) and the control sites (CNT01–CNT02) did not differ enough between the pre-BMP and post-BMP periods (with or without inclusion of events without runoff) to be considered statistically different.

The reason that the assessment of statistical significance of differences in the EDFs for sites BMP01 and BMP04 differed depending on whether events without runoff were included was in part a function of the proportion of events that had runoff. The proportion of events with runoff did not decrease much (about −3.1 percent) from the pre-BMP to post-BMP period at site BMP01; however, there was a relatively large decrease (about −10.1 percent) in the post-BMP period at site BMP04. It is worth noting that the percentage of the total number of events that had runoff decreased from the pre-BMP to post-BMP periods at only four sites: BMP01, BMP03, BMP04, and CNT02. The largest decreases, −10.1 percent and −7.5 percent, happened at sites BMP04 and BMP03, respectively (table 3).

Pre-BMP to Post-BMP Changes in the Distribution of Event Rainfall Totals

As discussed earlier, the EDF tests on event runoff percentage indicated statistically significant differences from the pre-BMP to post-BMP periods at only four sites; however, the reason for those differences remains uncertain. One possibility is that the changes in the EDFs may have resulted from changes in rainfall characteristics between those two periods. To test that hypothesis, the same EDF tests applied to event runoff percentages were applied to the rainfall totals associated with each event. Those tests did not indicate statistically significant differences between the pre-BMP and post-BMP periods in the EDFs of event rainfall totals for any of the sites (table 7). Although not definitive, these tests suggest that the BMP-period differences identified in the EDFs of event runoff percentage likely are not the result of changes in the distribution of rainfall totals.

Double-Mass Analysis of Cumulative Runoff for Paired BMP and Control Sites

The most direct comparisons of pre-BMP runoff to post-BMP runoff can be made for the two locations where runoff was measured in the adjacent catchments where soil amendments were installed in one catchment and the other catchment (the control) was left unmodified. The site designated BMP02 (that received the sand and compost amendment at a thickness of 6 inches) was paired with the control site designated CNT01, and the site designated BMP06 (that received the shale and compost amendment at a thickness of 4 inches) was paired with the control site designated CNT02. Double-mass plots, showing the cumulative runoff over time at paired sites, were prepared for both sets of collocated sites (fig. 9). If the relation between rainfall and runoff remained unchanged at both sites from the pre-BMP to post-BMP period, then the points will plot along a straight line because their catchments are expected to experience approximately the same rainfall. A change in the slope of the curve would indicate a change in the rainfall-runoff relation at one or both of the sites. If the soil amendment reduced runoff, the slope of the points associated with the post-BMP period is expected to be flatter than those associated with the pre-BMP period. Power losses that caused short periods of missing record caused some small jogs in the double-mass plots; consequently, lines were drawn manually through the points in figure 9 to avoid the effect that those power-loss periods would have on a regression-based fit to the points.

The slope of the post-BMP line in the plot for sites BMP02 and CNT01 is very slightly flatter than the slope of the pre-BMP line (fig. 9). The slopes of the pre-BMP and post-BMP lines in the plot for sites BMP06 and CNT02 appear to be nearly equal. This suggests that site BMP02, which received the sand and compost amendment, likely had a small reduction in runoff in the post-BMP period, whereas there was no perceptible reduction in runoff at site BMP06, which received the shale and compost amendment.

Factors Related to Event Runoff Percentage and their Relative Importance

Multiple linear regression (MLR) analysis was used to identify factors that explain significant parts of the variability in event runoff percentage for post-BMP period rainfall events that resulted in runoff. The MLR analysis was done twice: once excluding the control sites and once including the control sites. When the control sites were excluded, the following factors were found to be statistically significant (α=0.05):

1. event rainfall total, in inches;
2. total rainfall for the preceding 7 days, in inches;
3. cross-product term including the rainfall total, in inches, and the total rainfall for the preceding 7 days, in inches;
4. soil amendment type (sand or shale);
5. amendment thickness, in inches (4 or 6 inches);
6. drainage area, in acres;
7. main-channel slope, foot per foot;
8. percentage of the drainage area that is paved; and
9. intercept term.

Note that statistical significance of an explanatory factor does not necessarily indicate direct causation.

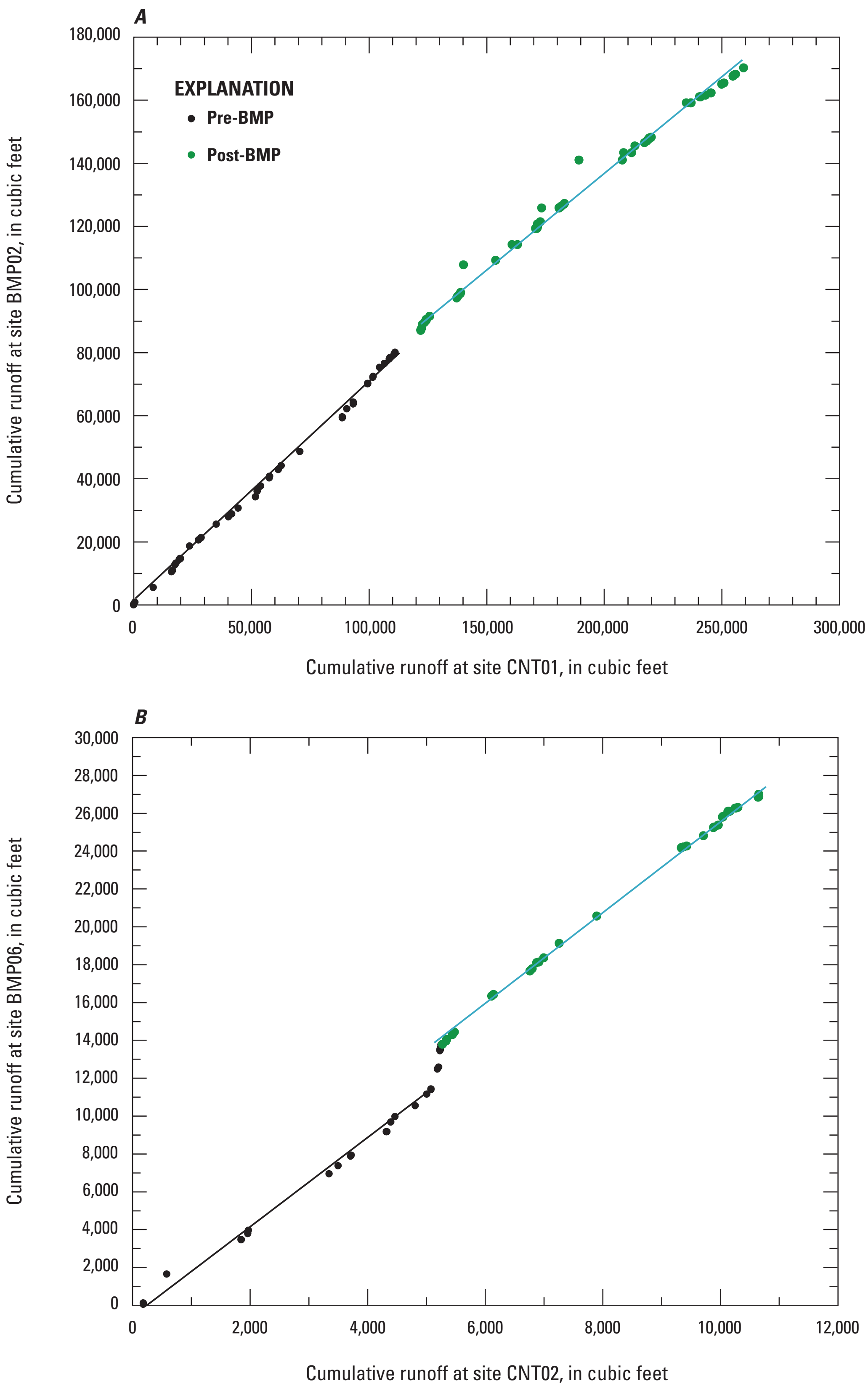

Figure 9. Double-mass plots showing relations between cumulative runoff at *A*, sites BMP02 and CNT01 and *B*, sites BMP06 and CNT02 during the pre-BMP and post-BMP periods. BMP, best-management practice.

Table 8. Scaled parameter estimates for multiple linear regression model with event runoff percentage (runoff volume as a percentage of rainfall volume) as the dependent variable, excluding events occurring before soil amendments were installed, events without runoff, and control sites.

[Bolded values indicate statistical significance at a 5-percent level. Regression results had an adjusted coefficient of determination (R^2) of 0.56 based on 681 observations. <, less than; BMP, best management practices]

Factor	Scaled parameter estimate	Standard error	*p*-value
Event rainfall total, in inches	0.5333	0.0202	**<0.0001**
Cross-product term including the rainfall total, in inches and the total rainfall for the previous 7 days, in inches	0.2914	0.0698	**<0.0001**
Intercept	0.2102	0.0056	**<0.0001**
Total rainfall for the previous 7 days, in inches	0.1593	0.0166	**<0.0001**
Drainage area, in acres	0.0696	0.0098	**<0.0001**
Percentage of the drainage area that is paved	0.0505	0.0092	**<0.0001**
Amendment thickness, in inches	0.0347	0.0066	**<0.0001**
Main-channel slope, in feet per foot	0.0273	0.0081	**0.0008**
BMP [Sand]	0.0192	0.0061	**0.0016**
BMP [Shale]	−0.0192	0.0061	**0.0016**

The cross-product term was used to account for the interaction between rainfall amount and the antecedent rainfall. This term helps account for the different runoff response that is expected when rainfall comes after a wet versus dry antecedent period. Antecedent rainfall totals for the preceding 24 and 48 hours were tested as alternatives to the 7-day antecedent rainfall totals, but the 7-day totals appeared to better explain the variability in the runoff response. Similarly, the 1-, 10-, and 30-minute maximum rainfall totals were tested as alternatives to the event rainfall totals; however, they were ultimately omitted because they were less effective than the rainfall total in explaining the variability of the runoff response.

Scaled parameter estimates were computed to illustrate the relative magnitude of the effects of each of the factors (table 8) on runoff percentages. All factors except amendment type were scaled by subtracting their means and dividing by one-half of their ranges. Without scaling, the magnitude of the parameter estimate depends in part on the factor's measurement units, making it more difficult to evaluate the relative importance of factors with different units. With scaling, the magnitudes of the parameter estimates are proportional to the relative effects of the corresponding factors on the response variable. The rainfall factors (factors 1–3 listed earlier) and the intercept term were the top four most important factors for explaining event runoff percentages. Notably, soil amendment type was the least important factor. This analysis indicates that event runoff percentages increased as a function of the rainfall factors, main-channel slope, drainage area, and percentage of the drainage area that is paved. The analysis also indicates that event runoff percentages increased with amendment thickness (a result that seems counterintuitive). Finally, accounting for all other factors, event runoff percentages tended to be lower for sites with shale amendments than sites with sand amendments.

Results from the MLR analysis that excluded control sites were similar to the MLR analyses that included control sites (table 9). The rainfall factors were again three of the top four most important factors for explaining event runoff percentages, and the intercept term was the fourth. The relative effect of soil amendment type continued to be small in comparison to the rainfall and intercept terms. The amendment thickness factor was excluded in the analysis that included control sites because amendment thickness was a perfect indicator of control sites (all control sites were assigned a thickness of 0) and so was highly correlated with soil amendment type. The *p*-value of the main-channel slope factor (*p*-value =0.0503) slightly exceeded the chosen α value (0.05) and so no longer met the criterion for statistical significance. Again, accounting for all the other factors in the MLR analysis, event runoff percentages tended to be lower for sites with shale amendments than sites with sand amendments; however, event runoff percentages tended to be even lower for control sites than for sites with shale or sand amendments. That counterintuitive result likely reflects that event runoff percentages tended to be lower at control sites (particularly at CNT02) than BMP sites even before soil amendments were installed (fig. 10).

Depending on the nature of the dataset, MLR may not be the best analytical tool when the dependent variable is truncated (as is the case with event runoff percentage, which has a lower bound of zero and an upper bound of 100). Consequently, a Tobit regression analysis was done to verify

Table 9. Scaled parameter estimates for multiple linear regression model with event runoff percentage (runoff volume as a percentage of rainfall volume) as the dependent variable, excluding events before soil amendments were installed, events without runoff, but including control sites.

[Bolded values indicate statistical significance at a 5-percent level. Regression results had an adjusted coefficient of determination (R^2) of 0.54 based on 810 observations. <, less than; BMP, best management practices]

Factor	Scaled parameter estimate	Standard error	*p*-value
Event rainfall total, in inches	0.5002	0.0184	**<0.0001**
Cross-product term including the rainfall total, in inches and the total rainfall for the previous 7 days, in inches	0.2223	0.0615	**0.0003**
Intercept	0.1688	0.0057	**<0.0001**
Total rainfall for the previous 7 days, in inches	0.1431	0.0149	**<0.0001**
Drainage area, in acres	0.1126	0.0090	**<0.0001**
BMP [Sand]	0.0709	0.0079	**<0.0001**
Percentage of the drainage area that is paved	0.0517	0.0096	**<0.0001**
BMP [Shale]	0.0435	0.0078	**<0.0001**
Main-channel slope, in feet per foot	0.0173	0.0088	0.0503
BMP [None]	−0.1144	0.0104	**<0.0001**

the MLR results using the qualitative and limited dependent variable model procedure in SAS (SAS Institute Inc., 2018). Tobit regression is widely used when the observed range of the dependent variable is truncated or censored in some way.

The same dependent and explanatory variables that were used in the MLR analyses were used in the Tobit regression. A truncated regression was done (with lower bound for truncation set to zero) using only data from the 681 post-BMP events that had runoff. The Tobit regression results (not shown) indicated that, except for main-channel slope, the explanatory variables listed in table 8 had statistically significant parameter estimates at a 5-percent level. The Tobit regression results also corroborated the MLR results that (a) rainfall factors and the intercept term were most important in explaining the variation in event runoff percentages, (b) the relative effect of soil amendment type was small in comparison to the rainfall and the intercept terms, (c) event runoff percentages tended to be lower for sites with shale amendments than for sites with sand amendments, and (d) event runoff percentages increased with increasing amendment thickness.

Conclusions

The EDFs of event runoff percentages at only four sites (BMP01–BMP04) changed enough from the pre-BMP to post-BMP period to be considered statistically different. The catchments for three of those sites (BMP02–BMP04) received sand amendments (two with 6-inch thickness and one with a 4-inch thickness). The catchment for the fourth site (BMP01) received a shale amendment with a 6-inch thickness. EDFs of event rainfall totals showed no statistically significant changes from the pre-BMP to post-BMP period, so changes in event rainfall totals do not appear to be a likely cause for the changes in event runoff percentages.

There were appreciable differences that existed in runoff characteristics between sites even before soil amendments were installed. Attempts were made to account for a variety of physical and climatic factors that could have caused those differences; however, even after doing so, there appears to be one or more site-specific unmeasured factors that affected runoff characteristics during the pre-BMP and post-BMP periods. Those unmeasured factor/factors, in part, confound the ability to aggregate results by BMP treatment. A few sites (such as BMP02 and BMP03, both with sand amendments) exhibited relatively large decreases in the mean event runoff percentage from the pre-BMP to post-BMP period, although other sites with sand amendments (BMP04 and BMP05) did not. These disparate results make it more difficult to attribute any changes in event runoff percentage to the BMP treatment in aggregate. Still, three out of the four BMP sites with statistically significant changes between the pre-BMP and post-BMP periods in EDFs of event runoff percentage had catchments where sand amendments were installed (constituting 60 percent of the sites with sand amendments). Although not definitive, the conclusion that the sand amendment was generally more effective at reducing runoff than the shale amendment is supported by EDF test results and the facts:

1. mean runoff percentages for all events (including those without runoff) decreased from the pre-BMP to post-BMP period in those same three BMP sites with sand-amended catchments,

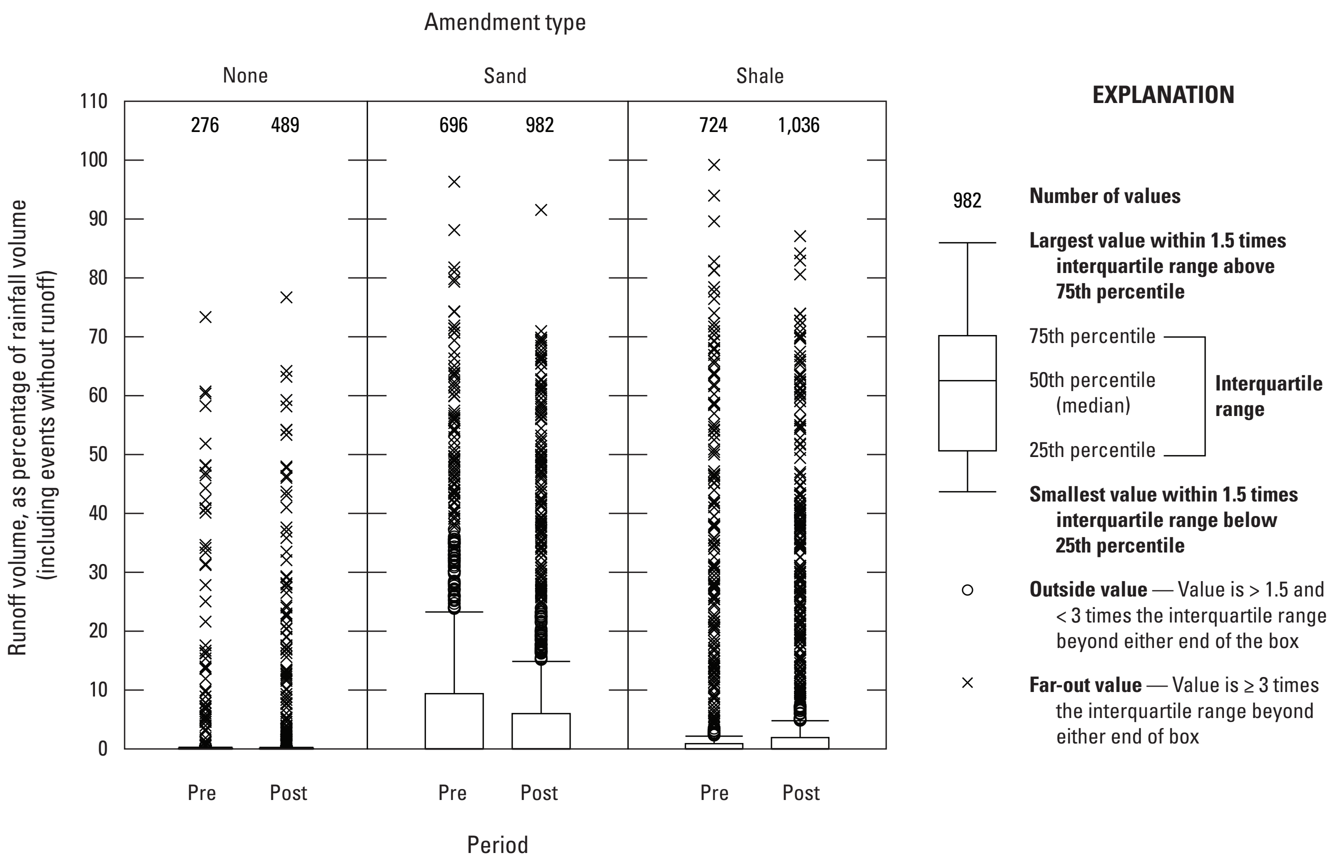

Figure 10. Boxplots showing the distribution of runoff volumes as percentages of rainfall volumes as a function of amendment type during periods before ("Pre") and after ("Post") soil amendments were installed. >, greater than; <, less than; ≥, greater than or equal to.

2. two of those three sites exhibited the two largest decreases in mean event runoff percentages out of all sites (when including all events), and
3. double-mass analyses of cumulative runoff from paired BMP and control sites indicated some post-BMP reduction in runoff at site BMP02 whose catchment received the sand amendment but not at site BMP06 whose catchment received the shale amendment.

Summary

Rainfall and runoff were measured at 10 sites (designated BMP01–BMP10) that are draining small catchments on Ohio Department of Transportation highway median strips located in north-central and northeast, Ohio, where stormwater best management practices (BMPs) were eventually installed. The BMPs comprised removing the top layer of the existing soil, rototilling the remaining soil to a 6-inch depth, mixing the soils with one of two soil amendments (compost with sand or compost with shale) at one of two thicknesses (4 inches or 6 inches), topping with a compost blanket, seeding, and installing erosion control matting. Rainfall and runoff were also measured at two control (CNT) sites (designated CNT01 and CNT02), which did not receive soil amendments. The control sites were located adjacent to BMP sites in the same median strip.

The study site locations were instrumented with rain gages for measuring rainfall and H-flumes for measuring runoff in March of 2018, and then data were collected from these instrumented sites until December of 2018. Data collection restarted in March of 2019, and the soil amendments were installed beginning April 1 through May 20, 2019. Data were collected during periods when air temperatures were above freezing (including all months except January, February, and parts of December and March) through September 2020. The data were divided into two periods: the period before the soil amendments were installed (the pre-BMP period) and the period after the soil amendments were installed (the post-BMP period). The post-BMP period for the control sites was designated to begin with the first event after the sites were restarted in 2019.

A rainfall-runoff "event" was defined to begin at the time of the first measured rainfall and end when rainfall and runoff (if any) ceased and remained ceased for at least 3 hours. The distribution of rainfall amounts associated with events was similar between the pre-BMP and post-BMP periods. About 34 percent of the pre-BMP events at BMP sites had measurable runoff, whereas only about 28 percent of the events at control sites had measurable runoff during the same period. About 37 percent of the post-BMP events at BMP sites had measurable runoff, and about 28 percent of the post-BMP events at control sites had measurable runoff. In aggregate, the percentage of events with runoff increased slightly from the pre-BMP to post-BMP period at BMP sites and remained about the same at control sites.

A value referred to as "event runoff percentage" was computed for each event. Event runoff percentage was defined as the total volume of runoff during an event expressed as a percentage of the total volume of rainfall falling over the catchment, assuming a spatially uniform distribution of rainfall. There were appreciable differences between sites in the distribution of event runoff percentages during the pre-BMP and post-BMP periods. The distributional differences in event runoff percentages were not as distinct when looking only at events that had runoff; however, it was obvious that the pre-BMP and post-BMP medians and interquartile ranges of event runoff percentages were much smaller at some sites than at others, including sites with the same BMP treatment.

Empirical distribution function (EDF) tests were done to determine whether there was statistically significant indication that the distribution of event runoff percentage at a given site changed from the pre-BMP period to the post-BMP period. The EDF tests were done for each site two ways. The first way included all events (including those without runoff), and the second way included only those events with runoff. When all events were included, the null hypothesis of equal distributions was rejected for sites BMP02, BMP03, and BMP04 (all sites with sand amendments). The analyses indicated that proportionally more events had lower runoff percentages during the post-BMP period than during the pre-BMP period at sites BMP02–BMP04. When only events with runoff were included in the EDF tests, the null hypothesis was rejected for sites BMP01–BMP03 (one site with a shale amendment and two sites with sand amendments). The EDFs of event runoff percentage for the other six BMP sites and the control sites did not differ sufficiently between the pre-BMP and post-BMP period (with or without inclusion of events without runoff) to be considered statistically different.

Additional EDF tests performed to determine whether there were changes in distributions of event rainfall totals between the pre-BMP and post-BMP periods did not indicate statistically significant differences for any of the sites. Those results suggested that the BMP-period differences identified in the EDFs of event runoff percentage likely are not the result of changes in the distribution of rainfall totals.

Double-mass plots of cumulative runoff were prepared for the collocated sites BMP02 and CNT01 and sites BMP06 and CNT02. Comparison of the slopes of lines fit to the pre-BMP and post-BMP period values suggest that the site BMP02, which received the sand and compost amendment, likely had a small reduction in runoff in the post-BMP period, whereas there was no perceptible reduction in runoff at site BMP06, which received the shale and compost amendment.

Multiple linear regression (MLR) analysis was used to identify factors that explain statistically significant parts of the variability in event runoff percentage for post-BMP period rainfall events that resulted in runoff. The MLR analysis was done twice: once excluding the control sites and once including the control sites. Nine factors were identified as being statistically significant at a 5-percent level in the analysis that excluded control sites. Scaled parameter estimates were computed to illustrate the relative magnitude of the effects of each of the factors on event runoff percentages. Rainfall factors (event rainfall totals, total rainfall for the previous 7 days, and a cross product of the factors) and the intercept term were the top four most important factors for explaining the runoff response. Notably, soil amendment type was the least important factor. Similar results were found in the MLR analyses that included control sites. Event runoff percentages still tended to be lower for sites with shale amendments than sites with sand amendments; however, this analysis also indicated that event runoff percentages tended to be even lower for control sites than for sites with shale or sand amendments. That counterintuitive result likely reflects that event runoff percentages tended to be lower at control sites than BMP sites even before soil amendments were installed.

A truncated Tobit regression analysis was done to verify the MLR results using only data from post-BMP events with runoff. The Tobit regression results indicated that, except for one factor (main-channel slope), all the explanatory variables used in the MLR analysis of events with runoff had statistically significant parameter estimates at a 5-percent level. The Tobit regression results also corroborated the MLR results that specified that (a) rainfall factors and the intercept term were most important in explaining event runoff percentages, (b) the relative effect of soil amendment type was small in comparison to the rainfall and the intercept terms, (c) event runoff percentages tended to be lower for sites with shale amendments than sites with sand amendments, and (d) event runoff percentages increased with increasing amendment thickness.

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