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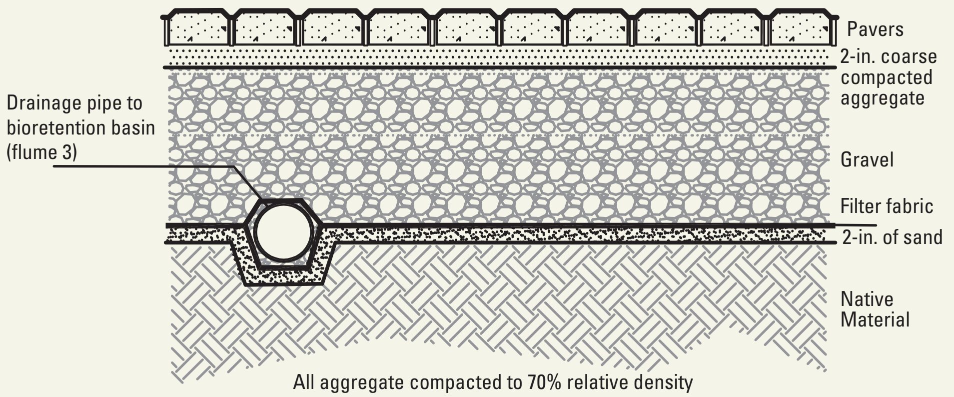
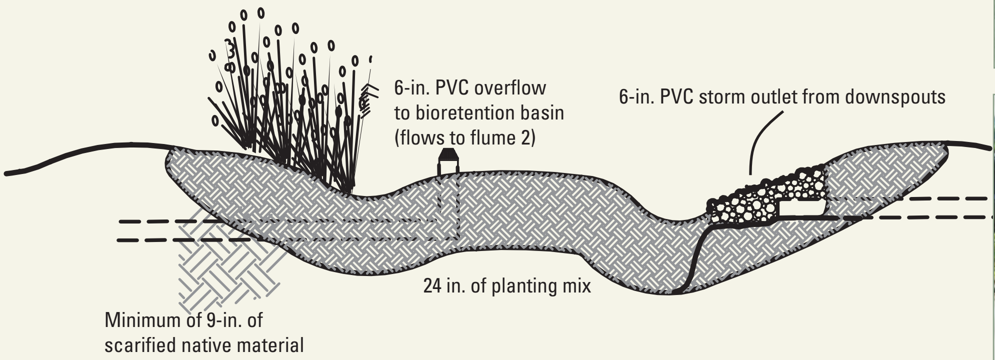
In cooperation with the Chagrin River Watershed Partners

Hydraulic Characteristics of Low-Impact Development Practices in Northeastern Ohio, 2008–2010





Scientific Investigations Report 2011–5165

U.S. Department of the Interior
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Cover drawing. Construction detail of paver parking lot and rain garden for Washington Street site, Geauga County, Ohio. (Modified from engineer drawings provided by Cawrse and Associates, Inc.)

Inset photo, top. One of the rain gardens along Sterncrest Drive site, Cuyahoga County, Ohio, showing monitoring equipment, drainage grate, and plant growth from October 2008.

Inset photo, center. Flume 2 at Washington Street site, Geauga County, Ohio. measuring any overflow from the rain garden.

Inset photo, bottom. Washington Street rain garden showing weather station and plant growth, August 2008. (Photograph by Cawrse and Associates, Inc., employees.)

Hydraulic Characteristics of Low-Impact Development Practices in Northeastern Ohio, 2008–2010

By Robert A. Darner and Denise H. Dumouchelle

In cooperation with the Chagrin River Watershed Partners

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

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U.S. Geological Survey, Reston, Virginia: 2011

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter (cm)
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	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)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$°F=(1.8\times°C)+32$

Hydraulic Characteristics of Low-Impact Development Practices in Northeastern Ohio, 2008–2010

By Robert A. Darner and Denise H. Dumouchelle

Abstract

Low-impact development (LID) is an approach to managing stormwater as near to its source as possible; this is accomplished by minimizing impervious surfaces and promoting more natural infiltration and evapotranspiration than is typically associated with developed areas. Two newly constructed LID sites in northeastern Ohio were studied to document their hydraulic characteristics.

A roadside best-management practice (BMP) was constructed by replacing about 1,400 linear feet of existing ditches with a bioswale/rain garden BMP consisting of a grassed swale interspersed with rain-garden/overflow structures. The site was monitored in 2008, 2009, and 2010. Although some overflows occurred, numerous precipitation events exceeding the 0.75-inch design storm did not result in overflows.

A second study site consists of an 8,200-square-foot parking lot made of a pervious pavers and a rain garden that receives runoff from the roof of a nearby commercial building. A comparison of data from 2009 and 2010 indicates that the median runoff volume in 2010 decreased relative to 2009. The centroid lag times (time difference between centroid of precipitation and centroid of flow) decreased in 2010, most likely due to more intense, shorter duration precipitation events and maturation of the rain garden. Additional data could help quantify the relation between meteorological variables and BMP efficiency.

Introduction

The Chagrin River watershed, which covers parts of Cuyahoga, Geauga, Lake, and Portage Counties in northeastern Ohio (fig. 1), is increasingly affected by impervious surfaces and stormwater runoff related to urban and suburban development. Geauga County, for example, comprises 54 percent of the watershed area and is northeast Ohio's second-fastest growing county in terms of population increase (Geauga County Planning Commission, 2005). Increasing amounts of impervious area can result in increased stormwater runoff and erosion, which deliver sediment and other pollutants to the Chagrin River and its tributaries. Some of these stormwater runoff impacts may be mitigated through planning and low-impact construction designs.

Low-impact development (LID) is a best-management practice (BMP) approach to managing stormwater as near to its source as possible; this is accomplished by minimizing impervious surfaces and promoting more natural infiltration and evapotranspiration than is typically associated with developed areas. A variety of BMPs can be incorporated into LID sites, such as rain gardens, bioretention features, and pervious pavements. Documenting the performance of the various practices, both in terms of water quantity and quality, is a significant facet in evaluating the impact of LID on stormwater runoff. LID performance metrics can include reductions in runoff volumes and (or) increases in infiltration or evaporation rates. The Chagrin River Watershed Partners, Inc. (CRWP), received a grant from the U.S. Environmental Protection Agency to help implement and monitor BMPs used at two LID study sites as a means to promote distributed stormwater management. The U.S. Geological Survey (USGS), in cooperation with the CRWP, installed monitoring equipment and collected hydrologic data at these two sites in the Chagrin River watershed where LID techniques were implemented. The results of the USGS study will be used in conjunction with water-quality data collected by the CRWP to better define the performance of bioswale, pervious-paver, and rain-garden stormwater BMPs. Installation of BMPs within each LID study site was completed by partnering landowners or community governments, in cooperation with the CRWP.

Purpose and Scope

The purpose of this report is to describe the BMPs installed at two LID sites in the Chagrin River watershed in northeastern Ohio and present hydrologic data gathered to help characterize their performance. Precipitation and runoff data for the Sterncrest Drive site were collected from April through October in 2008, 2009 and 2010; data for the Washington Street site were collected from April through October in 2009 and 2010.

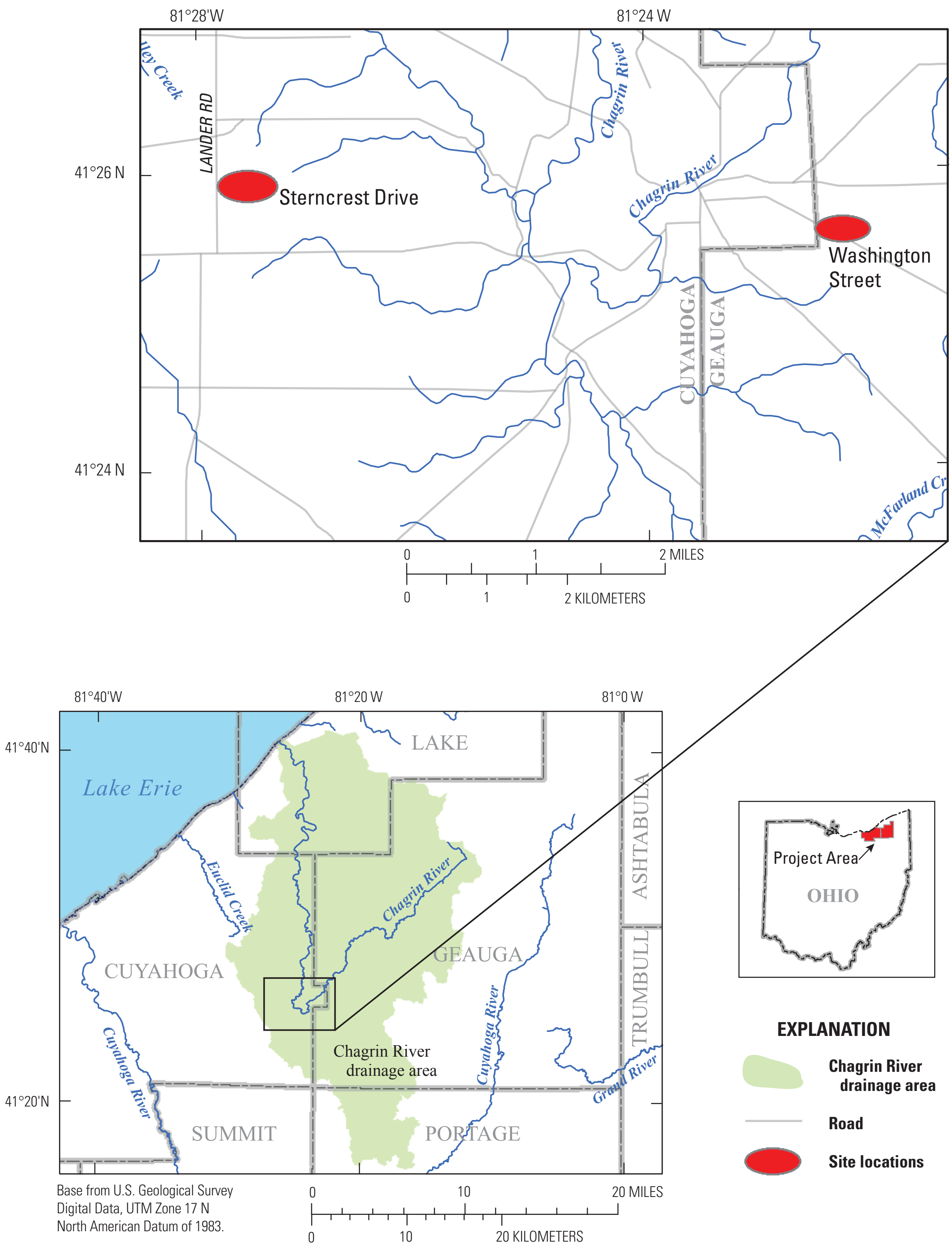


Figure 1. Location of the study area

Description of the Study Area

Located east of the Cleveland metroplex, the Chagrin River watershed drains 265 mi^2 of gently rolling hills in northeastern Ohio. The two study sites are near the Chagrin River crossing from Geauga into Cuyahoga County. The Sterncrest Drive site is in Cuyahoga County, near the western boundary of the watershed. The Washington Street site is in Geauga County, in the upper reaches of the watershed (fig. 1). The area has a humid, temperate climate with a 29-year average annual precipitation of between 38 and 47 in., 62 percent of which falls from April through October (Midwest Regional Climate Center, 2010). Land use is highly variable and includes urban, suburban, rural-residential, forested, and agricultural uses. Glacial sediments ranging from a few feet to around 100 ft in thickness overlie sandstone and shale bedrock. Most soils in the watershed are formed in the clay-rich glacial till; their permeability generally is low to very low, and they may need to be drained for development (Musgrave and Holloran, 1980; Williams and McCleary, 1982).

Hydrologic Characteristics at the Sterncrest Drive Site

The soil at the Sterncrest Drive site is a Wadsworth silt loam, described as “somewhat poorly drained” with moderately low to very low permeability. The water table is near land surface, particularly in the winter and spring or during unusually wet periods, so the soil has little capacity to store infiltrated water. In the area near the intersection of Sterncrest Drive and Lander Road, there has been a history of yard and road flooding during periods of moderate precipitation. In an effort to alleviate flooding, bioswales were installed along Sterncrest Drive, with construction ending in November 2007.

Site Description

About 1,400 linear feet of existing ditches along Sterncrest Drive were replaced with a bioswale/rain garden BMP consisting of a grassed swale interspersed with rain-garden/overflow structures. The bioswale receives stormwater runoff predominantly from the adjacent roadway and overland runoff from the single-family residential area. The road is not curb-and-gutter construction, so water flows from the paved surface into the swale.

The existing ditches were excavated to a depth of approximately 5 ft, after which an 8-in. perforated drain pipe was installed in the north bioswale and a 15-in. perforated drain was installed in the south bioswale. The ditches were backfilled with permeable sediments—engineered soil media that consisted of 70 percent sand and 30 percent peat/leaf compost—to create the bioswales. The 15-in. perforated drain pipe runs the length of the bioswale on the south side of the road, and nonperforated storm drain pipe crosses from the north drain pipe to the south drain pipe at the each of the paired rain gardens. There are nine rain gardens in all, five to the north and four to the south of Sterncrest Drive (fig. 2). Flow in the perforated drain north of Sterncrest Rd enters one of five rain gardens before passing to the drain to the south, where four additional rain gardens have been constructed. Each rain garden covers an oval area of about 95 ft^2 (20 ft by 6 ft), and the surface is planted with perennials and is mulched. In the center of each rain garden is a 2-ft-square elevated grate to allow water that ponds sufficiently, but that does not infiltrate through the rain garden, to overflow into to the storm-sewer. The top of the grate is approximately 6 in. higher than the surrounding land surface of the rain garden (fig. 3). One drawback to this design is that the drains discharge to the village’s stormwater drains at Lander Road (fig. 2) and, therefore, are subject to backwater if the storm drains reach capacity or become plugged.

The construction details of the bioswale are shown in figure 4. One important difference between the bioswale and the rain gardens is the type of vegetation used for cover. The bioswale is only 1.5 ft wide and covered with turf grass, whereas the rain gardens are 6 ft wide, planted with perennials, and mulched with double-shredded wood mulch (figs. 2 and 3).

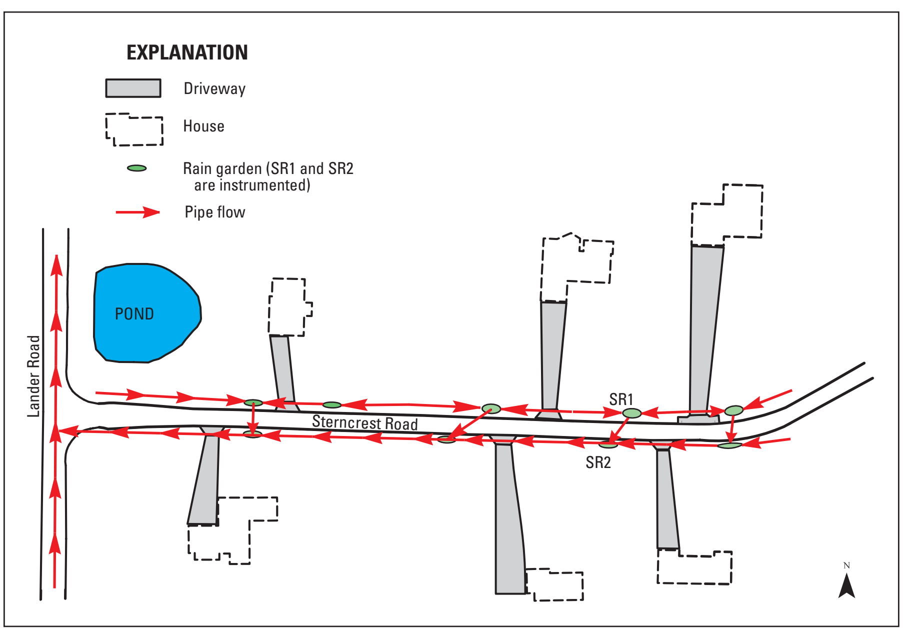
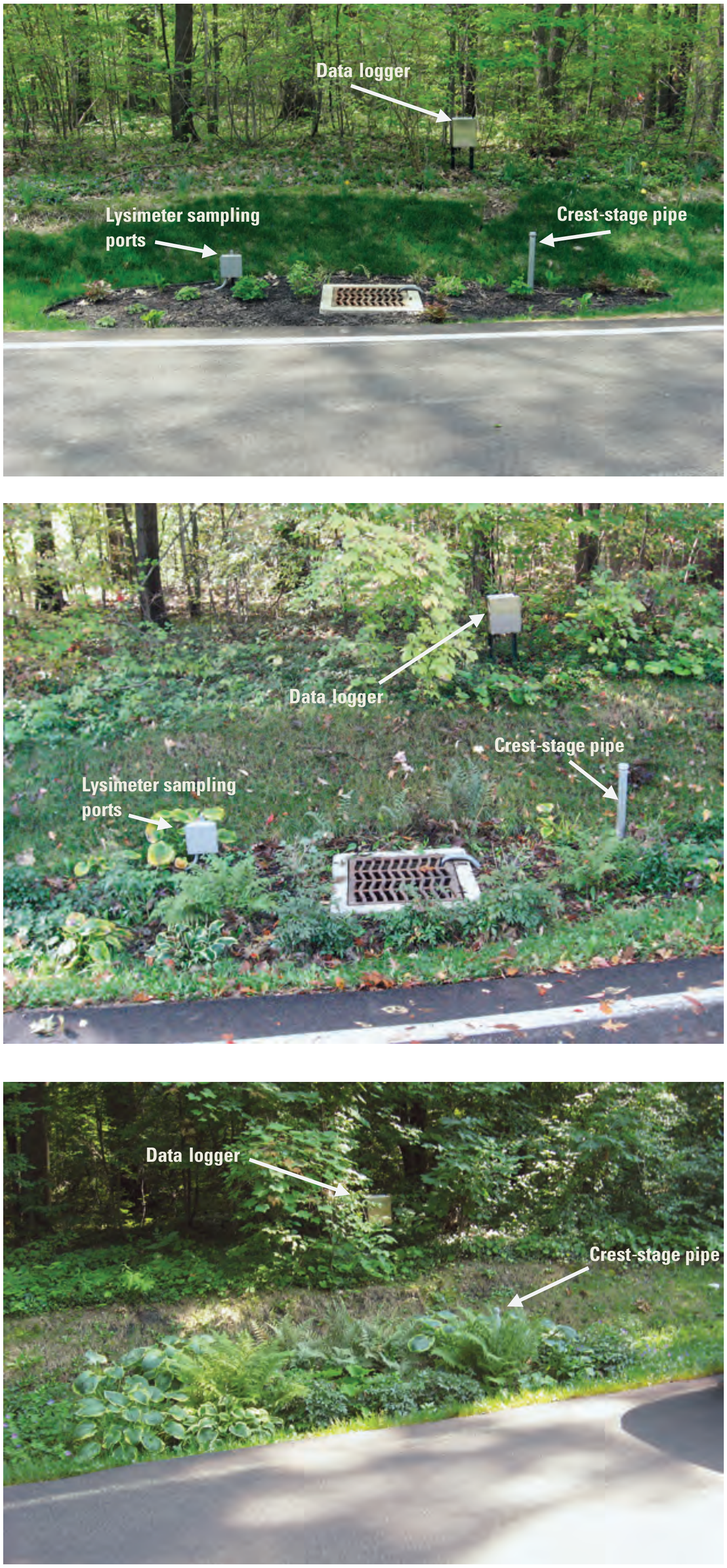


Figure 2. Site plan for stormwater best-management practice along Sterncrest Drive site, Cuyahoga County, Ohio.



A May 7, 2008

B October 9, 2008

C July 14, 2010
Lysameter sampling port obscured by plant growth

Figure 3. Photographs of one of the rain gardens along Sterncrest Drive site, Cuyahoga County, Ohio, showing monitoring equipment, drainage grate, and plant growth from May 2008 to July 2010.

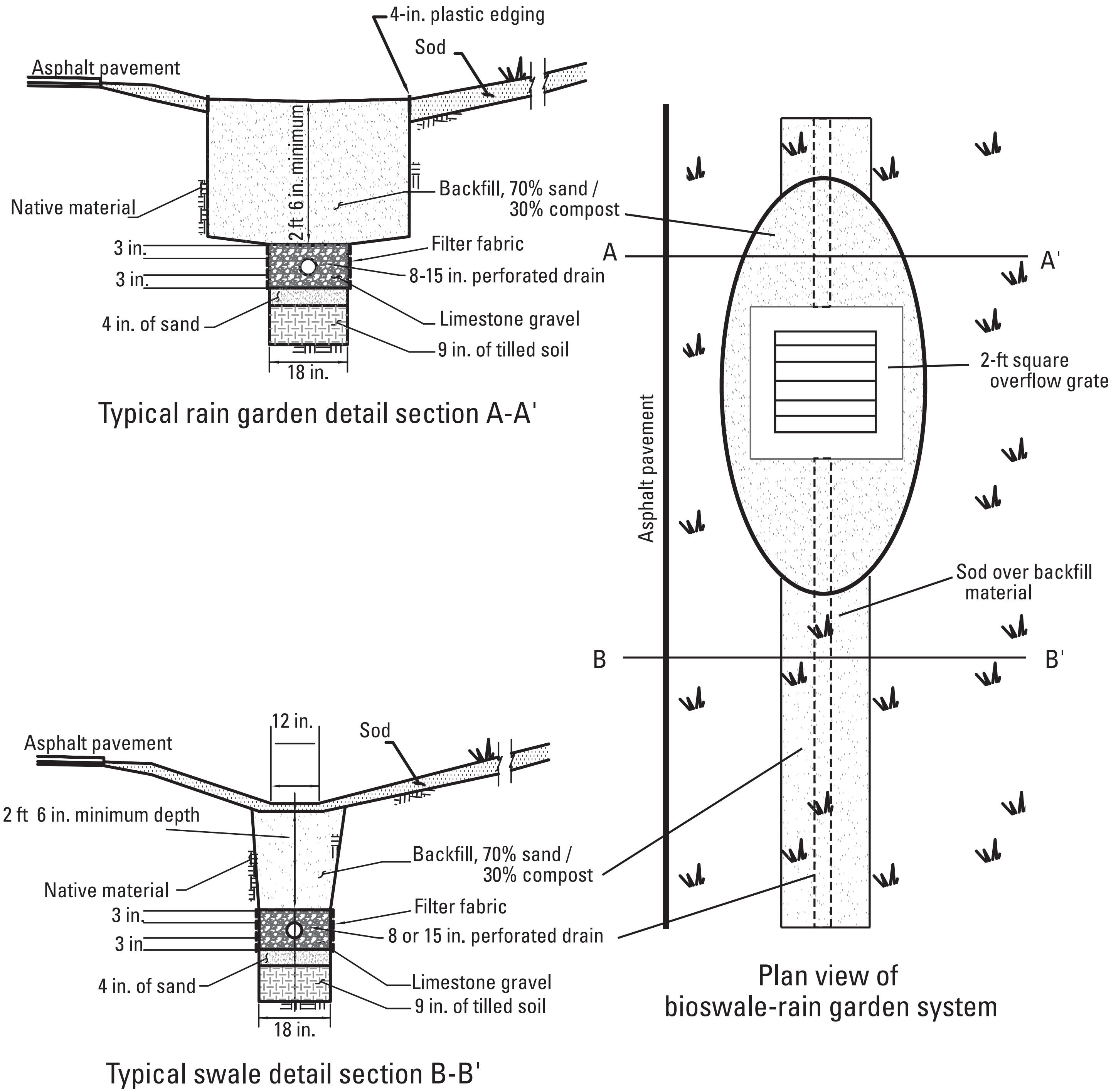


Figure 4. Construction detail for bioswale and rain gardens along Sterncrest Drive site, Cuyahoga County, Ohio (modified from engineer drawings provided by Orange Village, Ohio).

Methods

An unheated tipping-bucket rain gage and an air-temperature sensor were installed behind Orange Village Hall, approximately 1,400 ft west-northwest of the site. The rain gage registers precipitation in 0.01-in. increments that are summed by a data logger over intervals of 10 minutes. Precipitation depths and peak intensities for 10-, 30-, 60-, 120-, and 1,440-minute intervals were determined. Recurrence intervals of precipitation at the site were estimated by using precipitation-frequency tables compiled by the National Oceanic and Atmospheric Administration (Bonnin and others, 2004).

The overflow grates on two rain gardens, one north (SR1) and one south (SR2) of Sterncrest Drive (fig. 2), were instrumented with sensors that measured specific conductance and temperature. These sensors were used to determine the occurrence and duration of overflows; however, without additional instrumentation, the volume of the overflows could not be computed. The sensors were connected to a data logger adjacent to the rain garden. The data logger queried the sensor every minute and recorded the measurement if there was a change since the last measurement. Data also were recorded every 6 hours to ensure that the data logger was operational during periods when sensor readings were unchanging.

The maximum water levels in the SR1 and SR2 rain gardens were recorded with a crest-stage gage—a simple instrument that records only the highest water elevation, or stage, reached between routine maintenance visits when the gage is reset. The datum of the crest-stage gages and the elevations of the low points on the overflow grates (points of no overflow) were determined by means of differential leveling relative to common local reference points. The crest-stage reading was compared to the elevation of the overflow grate to verify that overflow did, or did not, occur as indicated by the sensor measurements. In no case was an overflow event indicated by a crest-stage gage without an overflow event also being indicated by a sensor reading. It cannot be said with certainty whether the reverse was true because more than one overflow event may have occurred between inspections of the crest-stage gage.

Data Analysis and Description

The following analysis pertains to the time periods April 3, 2008, to October 31, 2008; and March 1 to October 31 in 2009 and 2010. The design storm for the site is 0.75 in. of precipitation, but the associated duration was not specified; therefore, an analysis was done to determine the amount of time over which 0.75 in. of precipitation would not cause an overflow event. The weather-station data were used to determine how many times the total amount of precipitation in 24-, 48-, 72-, and 96-hour time periods exceeded the 0.75-in. design storm (table 1).

Table 1. Precipitation events that exceed 0.75 inch and rain-garden overflow events, April–October, 2008–2010, Sterncrest Drive site, Cuyahoga County, Ohio.

Total time prior to overflow (hours)	Number of storms >0.75 inch	Overflow events SR1	Overflow events SR2
24	35	9	4
48	38	12	5
72	39	14	5
96	47	14	5

There were 15 overflows at the SR1 rain garden, 14 of which occurred when the total precipitation exceeded 0.75 in. sometime in the previous 96 hours (table 2). The only exception was event 6, when the total precipitation was 0.74 in. There were seven overflows at the SR2 rain garden; five of the seven events occurred when the precipitation exceeded 0.75 in. sometime in the previous 96 hours (table 2). The only exceptions are two unexplained events (17 and 18, table 2) that occurred about 6 hours apart on April 25, 2010.

Most of the overflow events were the result of precipitation less than a 1-year recurrence interval (tables 2 and 3). Exceptions are events 2, 5, 16 and 20. Event 2 at SR1 received 0.81 in. of precipitation in a 10-minute period, exceeding the recurrence interval for a 10-year precipitation event. The same storm produced 1.15 in. of precipitation in 1 hour, exceeding the recurrence interval for a 1-year precipitation event. Event 5 at SR1 received 0.64 in. of precipitation in 10-minute period and 1.06 in. in 1 hour, equivalent to 2-year and 1-year precipitation events, respectively. Event 16 at SR2, the site received 1.11 in. in 1 hour, equivalent to a 1-year precipitation event. Event 20 at SR2 received 0.68 in. of rain in a 10-minute period, exceeding the recurrence interval for a 2-year precipitation event (Bonnin and others, 2004).

There is concern that, over time, fine-grained sediments will clog the surface of the bioswale and rain garden, resulting in more overflows (Ontario Ministry of the Environment, 2003). Counting the number of overflow events each year could help indicate whether the bioswale/rain garden BMP performance is changing; however, such an analysis requires that consideration be given to the characteristics of the precipitation events in each year. The average total precipitation depth in 2008 and 2009 was similar; however, average total precipitation depth decreased in 2010, and the events were more intense (fig. 5). Over the 3 years of available data, there appears to be a trend of increasing overflow events (table 4); however, 3 years of data are insufficient for a trend analysis. In 2008 and 2009, a difference in the number of overflows between SR1 and SR2 was documented (table 4). A possible explanation for this is the difference between the 8-in. drain pipe at SR1 and the 15-in. drain pipe at SR2 and (or) the variable precipitation characteristics.

Table 2. Rain garden overflow time, duration, and precipitation-event depths, Sterncrest Drive site, Cuyahoga County, Ohio.

[Red highlight, 10-year precipitation event; green highlight, 2-year precipitation event; yellow highlight, 1-year precipitation event (based on precipitation magnitude and frequency computations by Bonnin and others, 2004)]

Event	Overflow characteristics			Precipitation depth (inches)							
				Maximum in prior 24 hours				Total for time prior to start of overflow (hours)			
	Rain-garden location	Begin date	Duration (minutes)	10-minute	1-hour	3-hour	12-hour	24	48	72	96
1	SR1	5/3/08	149	0.21	0.44	0.49	0.98	1.00	2.00	2.00	2.04
2	SR1	7/8/08	25	0.81	1.15	1.15	1.15	1.15	1.15	1.15	1.15
3	SR1	10/3/08	116	0.04	0.12	0.25	0.26	0.26	0.72	2.49	3.21
4	SR1	7/1/09	219	0.13	0.25	0.30	0.32	0.37	1.18	1.18	1.22
5	SR1	7/17/09	5	0.64	1.06	1.06	1.07	1.07	1.07	1.07	1.07
6	SR1	8/1/09	157	0.12	0.22	0.35	0.59	0.59	0.59	0.74	0.74
7	SR1	8/10/09	66	0.42	0.74	0.74	0.74	0.74	1.03	1.15	1.15
8	SR1	8/29/09	48	0.30	0.88	0.94	1.46	1.89	1.96	1.99	1.99
9	SR1	4/25/10	69	0.23	0.51	0.51	0.53	1.02	1.02	1.02	1.02
10	SR1	5/17/10	49	0.01	0.05	0.09	0.11	0.11	0.11	0.11	1.13
11	SR1	5/31/10	209	0.39	0.78	0.78	0.89	0.89	0.89	0.89	0.89
12	SR1	6/6/10	161	0.48	0.48	0.74	0.77	0.77	0.92	0.92	0.94
13	SR1	6/28/10	124	0.24	0.44	0.44	0.64	1.08	1.08	1.08	1.08
14	SR1	7/14/10	66	0.01	0.01	0.01	0.02	0.02	0.80	0.80	0.80
15	SR1	9/16/10	7	0.46	0.57	0.57	0.86	0.86	0.86	0.86	0.87
16	SR2	8/10/09	15	0.42	1.11	1.11	1.11	1.11	1.39	1.52	1.52
17	SR2	4/25/10	3	0.05	0.17	0.20	0.29	0.29	0.29	0.29	0.29
18	SR2	4/25/10	52	0.05	0.17	0.37	0.51	0.51	0.51	0.51	0.51
19	SR2	4/26/10	8	0.23	0.52	0.55	0.72	0.88	1.23	1.23	1.23
20	SR2	5/14/10	15	0.68	0.70	0.88	0.88	0.94	0.94	1.58	1.58
21	SR2	6/6/10	12	0.48	0.48	0.74	0.77	0.77	0.92	0.92	0.94
22	SR2	7/14/10	4	0.00	0.00	0.00	0.00	0.00	0.79	0.80	0.80

Table 3. Precipitation depths that exceed the 1-, 2-, 5-, and 10-year recurrence intervals for the area including Sterncrest Drive site, Cuyahoga County, Ohio.

[Based on precipitation magnitude and frequency computations by Bonnin and others, 2004]

Recurrence interval (years)	Precipitation depth (inches)				
	10-minute	1-hour	3-hour	12-hour	24-hour
1	0.50	0.99	1.24	1.75	2.04
2	0.60	1.21	1.51	2.10	2.45
5	0.72	1.53	1.92	2.62	3.05
10	0.81	1.77	2.24	3.06	3.54

Table 4. Number of overflow events and precipitation events that exceeded the 0.75-inch design storm at Sterncrest Drive site, Cuyahoga County, Ohio.

Year (Apr.–Oct.)	Overflows, SR1	Overflows, SR2	24-hour precipitation >0.75 inch
2008	3	0	12
2009	5	1	11
2010	7	6	12

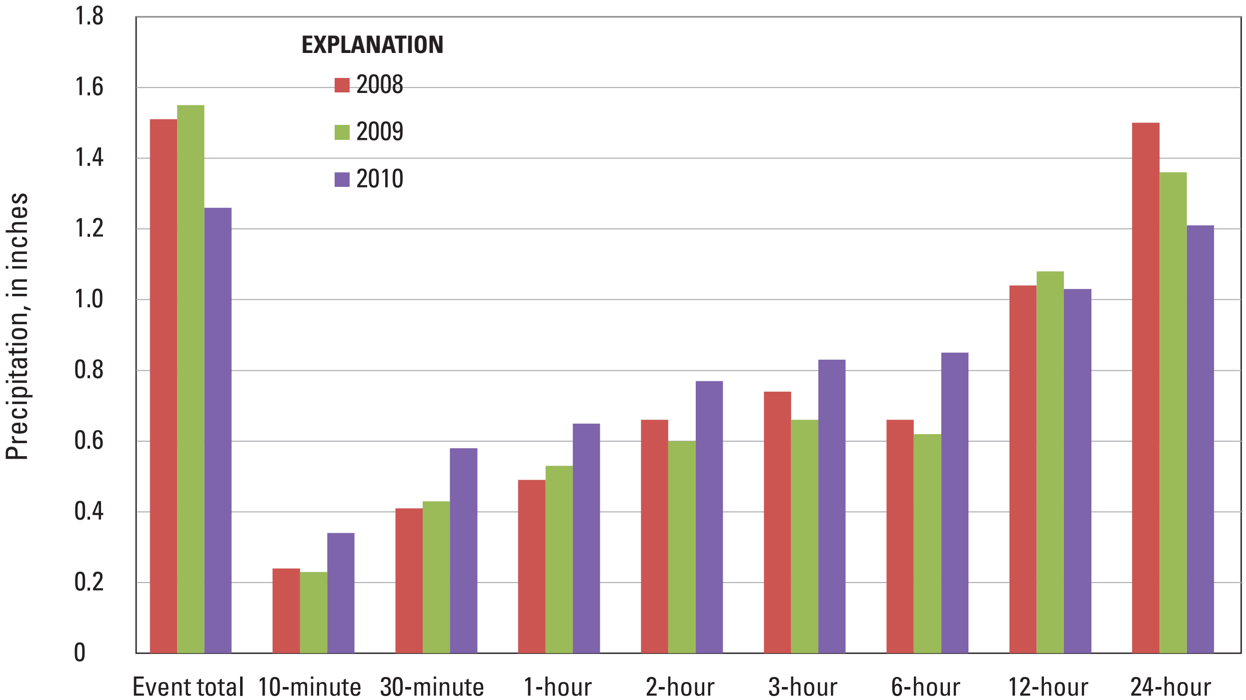


Figure 5. Annual average duration and depths for precipitation events that exceeded the 0.75-inch design storm at Sterncrest Drive site, Cuyahoga County, Ohio.

The current dataset shows the variability in the performance of a newly established rain garden BMP. Sometimes a slow steady rain over a number of days will eventually overwhelm the BMP (overflow event 3). In other situations a short, intense storm will cause an overflow (overflow event 2). Of the 22 total recorded overflow events, 13 occurred when precipitation in the previous 24 hours exceeded the design storm (0.75 in.); 7 other events can be linked to precipitation within the previous 96 hours, and, as mentioned previously, 2 unexplained events at the SR2 site occurred 6 hours apart. The BMP performed better than expected in that there were more precipitation events exceeding the design storm of 0.75 in. without causing overflows than events that caused an overflow. However, the long-term sustainability in performance of the bioswale/rain garden BMP is unclear.

Hydrologic Characteristics at the Washington Street Site

The Washington Street site is a commercial site in west-central Geauga County (fig. 1) near the headwaters to an unnamed tributary to McFarland Creek (tributary to Aurora Branch of the Chagrin River). This was a new commercial construction project in 2008 that followed Leadership in Energy and Environmental Design (LEED) principles to maximize land use in a sustainable manner. The site has pervious pavers, a rain garden, and a bioretention basin to minimize runoff and maintain an aesthetically pleasing look to the site.

Site Description

Stormwater BMPs on the site include a rain garden, an 8,200-ft^2 parking lot made of pervious pavers (with surface and subsurface drains), and a detention basin and vegetated swale (figs. 6 and 7). The rain garden is 400 ft^2 in area (20 ft by 20 ft) (fig. 7) and receives runoff from approximately one-half (3,400 ft^2) of a nearby commercial roof. The rain garden is not isolated from the parking-lot subsurface gravel; therefore, drainage from the gravel may contain a portion of the roof runoff not used or infiltrated in the rain garden. Runoff from the other half of the commercial roof drains to a detention basin via a vegetated swale. The detention basin also receives discharge from the pervious paver subsurface drain, an overflow drain from the rain garden, and any overland runoff from the driveway, parking area, and adjacent properties. Because the detention basin receives water from sources other than the new construction (a preexisting building and some flow from neighboring properties), not all inputs required to determine a water budget could be measured; therefore, data collection and analysis were focused on a water budget for the pervious paver-parking lot and the rain garden.

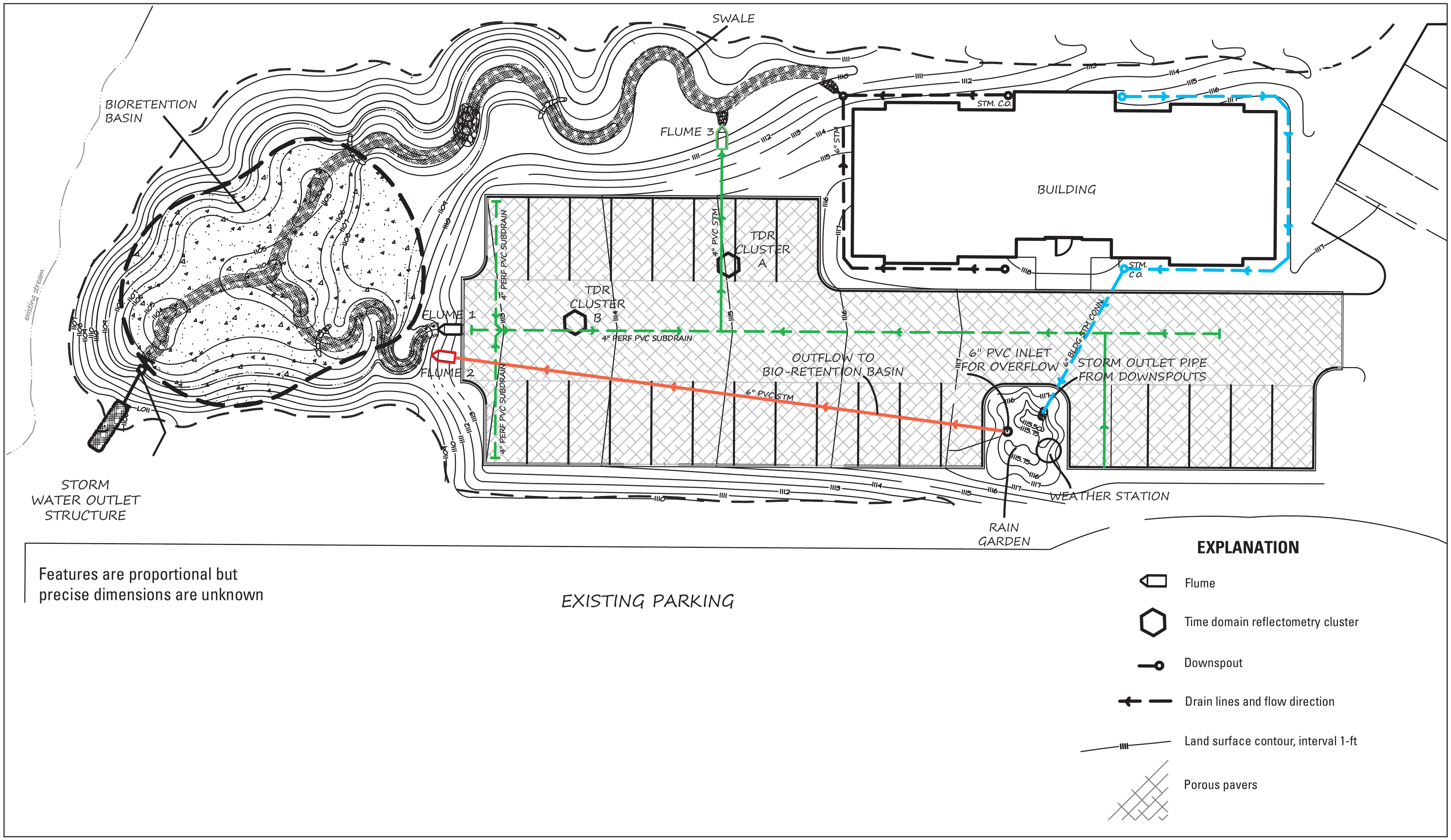


Figure 6. Site plan for stormwater best-management practices at Washington Street site, Geauga County, Ohio (modified from engineer drawings provided by Cawrse and Associates, Inc.).

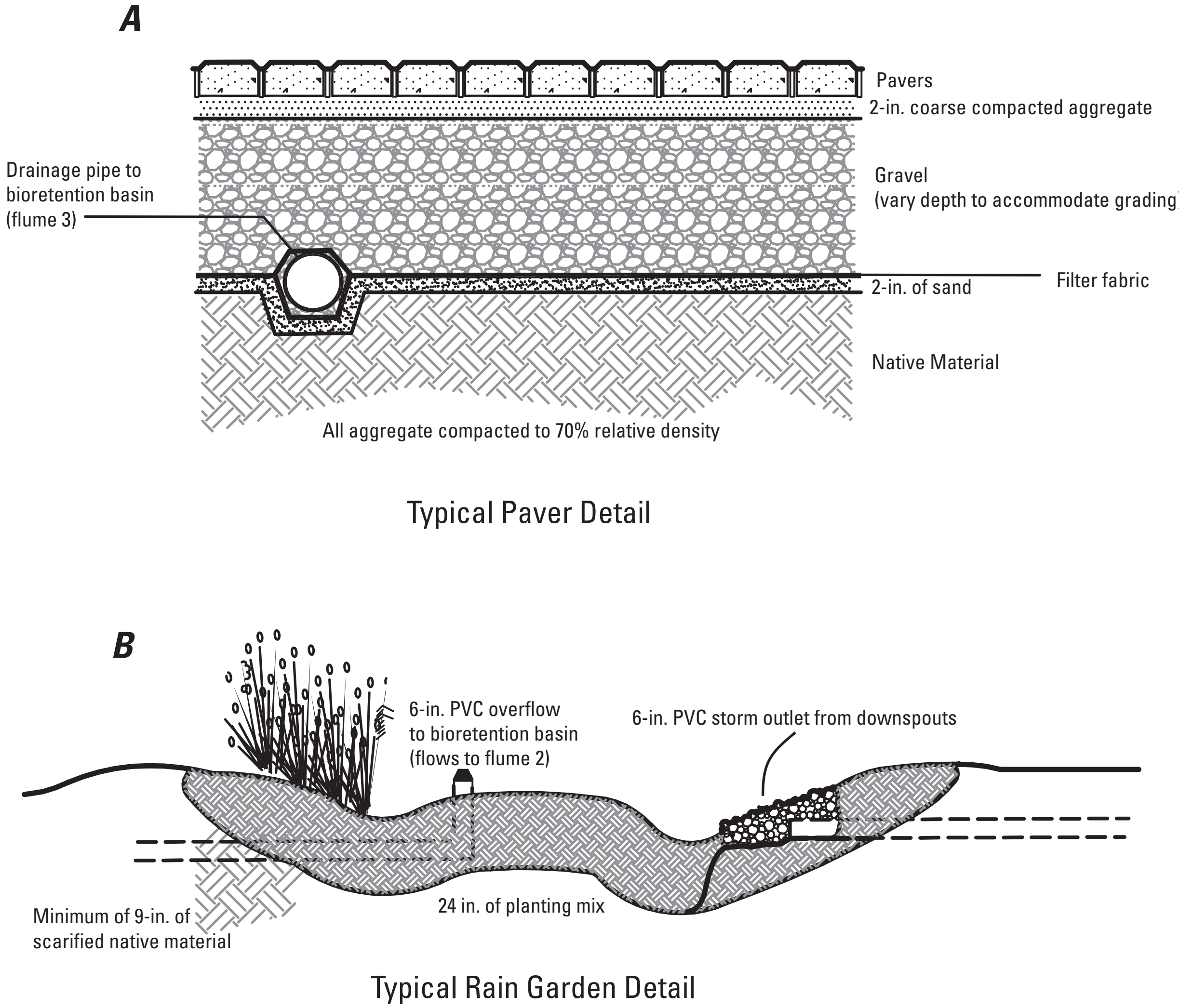


Figure 7. Construction detail for Washington Street site, Geauga County, Ohio. *A*, Paver parking lot. *B*, rain garden. (Modified from engineer drawings provided by Cawrse and Associates, Inc.)

Methods

Discharge from the pervious-paver subsurface drains (flume 3, fig. 6), overland flow from the parking lot (flume 1, fig. 6), and overflow from the rain garden (flume 2, fig 6 and 7) were determined by means of prefabricated H-flumes (fig. 8). Water levels in the flumes were measured in attached external stilling wells by means of pressure transducers connected to data loggers that initiated and stored the water-level readings. Water levels, specific conductance, and temperatures were measured every minute and, at a minimum, recorded every 10 minutes. When the stage exceeded 0.05 ft above no flow, any change in water level of more than 0.01 ft also was recorded. The corresponding specific conductance and water temperature were stored with each coincident water-level reading.

A weather station that included a heated tipping-bucket rain gage and an air-temperature sensor was maintained at the site. The rain gage registered precipitation in 0.01-in. increments, summed by the data logger over intervals of 10 minutes. Precipitation peak depths and the intensities for 10-, 30-, 60-, 120-, and 1,440-minute intervals were determined for each precipitation event and compared to recurrence intervals determined from the tables in Bonnin and others (2004).

During construction of the parking lot, two clusters of three time-domain reflectometer (TDR) sensors were permanently installed in the permeable base under the pavers. The TDRs determines soil moisture content by measuring the permittivity, or dielectric constant, of the soil resulting from changes in soil moisture. Sensors in each cluster were installed at different depths below the ground surface to facilitate

A Flume 1

B Flume 2

C Flume 3

Figure 8. Photographs of the flumes at Washington Street site, Geauga County, Ohio. Flume 1, *A*, measures surface flow over the parking lot; flume 2, *B*, measures any overflow from the rain garden, and flume 3, *C*, measures the flow from the drain line.

analysis of the depth-dependent wetting characteristics of the permeable base material above the subsurface drains. The TDRs were controlled by a data logger that computed and recorded moisture content every 10 minutes.

The precipitation and flume-flow time-series data were analyzed by means of a spreadsheet. Each rainfall-runoff event (hereafter referred to simply as an “event”) was evaluated independently. For an event to be included in this study, it had to meet the following conditions: (1) for onset, a total at least 0.05 in. of rainfall; and (2) for termination, discharge in the flume less than or equal to its pre-precipitation levels.

The beginning and end of the precipitation and runoff (discharge from flumes 2 and 3) were determined by first visually examining the rainfall hyetograph. For this study, the beginning of a precipitation event was defined as the time of the first recorded precipitation pulse (indicating the accumulation of 0.01 in. of rainfall). Values such as centroid lag time, runoff ratio, and other precipitation- and flume-flow characteristics were then calculated within the spreadsheet to further characterize the event.

In order to facilitate the event selection process, certain constraints were placed on the data to ensure more consistent detection of event start and end times. The flume-flow time series was smoothed by use of a moving-average process in which the value assigned to a given point in time was the average of the value observed at that time plus N values occurring immediately before and after the target value (where N is a smoothing factor, chosen by the analyst, based on the amount of “noise” in the time series). To help detect runoff start and end times, averaging windows (short time periods) were used to help prevent noise in the data from triggering false selection of these characteristics. The following definitions describe analyst-selectable parameters used for time-series smoothing; these parameters ensure consistent detection of event-related characteristics:

1. The smoothing factor is the number of data values before and after the given data value that are used to calculate an average value which is then assigned to the position (time) of the given data value. For example, a smoothing factor of 2 would result in the average of five values, two preceding the current value, the current value, and two following the current value. Smoothing the discharge values deemphasizes “noisy” data and allows for more consistent selection of event end points. The smoothed curve is used only for end point selection; all volume and centroid calculations are based on the raw, unsmoothed data.

2. The leading-edge window is the number of values that are evaluated to determine whether there is an upward trend in the data.

3. The percentage of the leading-edge window that needs to be rising indicates the beginning of a runoff event. For example, if the leading-edge window is 10 and the upward trend is set to 80 percent, then the first instance where 8 of 10 data values after the beginning of precipitation are increasing relative to their preceding value would be set as the beginning end point of the event.

4. The analysis window is the total number of values after the start point that will be used to determine the end point. This is used to end the analysis before the beginning of the next precipitation event.

5. The trailing-edge window is the number of preceding values that are averaged to check for the end of the runoff event. If, for example, the trailing edge window is set to 4, then four values preceding the current value are averaged. The first such average occurring after the end of precipitation that is less than or equal to the average discharge from before the event start time triggers the end of the runoff event.

The following example is presented to illustrate the event selection process. In the example precipitation event, 0.86 in. rain fell over 20.5 hours starting on April 3, 2008 (fig. 9). The following values were used to analyze this event:

1. smoothing factor = 8
2. leading-edge window = 5
3. percentage of the leading-edge window = 80 percent
4. analysis window = 1,200
5. trailing-edge window = 4

So, a total of 17 values (8 + 1 + 8) were averaged to smooth the discharge curve. The beginning of the runoff event occurs when 80 percent of five smoothed values are determined to be increasing relative to their immediately preceding values. The average of four raw discharge values prior to the beginning is determined. After the precipitation stops, the end of the runoff event is determined to be the time at which the first average of four consecutive raw discharge values is less than or equal to the beginning average. Once the start and end points are determined, the spreadsheet calculates the centroid (center of mass) of the precipitation and runoff, centroid lag times, volumes, precipitation characteristics, timing characteristics, and the runoff ratio.

The runoff ratio is defined as the total volume of runoff divided by the total volume of rain that fell on the roof and parking lot. The runoff ratio characterizes each runoff event with a number between 0 and 1. Runoff events with ratios closer to 0 indicate that more water was abstracted (not available for runoff) through evapotranspiration (ET), infiltration, or other losses than runoff events with ratios closer to 1. For the event described in figure 9, the total volume of precipitation on the parking lot and half the roof was computed to be 834 ft^3, and the volume discharge through the flumes was 478 ft^3. The ratio is 0.57, meaning 57 percent of the precipitation that fell on the site entered the detention basin as runoff.

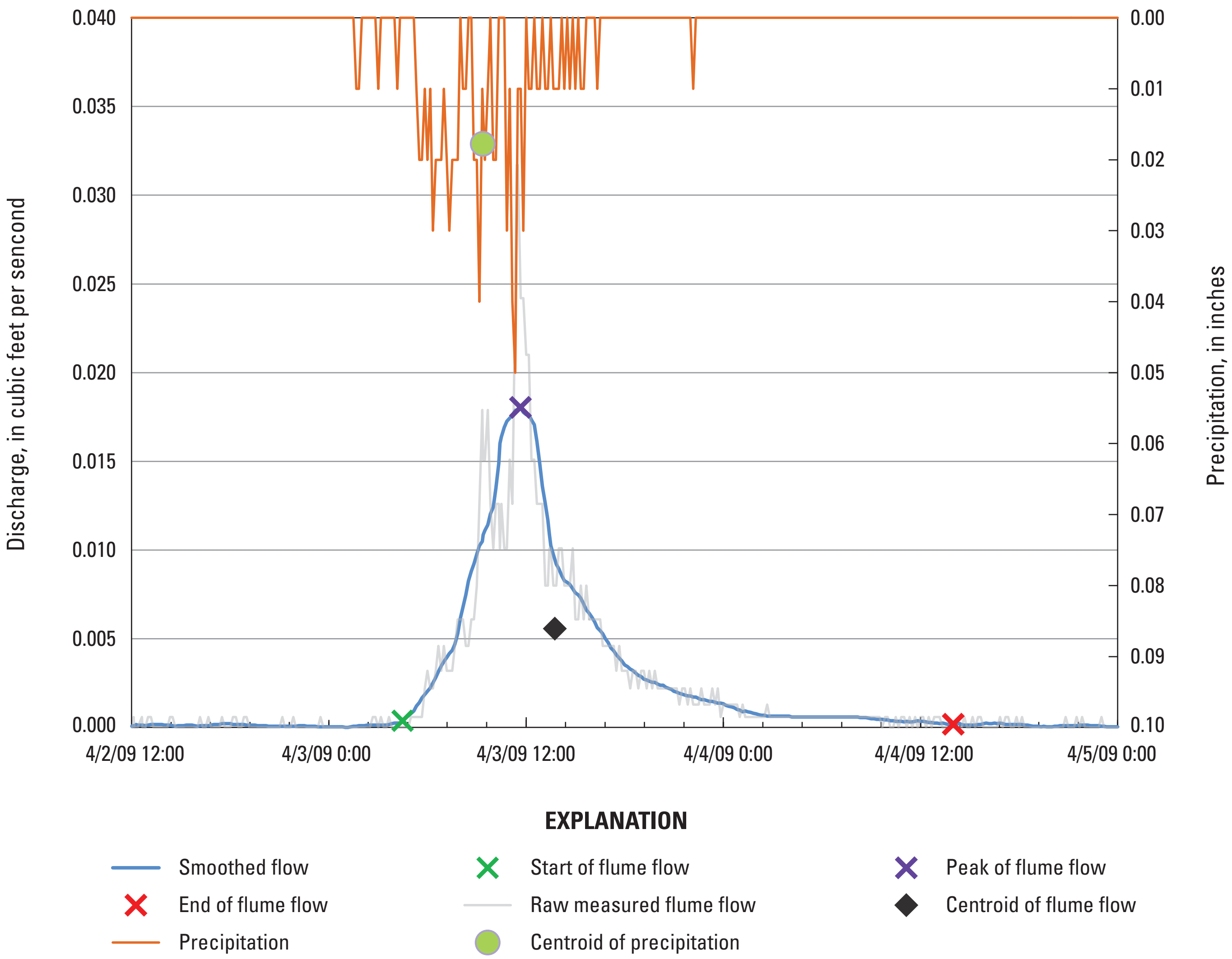


Figure 9. Hydrograph of typical precipitation event at the Washington Street site showing the spreadsheet selections of begin, peak, and end of flow, as well as the centroids of flow and precipitation.

Centroid lag time is the time, in minutes, between the centroid of precipitation and the centroid of the flume flow (runoff). Centroid lag time is a measure of how quickly water moves off or through the impervious surfaces and other drainage routes to the discharge points. For the event described in figure 9, the centroid of the precipitation event was on April 3, 2009, at 09:22, and the centroid of the flume flow was on April 3, 2009, at 13:45, so the centroid lag time was 263 minutes.

Data Analysis and Description

No runoff was recorded in flume 1, which measures surface runoff from the pervious paver parking lot, indicating all precipitation that fell on the parking lot either infiltrated through the void spaces between the pavers or evaporated. Runoff was recorded from flume 2, the rain-garden overflow, on three occasions with the largest volume being on August 10, 2009, when 19.9 ft^3 of water moved through the overflow in 24 minutes. Flume 2 also recorded overflows on May 14 and May 18, 2010; these flows were both smaller than that measured during the August 2009 overflow.

Flume 3 recorded runoff from the pervious paver subsurface drains, which included any roof runoff not infiltrated or removed by ET in the rain garden. The runoff data from flume 2 were included with the data from flume 3 to represent the total runoff from the site.

Only events with complete runoff hydrographs, precipitation, and TDR data were analyzed. A total of 34 out of 42 precipitation events in 2009 and 36 out of 46 precipitation events in 2010 produced sufficient data for analysis. The runoff ratios for 2009 and 2010 (fig. 10) suggest an improvement in the performance of the BMP over time. One explanation may be the maturation of vegetation in the rain garden promoted more rapid infiltration through a denser root mass (Selbig and Balster, 2010). In addition, transpiration in 2010 may have been greater because the plants in the rain garden were more fully established (fig. 12).

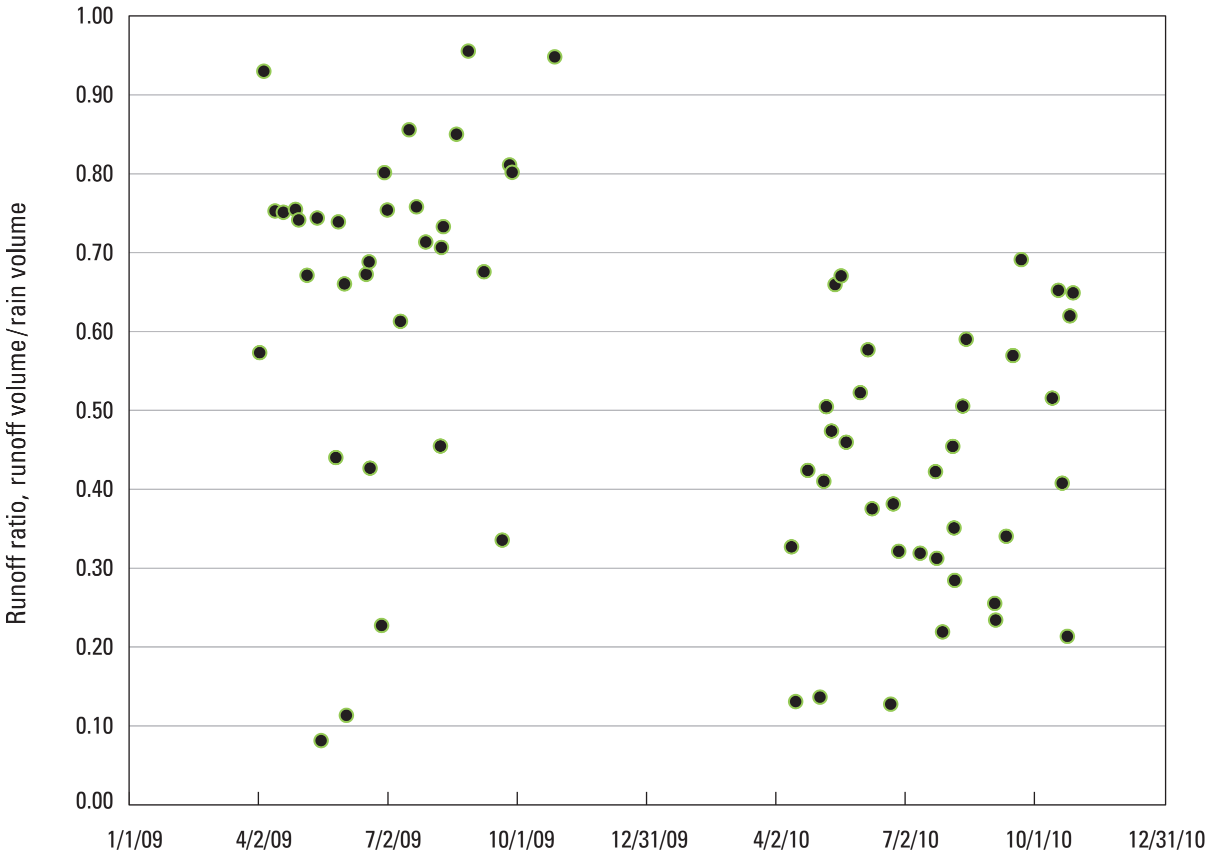


Figure 10. Runoff ratio for the pervious-paver/rain-garden BMP at Washington Street site, Geauga County, Ohio, April through October 2009 and 2010.

The Wilcoxon rank-sum statistic is a nonparametric test to compare two datasets, in this case different event characteristics from 2009 and 2010. Figure 11*A* shows that the runoff ratio decreased from 2009 to 2010 (p-value < 0.01), indicating that more water is being removed in 2010 than in 2009 (presumably through ET or infiltration). Figure 11*D* and *E* show that although precipitation-event depths in 2009 and 2010 were not statistically different, the intensity of the events increased (p-value = 0.02). During the same time, the centroid lag decreased (fig. 11*C*; p-value = 0.03), indicating that the water that moved through the BMP did so faster, possibly in response to the increased intensity (fig. 11*E*) and shorter duration (fig. 11*F*) of the precipitation events. Another possibility could be the development of preferential flow paths beneath the pavers.

Some of the decrease in runoff in 2010 may be attributable to increased evaporation due to higher maximum daily air temperature (fig. 11*B*). The warmer weather could have heated the pavers and base material more in 2010 than in 2009, thereby increasing evaporation. Another possible explanation for the lower runoff ratios in 2010 could be the maturation and increased growth of the plants in the rain garden (fig. 12), with roots penetrating the clay rich substrate and increasing infiltration (Selbig and Balster, 2010).

The TDRs were installed in gravel, which does not make sufficient contact with the sensors to permit an accurate measurement of moisture content. Therefore, soil moisture conditions for each TDR sensor were analyzed relative to each sensor's annual mean value. The depth from top of the pavers to the TDRs are listed in table 5.

Table 5. Depth of time-domain reflectometers at Washington Street site, Geauga County, Ohio.

Location on figure 6	Sensor number	Depth below top of pavers (feet)
Cluster A	1	2.8
Cluster A	2	1.5
Cluster A	3	1.2
Cluster B	4	2.7
Cluster B	5	1.7
Cluster B	6	1.5

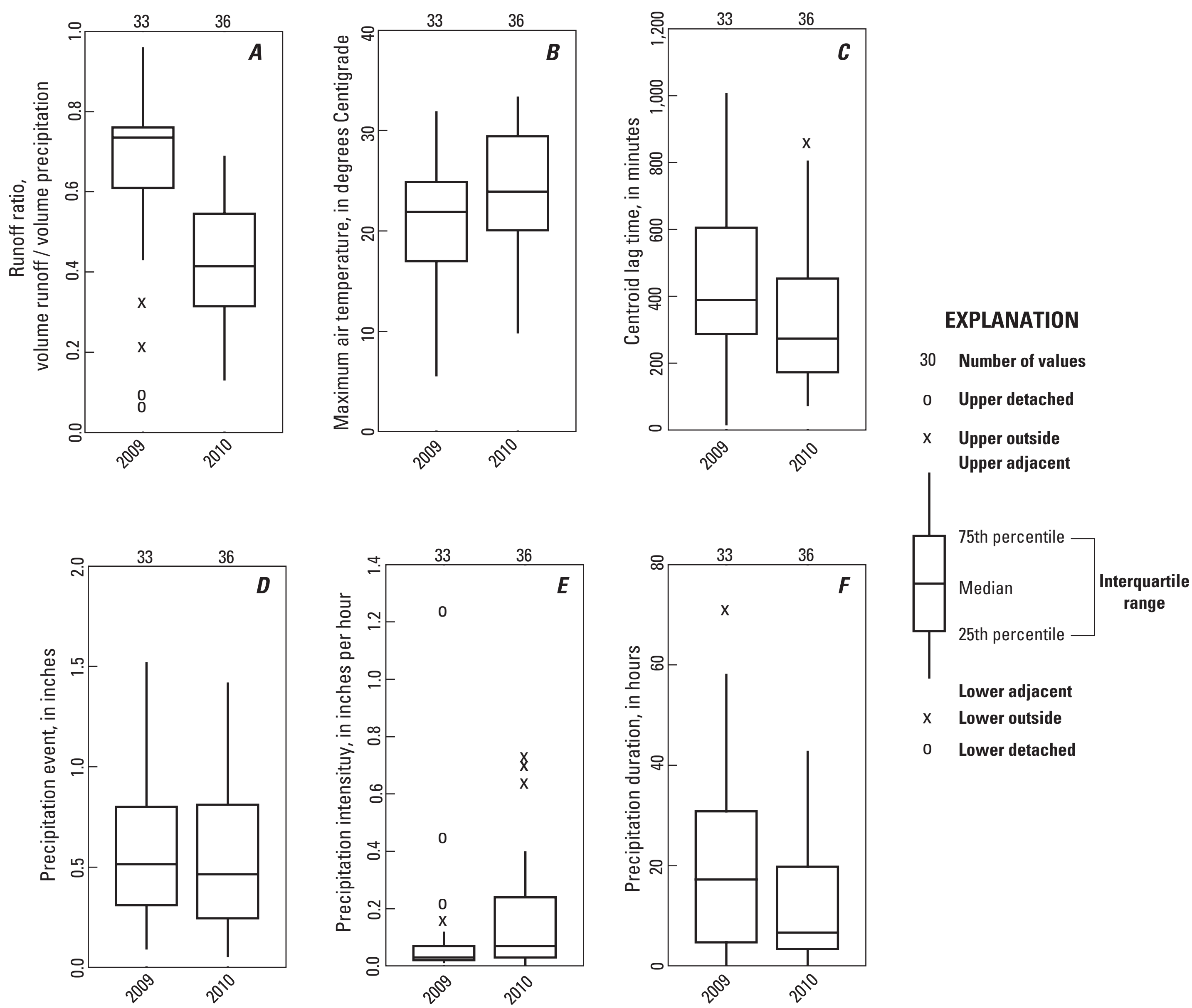


Figure 11. Boxplots of climatological and flow characteristics, Washington Street site, Geauga County, Ohio, 2009 and 2010. *A*, Runoff ratio. *B*, Maximum daily air temperature (degrees Celsius). *C*, Centroid lag. *D*, Precipitation event size. *E*, Precipitation intensity. *F*, Precipitation duration.

A October, 2008

B August, 2008

C August, 2010

Figure 12. Photographs of Washington Street rain garden showing weather station and plant growth from October 2008 to August 2010. (Photographs by Cawrse and Associates, Inc., employees.)

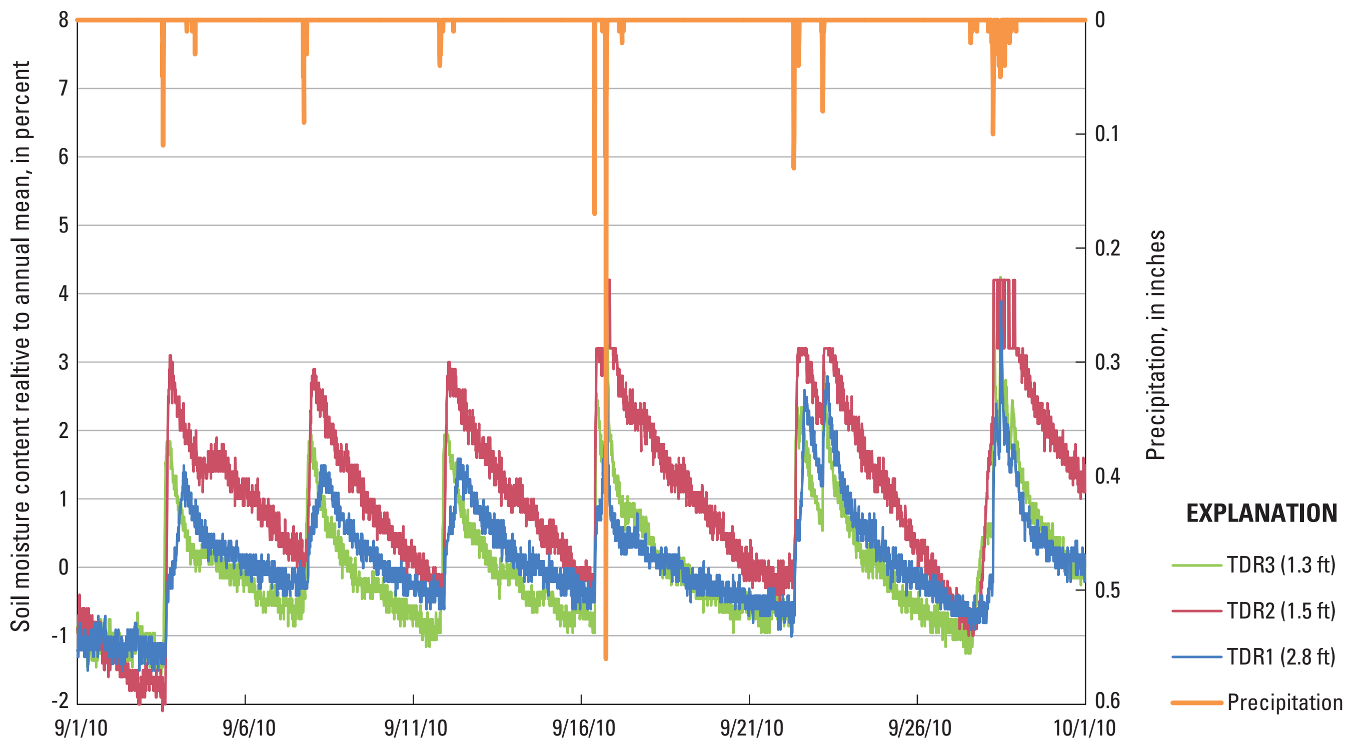


Figure 13. Time-domain reflectometer relative soil moisture for one month, cluster A, Washington Street site, Geauga County, Ohio. The graph shows that the BMP does not have time to return to a steady state before the next precipitation event.

An analysis similar to that done for flume-flow was done for TDRs 1 through 6. Time between the centroid of the precipitation to the centroid of the soil-moisture curve was not used because the soil-moisture curve sometimes did not return to pre-event levels before the next precipitation event (fig. 13). Therefore, in the TDR analysis, the time from initial precipitation to the time the sensor indicates the presence of the wetting front is defined as the SC lag (or in the case of the flume the SC lag is the time from initial precipitation to start of flow).

The SC lag times for the TDRs in 2010 are noticeably shorter than the those in 2009 (fig. 14). Part of this quicker response time could be attributed to the tendency toward more intense precipitation events in 2010 as compared to 2009 (fig.11E) and/or the possible development of preferential flow paths. Preferential flow paths can develop over time as water movement through the BMP forms channels or as desiccation or settling cause fractures. With additional data, provided that the storm intensities and durations are similar to those in 2009 or 2010, it may be possible to determine whether the quicker response is due to the precipitation intensity or the preferential flow paths.

Some additional evidence for the development of preferential flow paths can be seen by comparing the SC lag times in 2009 and 2010 with the runoff. The median SC lag time for runoff is much smaller than for the TDRs (fig. 14); this indicates that some water reaches the subsurface drains before the wetting front reaches the TDRs. This result is unexpected because the drains are deeper than the lowest TDR.

The BMPs at Washington Street were designed to reduce and delay runoff. The 2 years of data show that the median runoff ratio decreased from 2009 to 2010. The centroid lag times decreased in 2010, most likely in response to more intense, shorter duration precipitation events. Additional data could help quantify the relationship between meteorological variables and BMP efficiency.

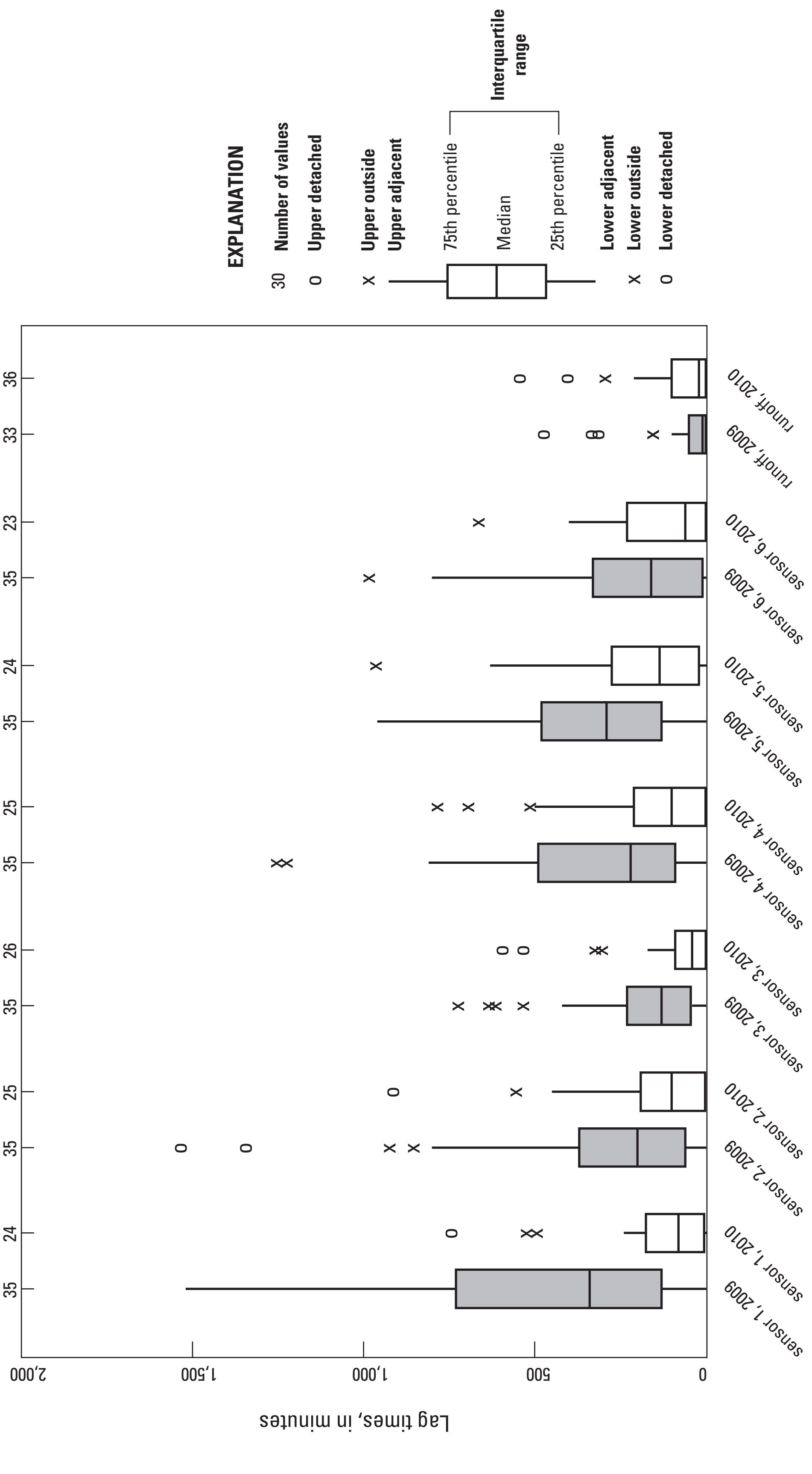


Figure 14. Boxplots of specific-conductance lag times for six soil-moisture sensors and runoff, 2009 and 2010, Washington Street site, Geauga County, Ohio.

Summary and Conclusions

Stormwater BMPs are intended to reduce the impact of additional runoff related to development. Low-impact development is a best-management-practice approach to manage stormwater as near to its source as possible by minimizing impervious surfaces and promoting the natural movement of water. To document the hydraulic characteristics of some of these designs, two newly constructed sites in northeastern Ohio were studied. One site consisted of a roadside rain-garden/bioswale combination to reduce flooding; the other site consisted of a rain-garden/pervious-paver combination to reduce and delay runoff from a newly constructed commercial building and parking lot.

The roadside BMP along Sterncrest Drive involved the replacement of about 1,400 ft of existing ditches with a bioswale consisting of a grassed swale interspersed with rain garden/overflow structures. The site was monitored in 2008, 2009, and 2010. Numerous precipitation events exceeding the 0.75-in. design storm were retained and infiltrated by the swales and rain gardens. The BMP performed better than expected, but the sustainability of the long-term performance is unclear.

The Washington Street site consisted of a rain garden that received runoff from 3,400 ft^2 of commercial roof and an 8,200 ft^2 parking lot made of pervious pavers. Data from 2009 and 2010 have shown a marked improvement in the reduction of runoff in just 1 year. Median runoff volume decreased in 2010 relative to 2009; however, the median runoff specific conductance lag time also decreased.

The results of this study indicate that low-impact development can be a useful approach to managing stormwater at these sites in northern Ohio. It should be noted, however, that this study did not assess winter months, so the analysis is not transferable to winter conditions.

Acknowledgments

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