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Stormwater Reduction and Water Budget for a Rain Garden on Sandy Soil, Gary, Indiana, 2016–18

Scientific Investigations Report 2022–5101

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

Cover. Top left: Gary City Hall in Gary, Indiana, before construction of green infrastructure; photograph by David C. Lampe, U.S. Geological Survey. Bottom right: Gary City Hall after construction of green infrastructure; photograph by the U.S. Geological Survey.

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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)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F –

32) / 1.8.

A water year is the period from October 1 to September 30 and is designated by the year in which it ends; for example, water year 2016 was from October 1, 2015, to September 30, 2016.

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

EMR	episodic master recession
EPA	U.S. Environmental Protection Agency
PET	potential evapotranspiration
PSR	percent stormwater reduction
SCM	stormwater control measure
USGS	U.S. Geological Survey

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Abstract

Stormwater reduction measures, or green infrastructure, were implemented in the parking area at Gary City Hall, Gary, Indiana, with the intention of reducing stormwater discharge to the sewers. A study area, including a centrally located rain garden and the surrounding paved surfaces and green space, was instrumented during both a preconstruction and a post-construction period to (1) develop water budgets to improve understanding of the rain garden hydrology and (2) determine the quantity of stormwater runoff that was diverted and retained by the green infrastructure instead of reaching the combined storm and sanitary sewer. The study was focused on warm-season precipitation and was monitored during spring, summer, and fall of 2016, 2017 and 2018.

Before construction of the rain garden in the parking lot of Gary City Hall in 2017, nearly all precipitation was conveyed away from the parking lot by underground drains, discharged to the sewer, and treated as sanitary waste at the Gary Sanitary District's treatment plant or discharged directly to local waterways if stormflow exceeded capabilities of the sewage treatment plant. A goal of the Great Lakes Restoration Initiative is the reduction of sewer overflows to local waterways to improve the quality of water entering the Great Lakes. Cities such as Gary benefit financially and environmentally by reducing discharges of stormwater runoff to the sewer system, eliminating the need for treatment. Before implementation of green infrastructure at Gary City Hall, approximately 25 percent of precipitation (approximately 10,200 cubic feet) discharged as stormwater to the sewers through the parking lot drain. After implementation, 2 percent of precipitation discharged to the sewers. For the spring, summer, and fall seasons of 2017 and 2018, 21–24 percent (about 10,700–19,700 cubic feet) of precipitation was captured by the newly installed rain garden. Stormwater discharged to the rain garden infiltrated the sandy soil and was later evaporated from the soil surface, was transpired by plants, or recharged the underlying groundwater aquifer. The percent reduction in stormwater discharged to the storm sewer after the construction of the rain garden was 80.3 percent, equating to approximately 21,400 and 39,300 gallons of stormwater in 2017 and 2018, respectively.

Introduction

The term "urban stormwater" refers to rainfall or snowmelt not absorbed by the pervious surfaces in the landscape or flows from impervious surfaces such as roads, roofs, and parking lots that are common in urban areas. Within the Great Lakes drainage basin, urban stormwater flows into storm drains that are either routed directly to receiving water bodies or transported through a network of drains and pipes to a sewage treatment plant where it is treated before being discharged to nearby tributaries of the Great Lakes. In urban drainage areas, excess stormwater can cause problems such as localized flooding, increased sedimentation, increased water temperature, reduced dissolved oxygen, degraded aquatic habitat structure, loss of fish and other aquatic populations, and decreased water quality (Baker and others, 2022). Stormwater contaminants can include sediment, metals, nutrients, bacteria, and organic compounds (Great Lakes Commission, 2018). During heavy rainfall, excess stormwater runoff can cause localized flooding and lead to combined sewer overflows, which collect stormwater runoff, domestic sewage, and industrial wastewater into one pipe and discharge directly into nearby streams, rivers, and other water bodies (U.S. Environmental Protection Agency, 2021b).

The U.S. Environmental Protection Agency (EPA), through authorization under the Clean Water Act (33 U.S.C. 1251 et seq.), has regulated stormwater runoff from drainage systems to waters of the United States. The EPA works with States to establish numerical limits on priority pollutants specified by total maximum daily loads (TMDLs; U.S. Environmental Protection Agency, 2021a). Some State and local agencies have established additional stormwater discharge and pollution reduction goals that differ from the EPA regulations.

Stormwater control measures (SCMs) may be implemented to protect land, water resources, and aquatic habitat from flooding and contaminant loading. Urban SCMs include the implementation of green infrastructure, which is designed to store (retain) and reduce or delay peak flow and volume of runoff (detain) by holding stormwater onsite and closer to the source of runoff generation. This is largely accomplished by enhancing hydrologic losses through the mechanisms of infiltration and enhancing evapotranspiration. The types and scales of green infrastructure options are numerous and varied, and each is designed and engineered to fit local conditions such as space limitations, climate, slope, drainage area, soil, and underlying geologic materials. Common green infrastructure options include bioswales and rain gardens, and, more generally, each of these practices can be used to convert impervious to pervious surfaces (Baker and others, 2022).

Successful implementation of a rain garden depends on the permeability of the soils, subsurface geology, transpiration capability of vegetation, and appropriate sizing and engineering (Kumar and others, 2017). The addition of engineered soils that are more permeable than native soils may initially improve effectiveness. The depth to groundwater will need to be sufficiently great to permit stormwater storage without flooding the rain garden and drowning plant roots in the garden (Kumar and others, 2017). Rain gardens and bioswales at sites with similar climates but more silty soils (northeastern Ohio) were effective at detaining and infiltrating most stormwater but overflowed when conditions exceeded design thresholds (Dumouchelle and Darner, 2014). Additionally, monitoring of those sites for 3–5 years showed decreased effectiveness as the surface permeability progressively decreased in response to an influx of fine-grained material (Darner and Dumouchelle, 2011; Darner and others, 2015). This was found to be particularly true where water entered a rain garden or bioswale and deposited sediment (Kumar and others, 2017).

Municipalities adjacent to the Great Lakes are implementing watershed management plans that call for green infrastructure and other measures that reduce the effects of urban stormwater on nearshore water quality at beaches and other coastal areas (Great Lakes Commission, 2018). Since 2010, the Great Lakes Restoration Initiative has sponsored several programs that support reducing nonpoint source pollution effects on nearshore ecosystem health and improving performance of urban drainage systems. Because of the relative novelty of green infrastructure SCMs compared to traditional gray infrastructures (such as wastewater inlets, conveyance, pumping, and treatment plants), the effectiveness of these practices is of great interest. There is particular interest in understanding how the effectiveness of practices such as stormwater runoff retention and detention and overall performance may be the result of onsite conditions, climate, and other factors. There is a lack of high-quality data on the operational and performance characteristics of green infrastructure and other SCMs to use in assessing their overall performance. In 2014, the U.S. Geological Survey (USGS), in cooperation with the EPA, began studies to monitor the effectiveness of green infrastructure on urban stormwater at several Great Lakes cities including Gary, Indiana; Detroit, Michigan; Buffalo, New York; and Fond du Lac, Wisconsin (fig. 1). These projects include monitoring to explore the effects of SCMs such as rain gardens (Gary, Ind.), vegetated swales (Detroit, Mich.), porous asphalt and street side planter boxes (Buffalo, N.Y.) and mature trees (Fond du Lac, Wis.).

Gary City Hall was constructed in 1927. Before 2017, stormwater from the paved parking area on the south side of the building drained via an underground conduit and entered the city's combined storm and sanitary sewer beneath Massachusetts Street (fig. 2). The water was treated at the sanitary treatment plant, or, if the plant's capacity was overwhelmed by the volume of stormwater, it mixed with sewage and discharged to nearby tributaries of Lake Michigan.

During 2014, the city took steps to begin implementing concepts of green infrastructure at city hall. As part of this integration effort, a hotel and attached parking garage about 150 feet (ft) south of the city hall parking area were demolished and the vacant space revegetated with a turf cover. From November 2016 to June 2017, the mostly impermeable parking surface immediately south of city hall was removed, and a newly designed parking area that sloped toward a centrally located rain garden was installed between the impervious source area and the sewer inlet to reduce stormwater discharges to the sewer (fig. 3). In 2016, before the installation of the rain garden, the USGS instrumented the parking lot drain to record flow, installed four monitoring wells to measure groundwater levels, and installed a weather station to record precipitation and estimate potential evapotranspiration. After the construction of the new parking area and central rain garden in 2017, additional monitoring stations were installed to measure the volume of water entering the rain garden. Most properties measured at the study area were monitored only during the warm-weather months from 2016 to 2018 with the goal of quantifying stormwater reduction and developing a water budget that would improve understanding of the fate of stormwater diverted from the sewer by installed green infrastructure.

Purpose and Scope

The purpose of this report is to quantify a water budget to better understand the fate of stormwater diverted from the sewer and to evaluate the effectiveness of the green infrastructure installation for stormwater reduction. The approximately 49,500-square-foot (ft^2) Gary study area and approximately 4,000-ft^2 rain garden were monitored during spring, summer, and fall from May 2016 through November 2018 (fig. 4). More than 70 instruments were used to continuously monitor weather properties, runoff volume, soil moisture, groundwater levels, and sewer-pipe discharge.

Description of Study Area

The city of Gary is in northwestern Indiana, approximately 1.6 miles (mi) south of Lake Michigan. The city was founded in 1906 (City of Gary, 2022) and is home to industries that include iron smelting and steel manufacturing, petroleum storage and refining, and other chemical manufacturing. The estimated population of Gary in 2018 was 75,282

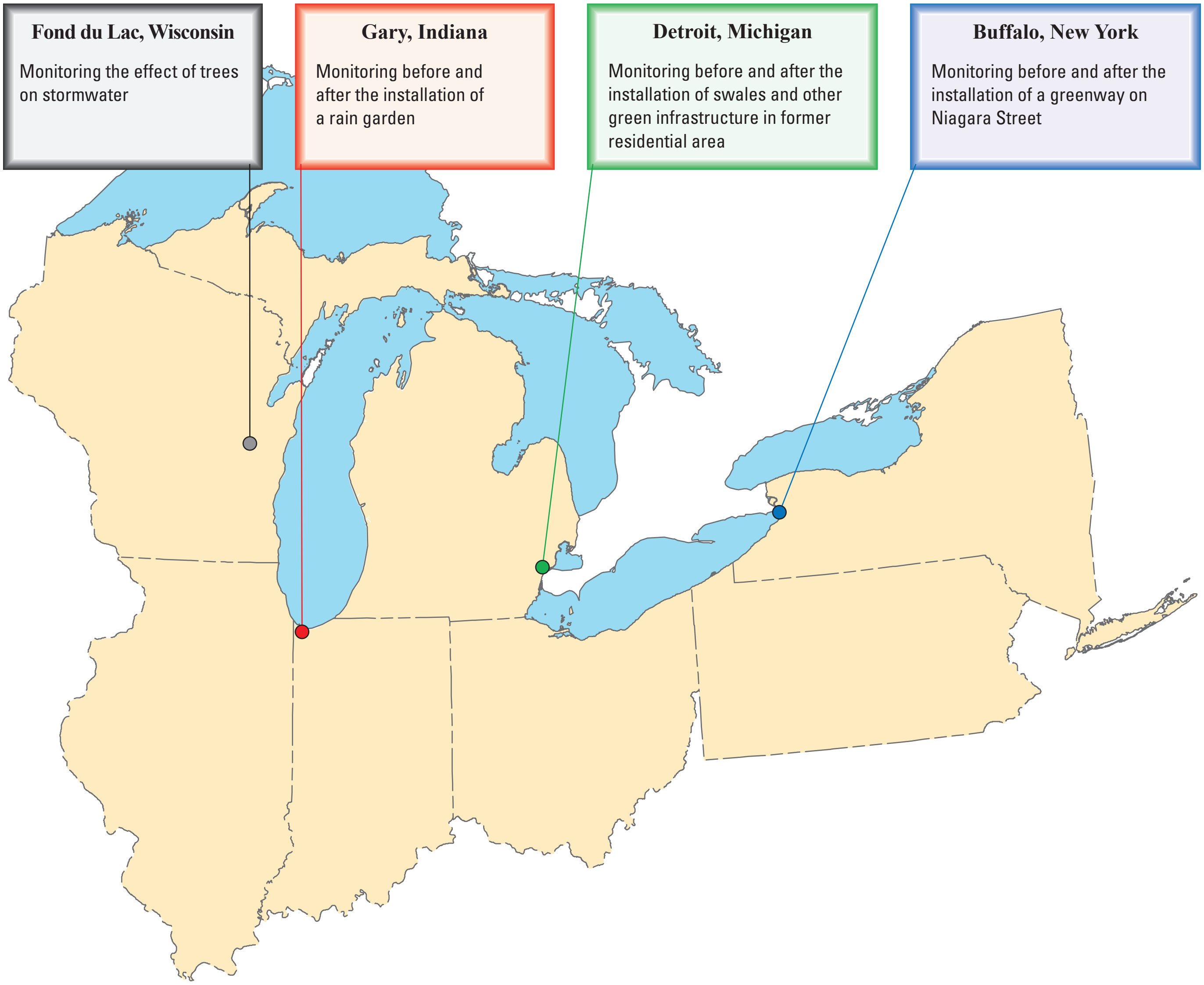


Figure 1. Green infrastructure sites being monitored by the U.S. Geological Survey as part of the Great Lakes Restoration Initiative.

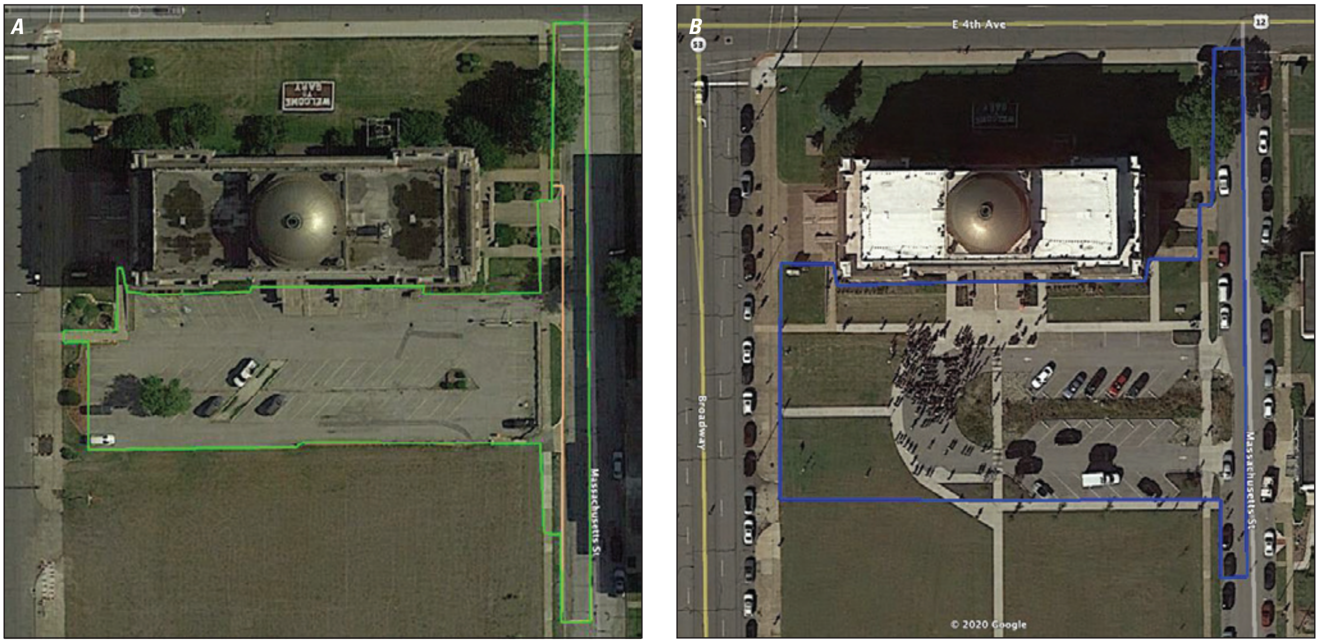
(U.S. Department of Commerce, 2019a), but the city is part of the larger Lake County metropolitan area with population of 484,411 (U.S. Department of Commerce, 2019b).

Hydrogeologic Setting

The study area is in the Calumet area of Lake County in northwestern Indiana and is in the Calumet Lacustrine Plain physiographic province (Schneider, 1966). The province is characterized by dune-beach complexes formed in the Pleistocene and Holocene Epochs when the water level in Lake Michigan was at higher altitude than it is today (Leverett and Taylor, 1915; Bretz, 1951; Hansel and others, 1985). The dune, beach, and lacustrine deposits of silt, sand, and gravel were deposited as a thin but laterally extensive surficial aquifer, referred to herein as the Calumet aquifer. Within the study area, the Calumet aquifer extends approximately 20–35 ft below the land surface (Hartke and others, 1975; Watson and others, 2001). A glacial ablation till known as the Wheeler Sequence underlies the Calumet aquifer (Brown and Thompson, 1995). The clay unit ranges in thickness from 50 to 140 ft in the area and forms a confining unit between the Calumet aquifer and the underlying carbonate bedrock aquifer (Fenelon and Watson, 1993). The geological deposits beneath implanted green infrastructure varied from the native setting: (1) engineered soils were used to fill the rain garden to a depth of about 5 ft, and (2) some areas of the green space south of the new parking area may contain construction waste from previous land uses and a fine-grained soil cap transported in after the demolition of the neighboring hotel.

Figure 2. Gary City Hall in Gary, Indiana, before construction of green infrastructure (2016). Massachusetts Street in the foreground. Photograph by David C. Lampe, U.S. Geological Survey.

Figure 3. Gary City Hall in Gary, Indiana, after construction of the green infrastructure and rain garden (2017). Massachusetts Street in the foreground. Photograph by the U.S. Geological Survey.



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General Perspective projection
World Geodetic System of 1984

Base image from Google, copyright 2019
General Perspective projection
World Geodetic System of 1984

EXPLANATION

Impervious areas

Study area boundary

Figure 4. *A*, Preconstruction and *B*, postconstruction areas at the Gary City Hall study site in Gary, Indiana, showing impervious areas (green line) and the study area boundary (blue line).

Rain Garden Design and Construction

Land use modifications and additions of green infrastructure at the Gary City Hall study site were made from October 2014 through April 2017 (fig. 5). In October 2014, the hotel south of Gary City Hall was demolished, and the construction waste was removed. Much of the largely impervious paved area, as well as cement sidewalks that filled the area between the preexisting city hall parking area and the area to the south of the hotel, were replaced with turf. The parking area between the hotel and city hall building remained unchanged. Of the 49,500-ft^2 study area, approximately 31,800 ft^2 (approximately 64 percent) was covered with impervious materials (table 1). Three drains collected stormwater in the parking lot and discharged it to the storm sewer on the northeastern side of the study area (fig. 6*A*). The total drainage area for the parking lot drains was approximately 13,600 ft^2. Stormwater was also collected and discharged to the storm sewer through a drain on Massachusetts Street on the east side of the study area from a drainage area of approximately 5,700 ft^2. Other parts of the impervious area were estimated to drain to the surrounding grassed area or were areas where water ponded because of depressions in the asphalt and either evaporated or infiltrated through cracks.

In 2017, the preexisting parking area was replaced with a new parking area in front of city hall (fig. 6*B*). The new parking surface was gently inclined toward the center of the parking area to encourage flow of water toward the centrally located rain garden. The drainage area of the rain garden is approximately 24,500 ft^2 (table 1; fig. 7). Unlike the old parking surface, the new parking surface did not have cracks and imperfections that allowed water to enter the subsurface or sunken areas where puddles of water accumulated after rainfall and snowmelt. The new parking area covered approximately 29,600 ft^2 (60 percent) of the study area with impervious material. The drain in Massachusetts Street was removed and incorporated within the area of the rain garden during construction. The area surrounding the parking lot drains were changed during construction with the addition of more permeable materials around the drains. The drainage area of the parking lot drains after the construction was approximately 1,900 ft^2.

A rain garden was built in the center of the parking area. Construction entailed excavating to a depth of 6 ft, placing a perforated pipe to act as a cistern along the long axis of the rain garden wrapped in no. 5 stone and fabric, refilling the excavation with native sediment and topping with engineered soils that were intended to approximate the native

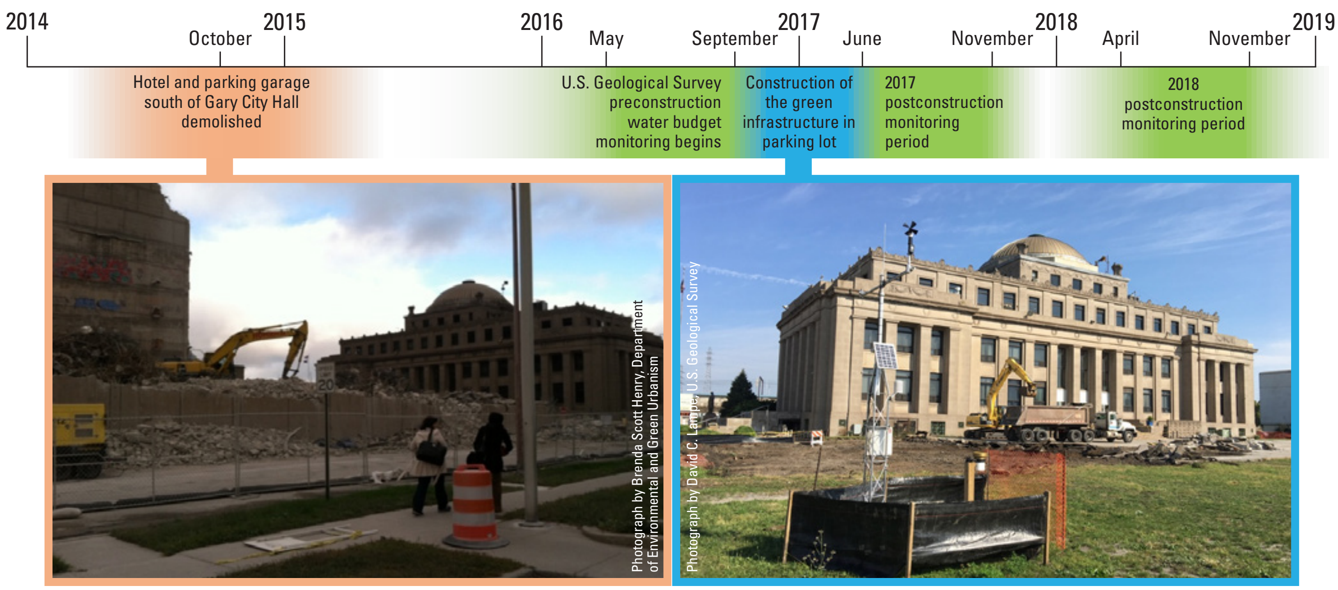

Figure 5. Timeline of construction and monitoring at the Gary City Hall study site, Gary, Indiana.

Table 1. Study areas and individual drainage areas for drains and flumes used during preconstruction and postconstruction periods of investigation at Gary City Hall in Gary, Indiana.

[Percent of total area values do not add to 100]

Description of drainage area	Total area, in square feet	Percent of total area
Total study area	49,500	100
Preconstruction		
Preconstruction impervious area	31,800	64.2
Preconstruction drainage areas		
Parking lot drain drainage area	13,600	27.5
Preconstruction Massachusetts Street drain drainage area	5,700	11.5
Postconstruction		
Postconstruction impervious area	29,600	59.8
Rain garden area	4,000	8.1
Postconstruction drainage areas		
Parking lot drain drainage area	1,900	3.8
Total rain garden drainage area	24,500	49.5
West flume drainage area	6,000	12.1
North flume drainage area	4,200	8.5
South flume drainage area	5,200	10.5
East flumes drainage area	9,100	18.4

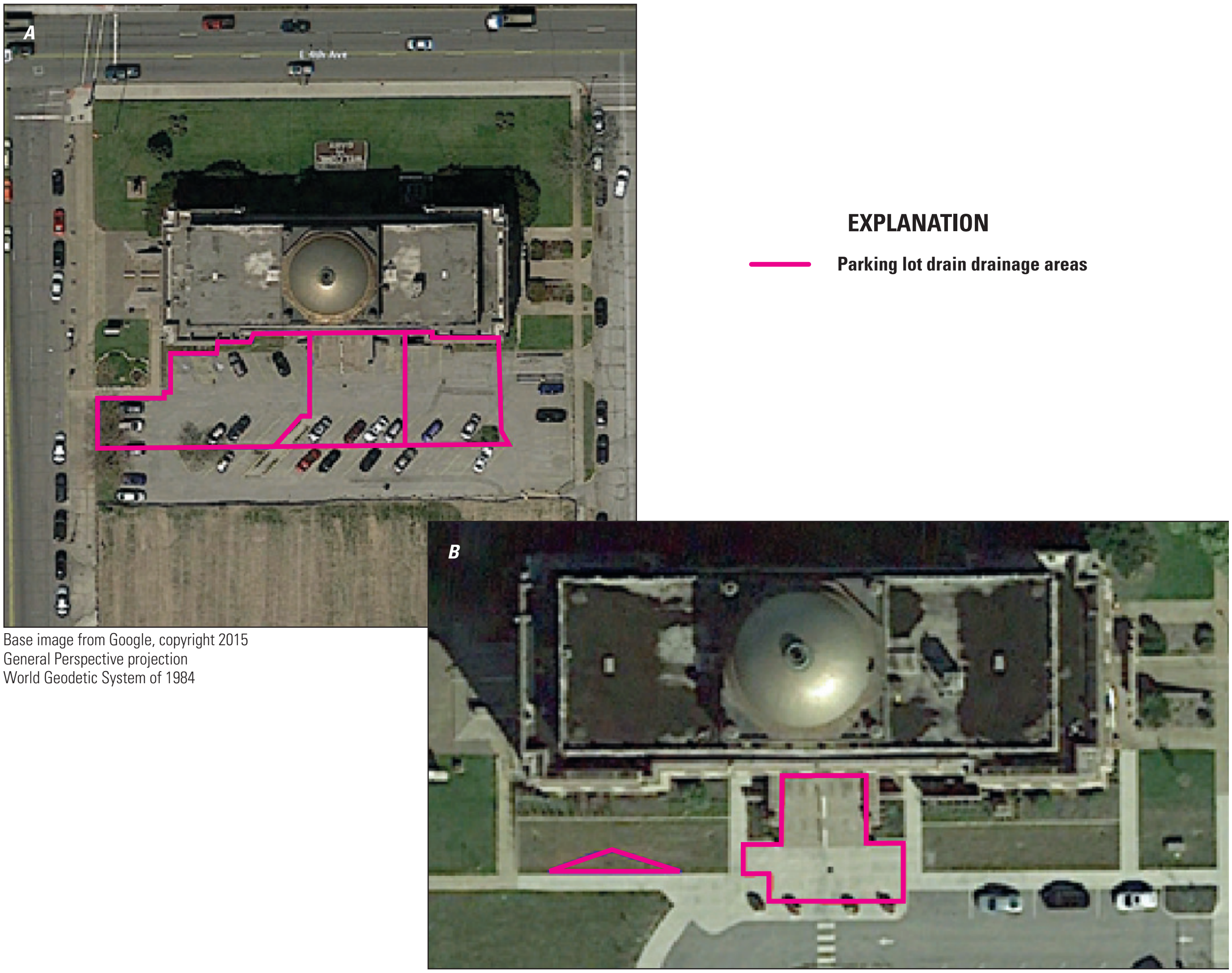

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Figure 6. Images showing the *A*, preconstruction and *B*, postconstruction areas contributing runoff to the drain that runs directly in front of Gary City Hall and discharges to the main sewer beneath Massachusetts Street in Gary, Indiana. The areas contributing runoff are surrounded by colored polygons in each image.

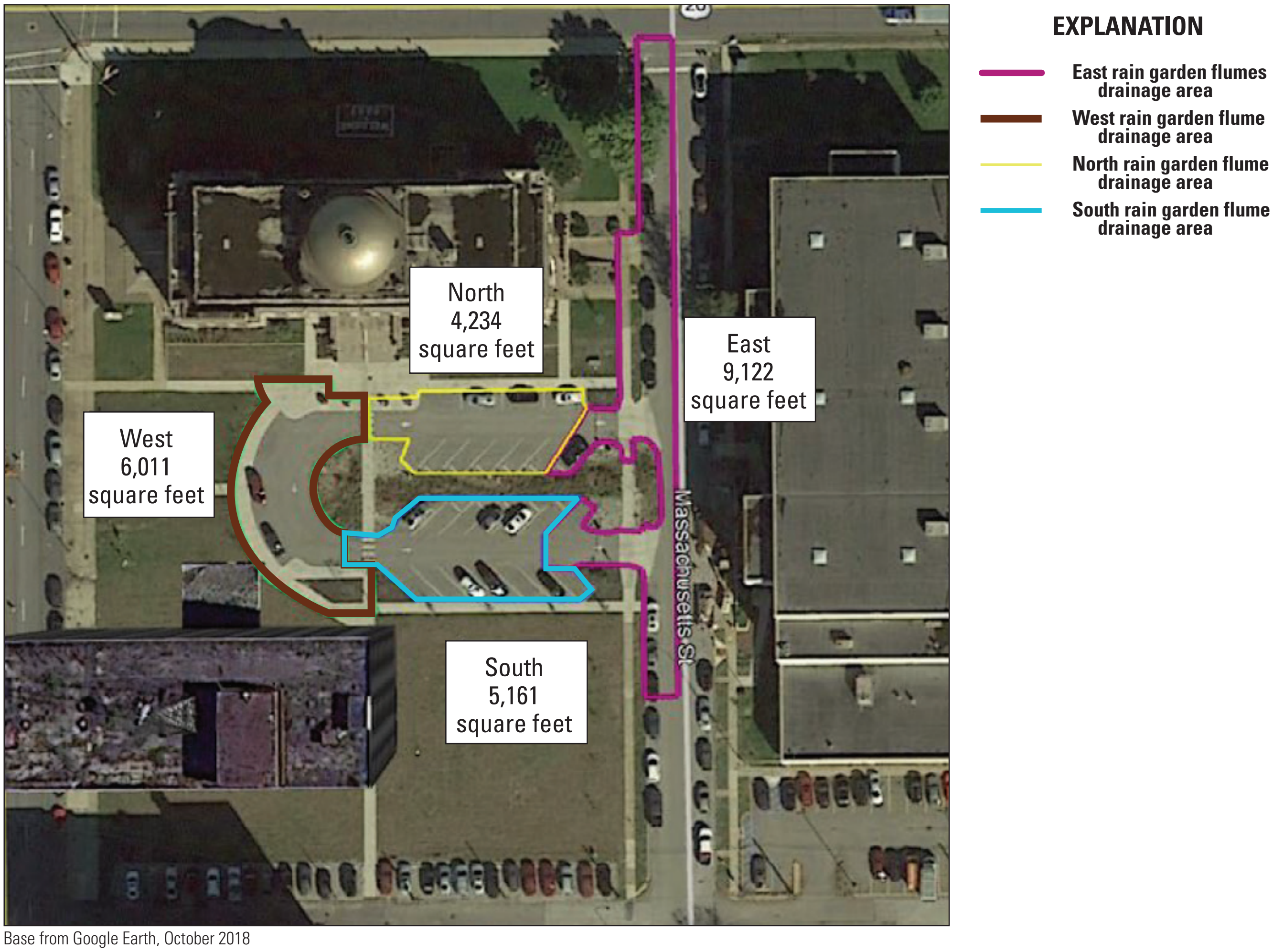

Figure 7. Image showing paved areas, delineated with colored lines, that contributed runoff to the rain garden at Gary City Hall in Gary, Indiana.

deposits, and stabilizing the land surface with native plantings (figs. 8–11). The land surface of the rain garden was sloped from the edge of pavement to the center of the garden to encourage infiltration in the area where the perforated plastic pipe was buried. The perforated pipe was intended as a temporary storage container for periods of high infiltration and would slowly release water later as the surrounding materials dried. The perforated plastic pipe was 12 inches (in.) in diameter and approximately 150 ft long. The perforated plastic pipe was accessed and instrumented at each end by way of 24-in. inner diameter concrete drop-down structures. The perforated plastic pipe was surrounded with 6–12-in. of very coarse no. 5 stone that was in turn wrapped in a fabric root barrier to maintain long-term flow to the pipe and backfilled with native soil. An overflow pipe connected the top of a drop-down structure to the storm sewer on the eastern side of the pipe. The rain garden was topped with an engineered soil.

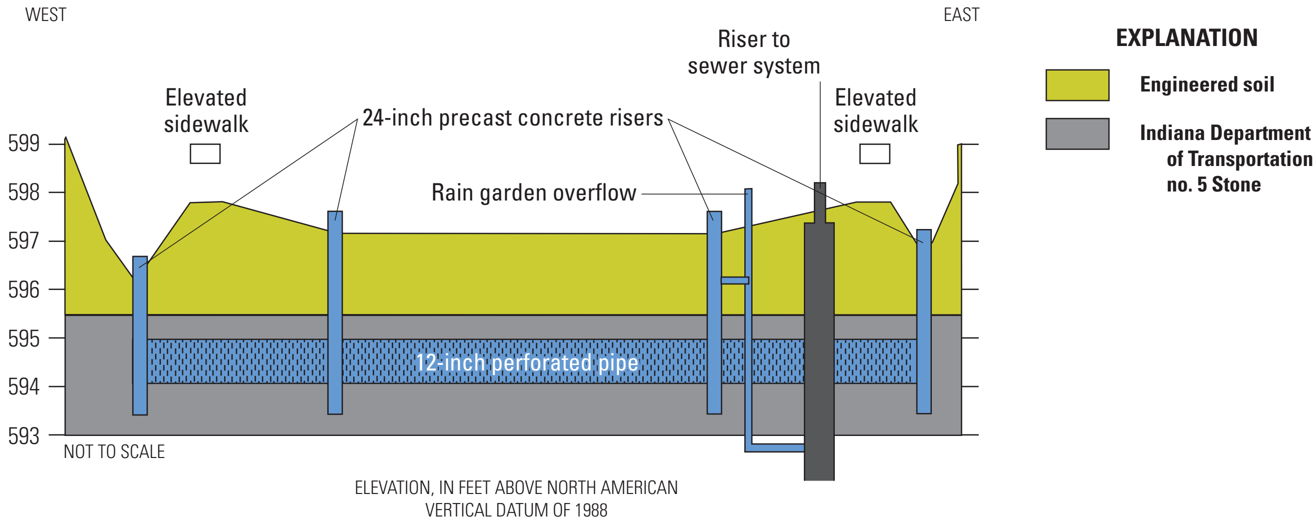

Figure 8. Cross-sectional schematic showing the perforated plastic pipe and drop-down structures in the rain garden at Gary City Hall in Gary, Indiana.

Figure 9. Photograph showing installation of perforated plastic pipe and concrete drop-down structure in the rain garden at Gary City Hall in Gary, Indiana. Photograph by David C. Lampe, U.S. Geological Survey.

Figure 10. Photograph showing installation of gravel and root barrier around the perforated plastic pipe in the rain garden at Gary City Hall in Gary, Indiana. Photograph by David C. Lampe, U.S. Geological Survey.

Figure 11. Photograph looking from east to west showing native plants growing in the rain garden at Gary City Hall in Gary, Indiana. Photograph by the U.S. Geological Survey.

Methods of Investigation

The effectiveness of the rain garden at reducing stormwater discharge to the sewer was evaluated by comparing warm-weather period flows of water discharging into the sewer before and after construction of the green infrastructure. A water budget was also quantified to improve understanding of ways that water entered, exited, and was stored in the rain garden by using data collected at the site through a network of continuously recording hydrologic instruments. Three monitoring periods were used in the analysis (fig. 5):

1. the preconstruction monitoring period from May 10, 2016, through September 7, 2016;
2. the 2017 postconstruction monitoring period from June 15, 2017, through November 6, 2017; and
3. the 2018 postconstruction monitoring period from April 25, 2018, through November 8, 2018.

Two postconstruction years were included to account for the relatively short period in 2017 because of the ongoing construction of the parking lot area and to accommodate for the potential for extreme hydrologic conditions that may have been encountered in 2017 (excessive wet or dry periods). Periods when equipment experienced malfunctions or data were not useable in the analysis were removed from the monitoring periods in 2016 (15 days) and 2017 (7 days).

Historical precipitation data from 1989 to 2018 are available from a nearby recording station at the Indiana Dunes National Park approximately 13 mi east of the study area (Midwestern Regional Climate Center, 2022). Monthly precipitation totals from the onsite weather station were compared to the historical precipitation record to identify how the monitoring periods related to the long-term precipitation record.

Estimation of Percent Stormwater Reduction

Percent stormwater reduction (PSR) for the postconstruction monitoring period was calculated by first determining the equation of a best fit line relating the cumulative event precipitation to the storm event discharge into the parking lot drain inlet structure for the preconstruction monitoring period:

$$V = m_1(P) + b_1, \tag{1}$$

where

V is the volume of stormwater discharged to the sewer during a storm event, in gallons;

b_1 is the Y-intercept of the best fit line, in gallons;

m_1 is the slope of the best fit line, in gallons per inches; and

P is precipitation for individual storm event, in inches.

Next, an equivalent preconstruction volume of stormwater (V) was estimated for each storm event during the postconstruction period by using equation 1 with the individual storm precipitation totals from the postconstruction period (P). The observed and estimated storm volumes for the postconstruction period were summed and used to determine the volume of stormwater reduced and the PSR by using the following equations:

$$\text{Volume reduced} = \sum V_2 - \sum V_1 \qquad (2)$$

and

$$\text{PSR} = 100\left(\frac{\sum V_2 - \sum V_1}{\sum V_2}\right), \qquad (3)$$

where

V_1 is observed storm event volume for the postconstruction period, and

V_2 is estimated equivalent preconstruction volume of stormwater for the postconstruction period.

Water Budgets at the Gary City Hall Green Infrastructure Study Area

A water budget is an accounting of the flows of water into and out of an area and the change in the amount of water that is temporarily held in storage. For areas undergoing new hydrologic management, such as the study area at Gary City Hall, a water budget shows changes in the overall hydrology. The generalized equation for computing a water budget uses a mass-balance approach, such that

$$\text{Inflows} - \text{Outflows} = \text{Change in Storage}. \qquad (4)$$

The general water budget equation was recast for the preconstruction period of monitoring at Gary City Hall for the monitored parts of 2016–18. Two individual water budgets were calculated for the postconstruction period of monitoring during 2017 and 2018: one for the study area excluding the rain garden and one for only the rain garden.

The equation for the preconstruction Gary City Hall study area water budget was

$$P - (Q_1 + Q_2 + ET + E + Re) \pm e = \Delta S, \qquad (5)$$

where

P is precipitation on the study area, measured in inches;

Q_1 is discharge to the storm sewer from the parking lot drain, in cubic feet;

Q_2 is discharge to the storm sewer from the Massachusetts Street drain,[1] in cubic feet;

ET is evapotranspiration from vegetated areas, in millimeters;

E is evaporation from paved surfaces, in millimeters;

Re is recharge to groundwater, in inches;

e is error in measurements or estimates; and

ΔS is storage change.

The equation for the postconstruction Gary City Hall study area water budget excluding the area of the rain garden was

$$P - (Q_1 + ET + E + Re + Rg) \pm e = \Delta S, \qquad (6)$$

where

P is precipitation on the study area, in inches;

Q_1 is discharge to the storm sewer from the parking lot drain, in cubic feet;

ET is evapotranspiration from vegetated areas, in millimeters;

E is evaporation from the paved surfaces, in millimeters;

Re is recharge to groundwater, in inches;

Rg is runoff from paved surfaces into the rain garden, in inches;

e is error in measurements or estimates; and

ΔS is storage change.

The water budget for the rain garden reflects a unique hydrologic system inset into the larger green infrastructure at Gary City Hall and was separately examined as a small, decoupled system. The equation for the rain garden water budget for the monitored part of 2018 was

$$(P + Rg) - (Q_3 + ET + Re) \pm e = \Delta S, \qquad (7)$$

where

P is direct precipitation on the rain garden, in inches;

Rg is runoff from paved surfaces into the rain garden, in cubic feet;

Q_3 is discharge to the rain garden overflow, in cubic feet;

ET is evapotranspiration from the vegetated area, in millimeters;

Re is recharge to groundwater, in inches;

e is error in measurements or estimates; and

ΔS is storage change.

The values for each item in the water budget equation, except for the error and storage terms, were measured or estimated from monitoring data collected at the Gary City Hall site and converted to cubic feet for analysis purposes. For long periods, storage is often assumed to be negligible (Ward and

[1]Removed during construction in 2017.

Trimble, 2004). Although some water-storage deficit may have existed in the unsaturated zone as monitoring progressed from the wet spring season to the dry summer season, the sandy subsurface at Gary City Hall does not retain much water. For purposes of this study, the storage term was set equal to zero. The buried perforated pipe beneath the rain garden is a potential storage compartment operating with a transient nature, filling and emptying in relation to the intensity of the storm event. The observed water level in the pipe was rarely high enough to induce discharge to the sewer system through the overflow pipe. Although the rain garden existed during 2017, the monitoring well required to estimate groundwater recharge within the rain garden was not available until 2018.

The error term in the water budget may include inaccuracies in the measurement and estimation of water budget components or unmeasured components that do not appear in the budget equation. At the Gary City Hall site, potential sources of error might include unmeasured canopy interception, ponding on surfaces other than pavement, drainage areas that varied based on storm intensity and duration, intense storm events causing the flumes leading to the rain garden to become submerged during periods of backwater, and inaccuracies in the estimations of evapotranspiration, groundwater recharge, seepage through cracks in the paved surfaces, wetting of all dry surfaces before the generation of runoff, and evaporation from paved surfaces. These errors are likely small in comparison to the quantities measured and quantified at the site.

Monitoring and Estimation of Water-Budget Components

Instruments were installed at the Gary City Hall rain garden and the surrounding area to (1) provide data needed to quantify the amount of stormwater reduction that resulted from installing the green infrastructure and (2) quantify the relative importance or role of various hydrologic components on the water budget. The hydrologic variables monitored in the study area during preconstruction and postconstruction were not identical. Components monitored before the green infrastructure installation included pipe flow in the subsurface drain to the storm sewer, precipitation, weather variables used to compute potential evapotranspiration, and groundwater levels with multidepth soil moisture and soil temperature at two onsite and two offsite wells (app. 1).

Postconstruction monitoring additionally collected data from five flumes installed to measure runoff from the new parking surface into the rain garden, a well installed to measure groundwater levels in the rain garden, soil moisture and soil temperature sensors at two depths (one above and one below the perforated pipe at three different locations), water level in the perforated pipe beneath the rain garden, and a pressure transducer to determine flow from the perforated pipe overflow outlet into the storm sewer (fig. 12; app. 1). Monitoring sites in the rain garden did not exist and were not measured during 2016. All data were measured and stored using electronic data loggers, and data modems were used to transmit the data hourly. All data were preserved in the National Water Information System (U.S. Geological Survey, 2020; app. 1). The methods used to monitor each of these water-budget components are described in the following sections.

Discharge to the Sewer

Discharge to the sewer was measured at two locations: (1) at the parking lot drain immediately southeast of Gary City Hall during the entire study and (2) at the connection between the overflow pipe and the east subdrainage site in the rain garden (fig. 12*B*). Discharge to the sewer was also estimated at the drain on Massachusetts Street for the preconstruction period only because the drain was removed during the rain garden construction before the monitoring period in 2017.

The instantaneous volume of water passing through the parking lot drain and overflow pipe was computed by using 1-minute-interval measurements of the water depth upstream from the opening of a 6-in.-diameter, in-pipe V-notch weir (fig. 13) and a manufacturer-supplied rating curve. The weirs were installed in the eastern terminus of the pipe connecting the subsurface parking lot drains to the storm sewer and at the terminus of the overflow pipe leading to the sewer (fig. 14). The depth of water passing over the weir was measured with a bubbler-style pressure sensor system. To quality assure water-depth measurements made by the bubbler system, a digital camera was installed opposite the weir in the parking lot drain to record storm event flows. The total volume of water flowing from the subsurface drainage into the storm sewer for the monitored period of each year was computed by summing the product of instantaneous discharge and measurement duration (1 minute, in this case) for the monitored period of each year. Discharge was estimated at the drain on Massachusetts Street by calculating the amount of precipitation that fell on the drainage area upstream from the sewer inlet for each storm event in 2016. This estimation was necessary because of the condition and type of drain inlet installed in the street that prevented the installation of monitoring equipment. Estimates for flow in the Massachusetts Street drain may differ from actual discharge because of changes in the size of the drainage basin based on the event magnitude and debris in the street that may block flow.

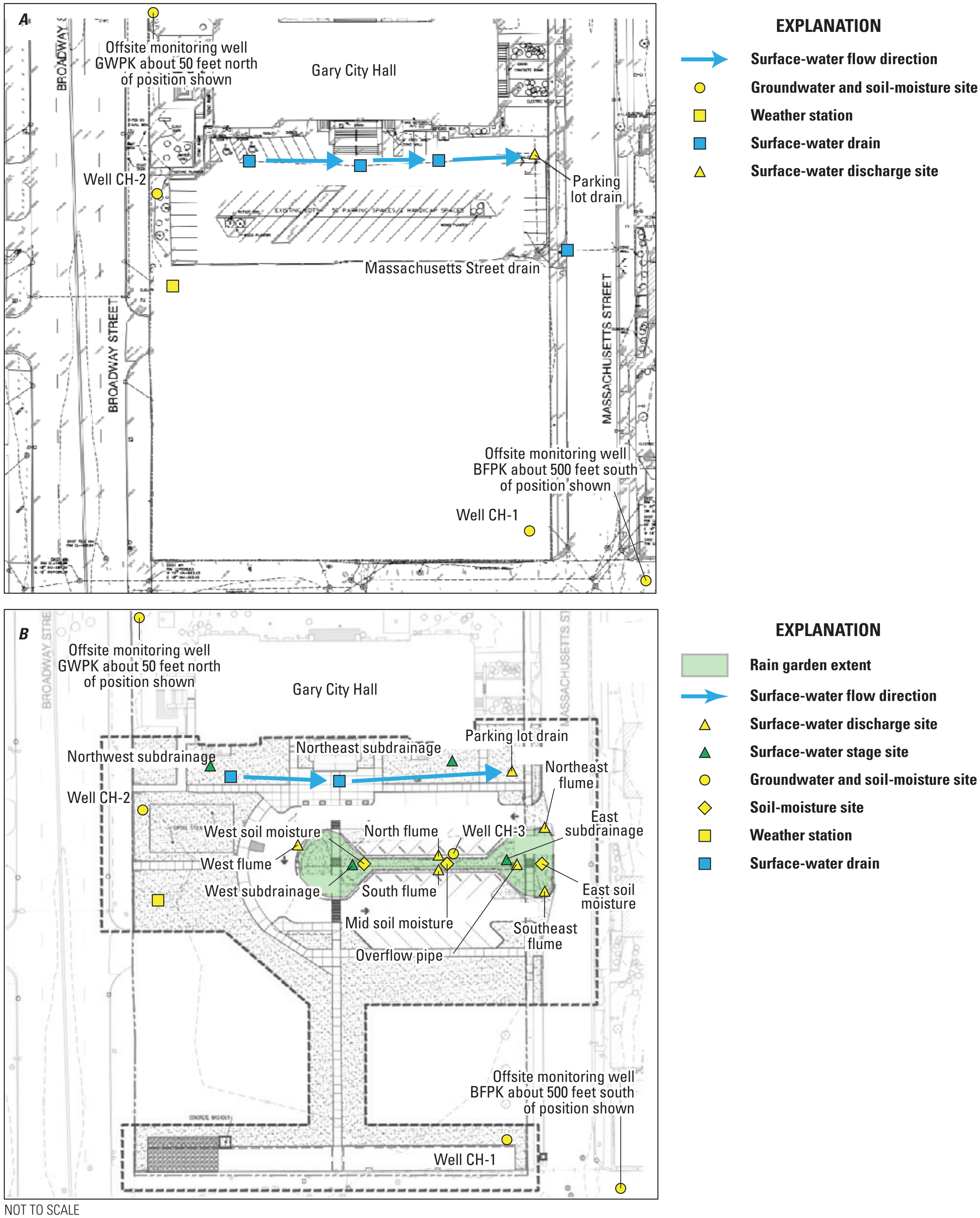

Figure 12. Maps showing instrumentation installed during the *A*, preconstruction and *B*, postconstruction monitoring periods at the Gary City Hall study site in Gary, Indiana. BFPK, Buffington Park; CH, city hall; GWPK, Gateway Park.

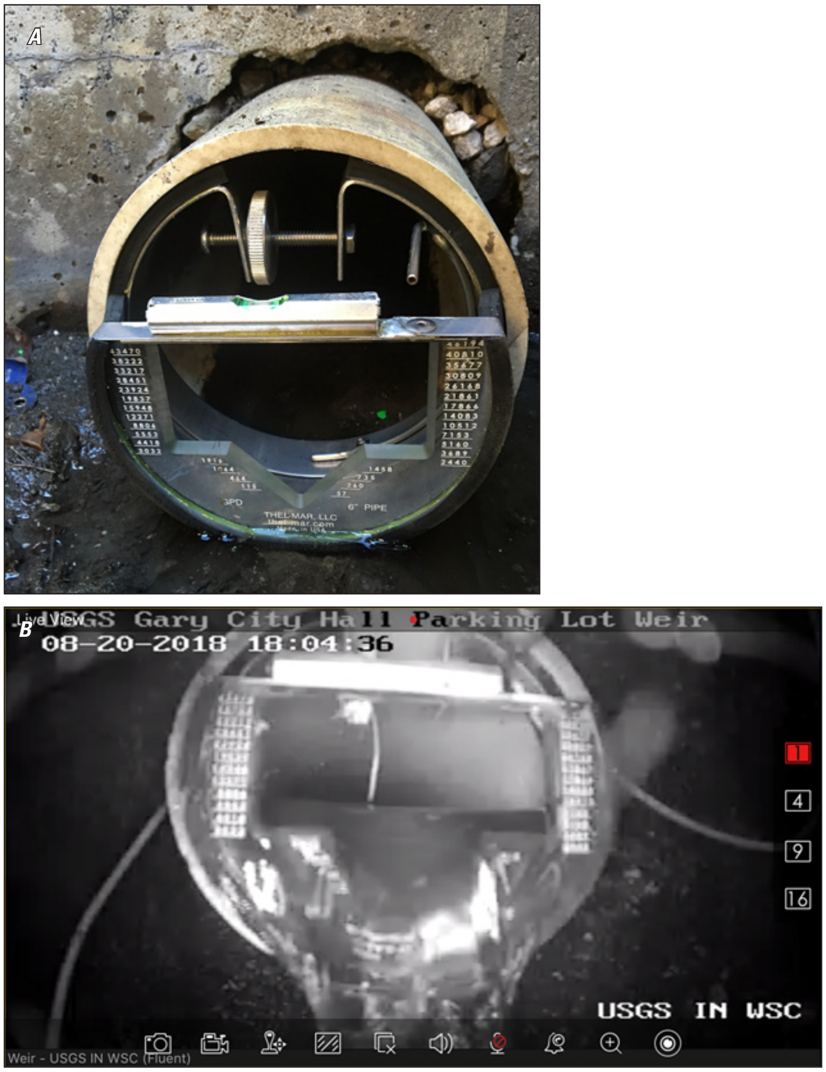

Figure 13. In-pipe V-notch weir installed in drain at the Gary City Hall study site in Gary, Indiana, *A*, during dry conditions and *B*, while flowing during a discharge event. Photograph *A* by David C. Lampe, U.S. Geological Survey; photograph *B* by the U.S. Geological Survey.

Precipitation

Precipitation data were continuously collected by using an unheated tipping-bucket rain gage colocated with the weather station about 175 ft southwest of Gary City Hall and 100 ft west of the rain garden (figs. 12 and 15; app. 1). The rain gage was mounted to a 5-ft tall post. The weather station and rain gage were serviced as per the USGS technical procedures available in USGS office of surface water technical memorandum No. 2006.01 (U.S. Geological Survey, 2006). The rain gage was not designed to measure snowfall, and data were removed from the record during periods when temperatures were below freezing.

Precipitation measured at the weather station during the analysis was compared to the 29-year record of precipitation recorded at the weather station at the Indiana Dunes National Park approximately 13 mi east of the study area (fig. 16; Midwestern Regional Climate Center, 2022). Precipitation recorded during the preconstruction period of monitoring was lower than typical for May, June, and September, although July and August were wetter than typical. Precipitation recorded during the 2017 postconstruction period of monitoring was dryer than typical for June, August, and September, near typical for July and November, and much higher than typical for October. Precipitation recorded during the 2018 postconstruction period of monitoring was near typical for months April through November.

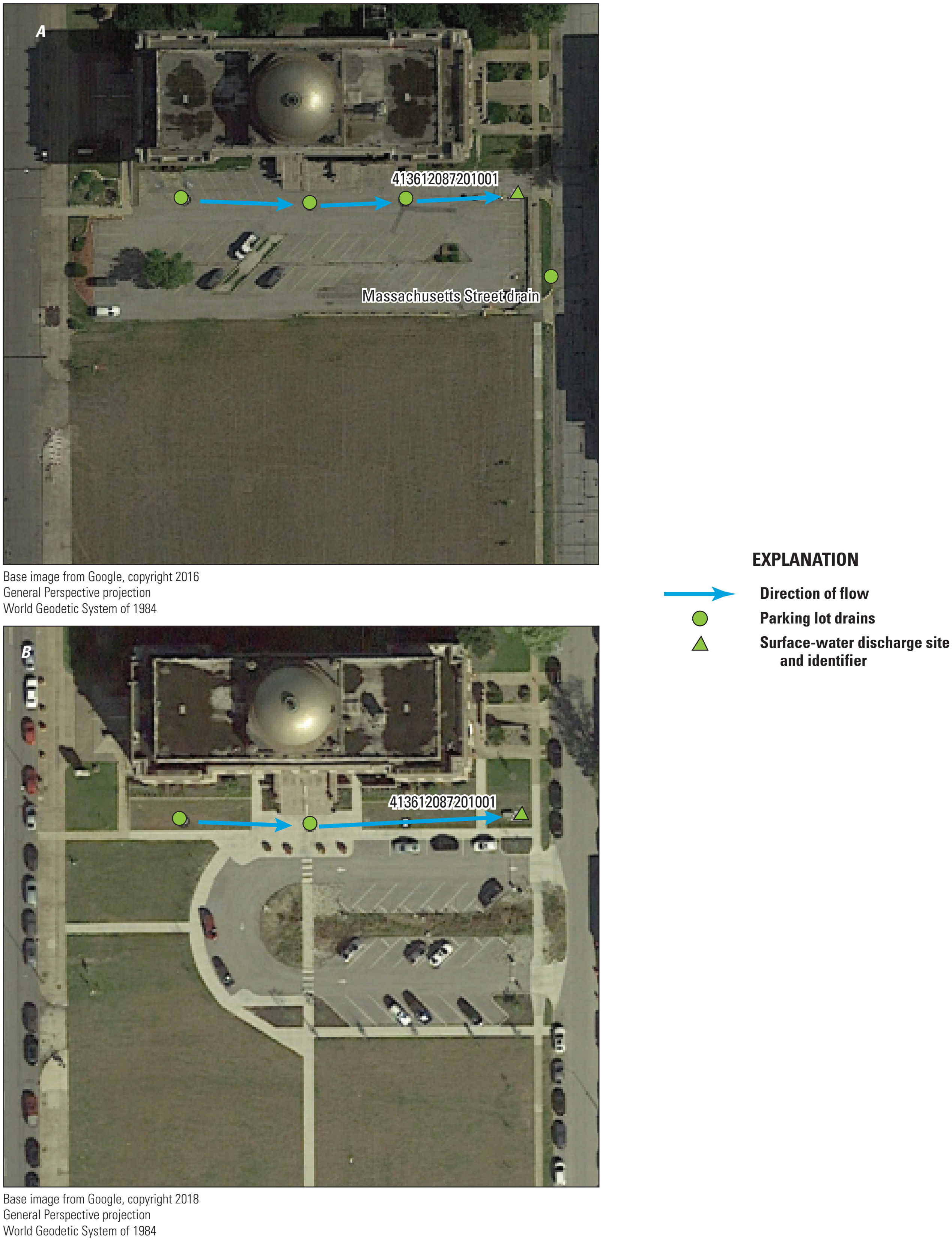

Figure 14. Photographs showing *A*, preconstruction and *B*, postconstruction parking lot drains connecting to the storm sewer at U.S. Geological Survey site city hall drain outflow at Gary, Indiana (413612087201001).

Figure 15. Rain gage and weather station at Gary City Hall study site in Gary, Indiana. Photograph by David C. Lampe, U.S. Geological Survey.

Atmospheric Variables and Evapotranspiration

The weather station installed for the study measured wind speed, wind direction, relative humidity, solar radiation, and air temperature (app. 1). Weather instruments were mounted to a single 10-ft-high tower near the western edge of the study area (fig. 15). The weather-station instruments were disassembled and cleaned, and calibrations for sensors measuring air temperature, humidity, wind speed and direction, and solar radiation were checked at least semiannually by comparing measurements with similar measurements made with sensors certified by the National Institute of Standards and Technology (https://www.nist.gov).

Potential evapotranspiration (PET)—a measure of the atmosphere's ability to remove water from the surface through the processes of evaporation (largely a soil process) and transpiration (a consequence of plant physiology) assuming nonlimiting soil moisture—was computed for unpaved areas only by using data measured by instruments at the onsite weather station. Estimates of PET, the sum of evaporation and plant transpiration, were computed to characterize the volume of water transmitted to the atmosphere as a result of these processes. The PET calculations were made using hourly weather data and the Penman equation (Penman, 1948). The Penman method was developed for a grass reference crop (Ward and Trimble, 2004). Most of the nonpaved study area in Gary is covered with grass and the vegetated rain garden. Although the rain garden surface was bare soil or vegetated with native plant species, the grass PET rate was also applied over this area.

Pavement Evaporation

The amount of water evaporated from paved surfaces in the study area was assumed to be the amount of water held on the pavement by surface tension after the cessation of runoff. The amount of water that surface tension held on the surface before the start of runoff, as indicated by a rise in gage height at the flumes, was assumed to be an equal amount.

To estimate the amount of water available for evaporation from the paved surfaces in the study area, the amount of water available was computed for every precipitation event at each flume during the monitored period of 2018. The amount of precipitation falling before a rise in gage height (including the 1-hour period when the gage began to rise) was summed and represented the amount of water retained by the pavement. The median for all precipitation events was used to indicate the median evaporation from paved surfaces after each storm during the monitored period in 2018. The median estimated evaporation computed for 2018 was assumed to be constant from year to year. A dry paved surface was the required starting point for each estimate, and for purposes of this study it was defined as a period of at least 12 preceding hours without precipitation. Storms that exceeded the necessary amount of precipitation to induce flow to the flumes were identified, and the median evaporation value was applied to the total impervious area and summed for the period of monitoring. The method used for estimating evaporation from the pavement unavoidably includes the amount of water that flowed directly into the rain garden where edging was not installed to redirect runoff into the flumes.

Soil Moisture, Groundwater Levels, and Recharge

Soil moisture was measured to document the redistribution of soil moisture in subsurface soils. Hourly soil-moisture measurements were made by using time-domain reflectometers (Campbell Scientific CS–655 Water Content Reflectometers) installed next to monitoring wells CH–1, CH–2, GWPK and BFPK at 10-, 20- and 30-in. depths and above and below the buried 12-in. perforated pipe in three places (fig. 17; app. 1). The probes have a range of 5–50 percent volumetric water content (cubic feet [ft^3] moisture/ft^3 soil volume) and an accuracy of ±3 percent. These ancillary data were collected to support observations about the hydrologic system at the study site (fig. 18).

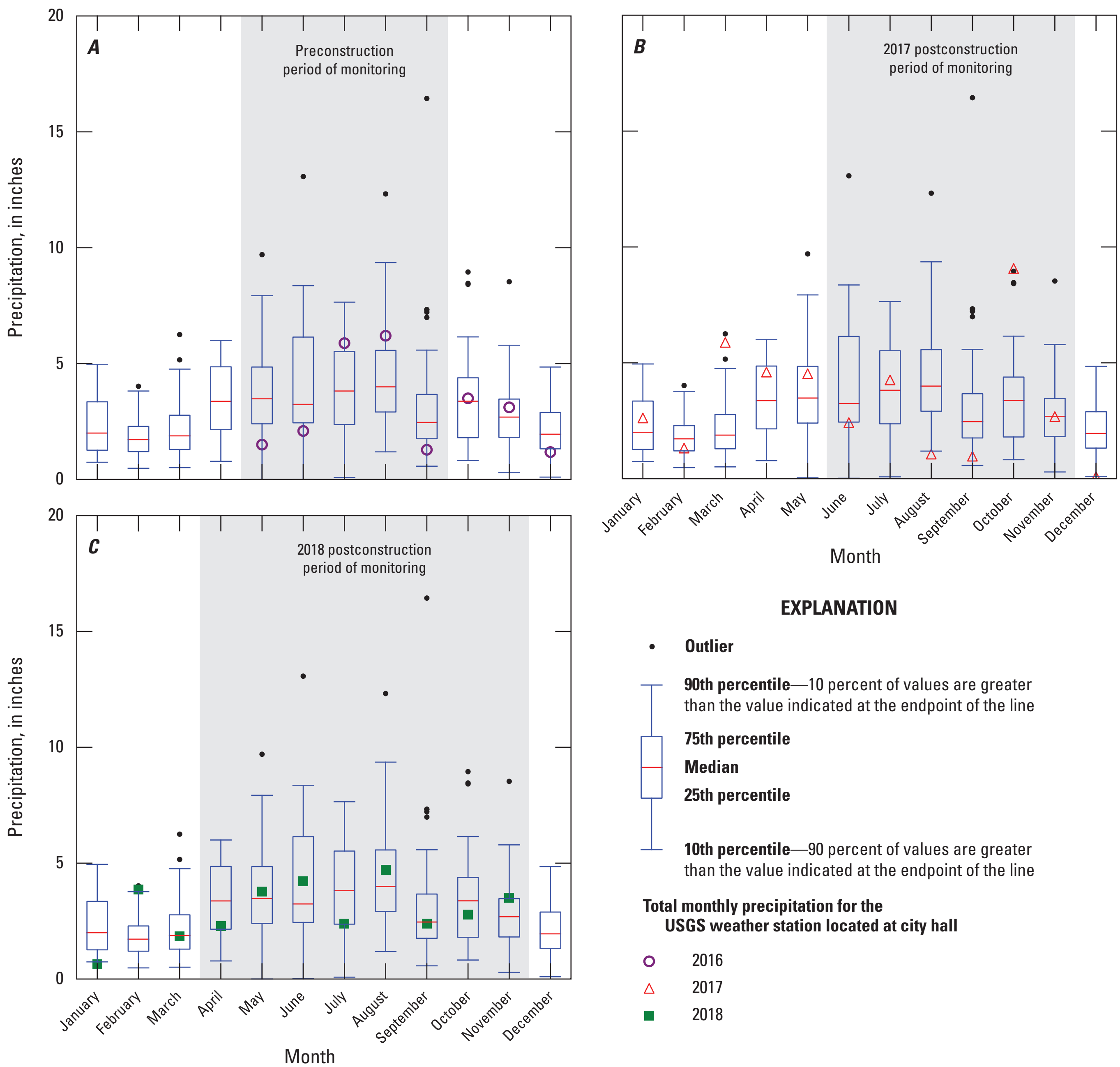

Figure 16. Box and whisker plots of monthly precipitation statistics from the weather station at Indiana Dunes National Park, northwestern Indiana (1989–2018), and monthly precipitation recorded at the U.S. Geological Survey (USGS) weather station (413611087201301) installed at the study site in Gary, Indiana, from May 2016 to November 2018.

Figure 17. Soil-moisture sensors installed in the wall of an excavation at well CH–2 (413612087201301) at the Gary City Hall study site in Gary, Indiana. Photograph by David C. Lampe, U.S. Geological Survey.

The altitude (or level) of groundwater was continuously monitored in five wells (fig. 19). Two wells, CH–1 and CH–2, were installed in the green space south and west of Gary City Hall, respectively, in May 2016 (fig. 12; app. 1). Two background wells, Gateway Park (well name GWPK) and Buffington Park (well name BFPK), were installed in May 2016 140 ft north and 1,500 ft south of city hall, respectively. Well CH–3 was installed on the north side of the rain garden in April 2018 (fig. 12). Groundwater levels were measured at 1-minute intervals for CH–3 because of its depth and location in the rain garden and at 1-hour intervals in the other wells by using vented pressure transducers. Quality-assurance measurements of the depth to water were made with an electric tape approximately every 60 days.

Groundwater recharge, the amount of infiltrating precipitation that reaches the water table, was estimated from continuous groundwater levels by using the episodic master recession (EMR) method (Heppner and Nimmo 2005; Nimmo and others, 2015). The EMR method is appropriate for hydrologic systems where groundwater levels indicate a rapid response to precipitation events (figs. 18 and 19). Rapid transmission of infiltration at Gary City Hall was indicated by sharp rises in groundwater levels that accompanied precipitation events (Follette and others, 2022).

Input for the EMR program consists of cumulative precipitation measured by the weather station installed onsite and continuous groundwater levels collected from wells CH–1, CH–2, CH–3, GWPK, and BFPK. The EMR method additionally required user-supplied values for the drainage area (table 1), fluctuation tolerance (a measurement noise criterion used to ascertain whether a given fluctuation in the water-table level is hydrologically significant), and specific yield of the aquifer (S_y; the volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table) as computational variables in addition to empirically driven variables, such as those defining the beginnings and ends of recharge events.

The EMR method yields two master recession curve coefficients used in the estimation of a theoretical hydrograph estimating the water table without effect from precipitation. The program output includes two graphs identifying periods of recharge and estimates of recharge quantity for each episode. Recharge is calculated by the EMR functions that take the difference between two curves, one with no expected change from precipitation inputs and another curve at the end of a perceived event. The episodic recharge is calculated by the following equation:

$$R = S_y \times H'R, \tag{8}$$

where

- R is the episodic recharge,
- S_y is specific yield, and
- H' is rise in groundwater level attributed to recharge.

Rosenshein and Hunn (1968) determined that a representative storage coefficient for the Calumet aquifer, equal to the specific yield in an unconfined aquifer, was 0.12 (dimensionless). The method assumes the only inputs to groundwater recharge are from precipitation, which is appropriate for conditions at the study site. As an example, figure 20 shows the recharge periods identified by the EMR method for well CH–3 during the monitored period in 2018. Results of the recharge estimation analysis are provided by Follette and others (2022).

Because only data for CH–3 were available to estimate recharge for use in the 2018 water budget, a simple proportion was used to estimate recharge at CH–3 in 2017 based on the values estimated for well CH–1 in 2017 and 2018.

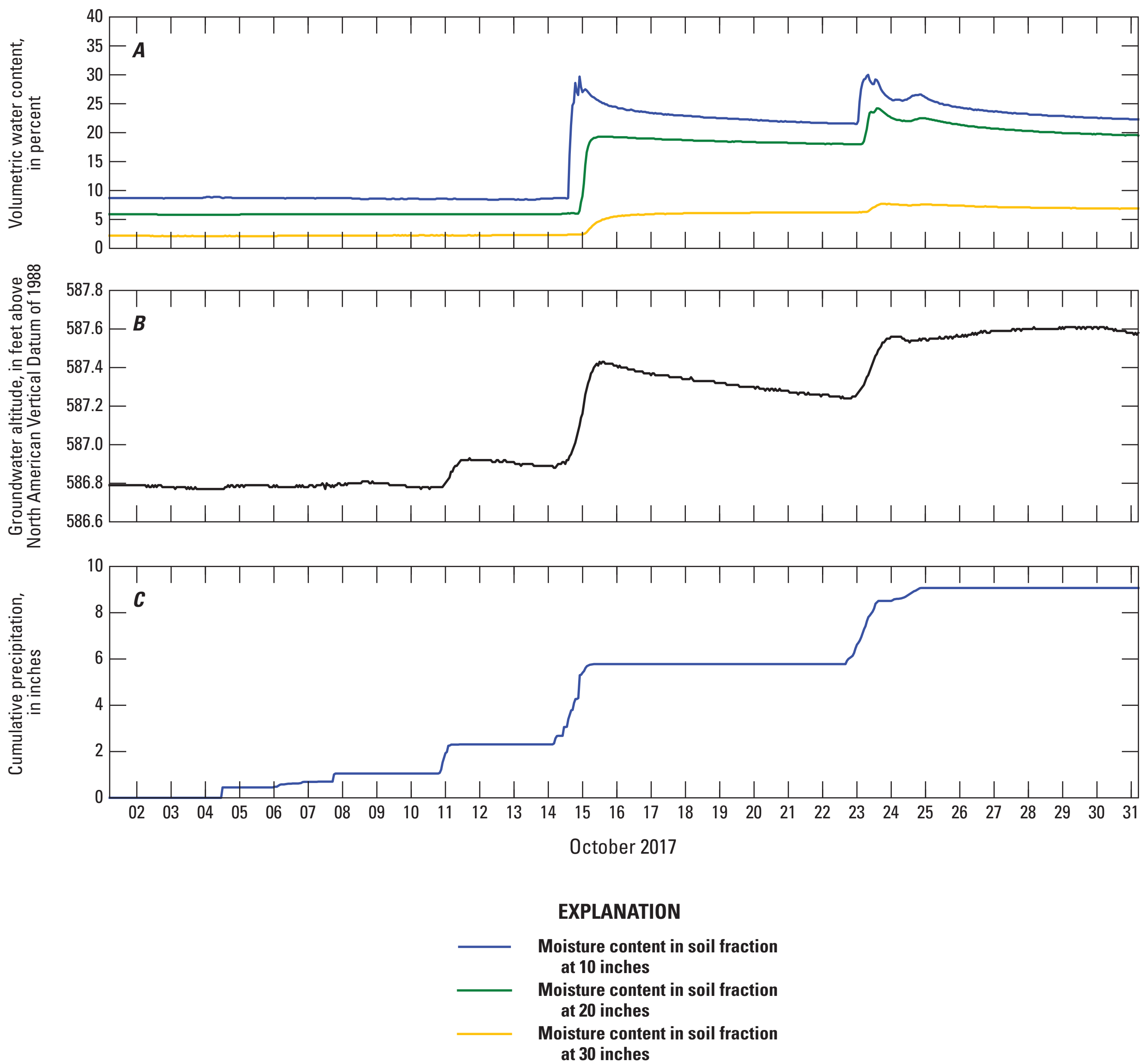

Figure 18. Example soil moisture and groundwater altitude hydrographs from data collected at well CH–2 showing the response of the soil moisture sensors and water level to multiple precipitation events in October 2017, Gary, Indiana.

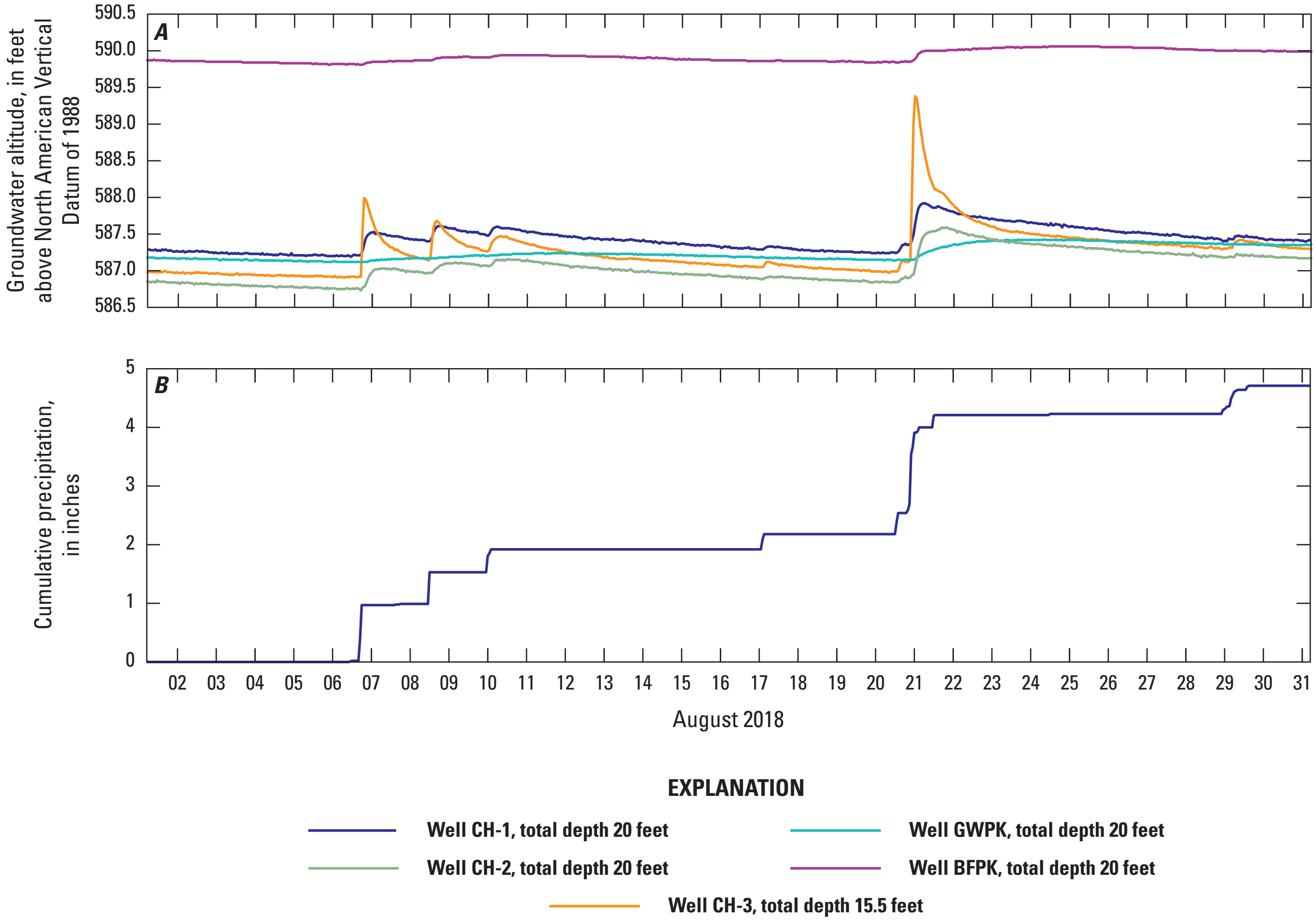

Figure 19. Example groundwater hydrographs for monitoring wells CH–1, CH–2, CH–3, GWPK, and BFPK for August 2018 showing the response of water levels to precipitation, Gary, Indiana.

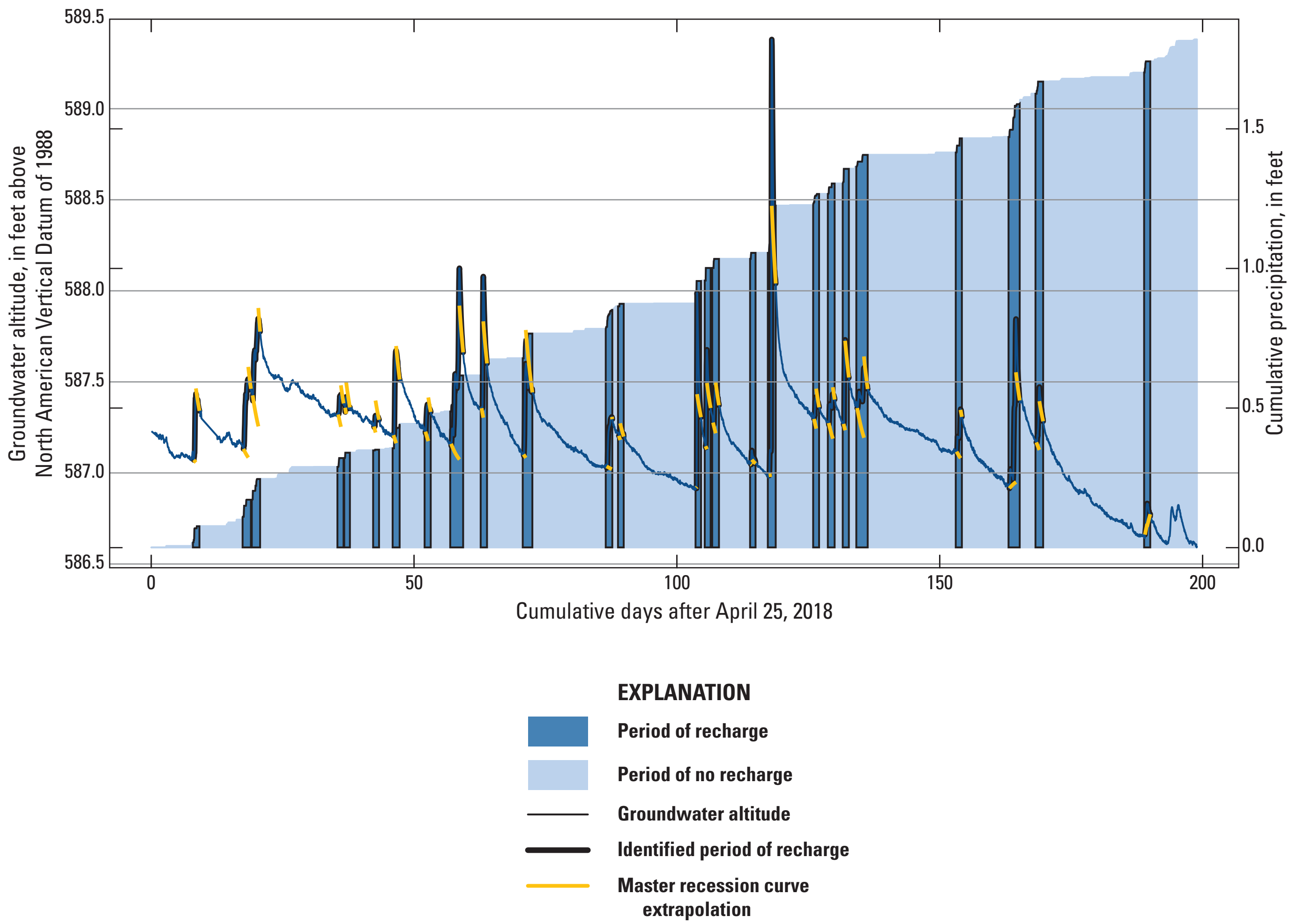

Figure 20. Example plot showing the continuous groundwater hydrograph, cumulative precipitation, and periods of episodic recharge identified by using the episodic master recession method for well CH–3 during the monitored period of 2018, Gary, Indiana.

Runoff from Paved Surfaces into the Rain Garden

Runoff from the paved surfaces that entered the rain garden was measured by using 12-in. H-flumes (fig. 21). Five flumes were spaced around the perimeter of the rain garden. Flumes were instrumented with continuously recording pressure transducers, installed in prefabricated stilling wells, to measure the depth of water passing through the downstream V-shaped opening in the flume. The discharge of runoff was calculated from the water depth by use of a manufacturer-supplied rating curve. Stilling wells were cleaned and transducers were checked for quality assurance approximately every 60 days. A 6-in. border of metal edging was installed around the parking lot to prevent runoff from flowing into the rain garden and instead directly through the inlets where the flumes were located.

Figure 21. Photographs showing *A*, the metal border between the parking surface and rain garden and an H-flume used to measure runoff at Gary City Hall in Gary, Indiana, and *B*, the H-flume used during the study. Photographs by David C. Lampe, U.S. Geological Survey.

Stormwater Reduction

The changes in discharges to the storm sewer during the preconstruction and postconstruction monitoring periods were used to evaluate the stormwater reductions resulting from the green infrastructure implementation at Gary City Hall.

The volume of water leaving the study area and entering the storm sewer as measured through the parking lot drains (fig. 22) and as estimated through the Massachusetts Street drain during the preconstruction period (May 11–September 7, 2016) was approximately 10,200 cubic feet (ft^3) or 25 percent of the total precipitation recorded during the period. The postconstruction volumes of water entering the storm sewer after installation of the Gary City Hall green infrastructure during the monitored periods (June 15–November 6, 2017; and April 25–November 9, 2018) were approximately 1,000 ft^3 and 1,600 ft^3, respectively, or 2 percent of the total precipitation recorded during both periods. Most of the precipitation during the unmonitored period from November through March likely fell as snow that melted slowly and infiltrated in place or flowed into the rain garden where it infiltrated and did not cause water to be discharged to the sewer.

The reduction in stormwater discharge to the sewer is largely a consequence of (1) reducing the amount of directly connected impervious area surrounding the sewer inlets immediately south of city hall by surrounding them with turf and native plantings and (2) constructing parking area to drain into a centralized rain garden in native and engineered soils that could infiltrate most runoff from the parking area. A plot of total precipitation in relation to total discharge to the sewer for all precipitation events during the preconstruction and postconstruction warm-weather monitoring periods shows the reduced stormflow discharge to the sewer for an equivalent amount of rainfall after the installation of the green infrastructure (fig. 23).

The equation of the best fit line relating the cumulative precipitation to the storm event discharge into the parking lot drain inlet structure for the preconstruction monitoring periods shown in figure 23 was calculated and is shown below in the form of equation 1:

$$V = 3{,}245.60(P) - 67.62 \qquad (9)$$

The coefficient of determination (R^2 statistic) for the linear regression in figure 23 indicates that the observed precipitation can explain 97 percent of the volume variability of water contributing to the storm sewer for individual storm events.

Equation 9 was used to calculate an equivalent, preconstruction volume of stormwater for individual storm events during the postconstruction monitoring period by using observed storm precipitation totals during the postconstruction period. The sum of the observed and estimated discharges from each storm event during the postconstruction monitoring period was used to determine the volume of stormwater reduced and the PSR. The reductions in the volumes of stormwater discharged to the sewer system in the postconstruction periods of monitoring (calculated using equation 2) were estimated as 2,900 and 5,300 ft^3 (21,400 and 39,300 gallons) in 2017 and 2018, respectively. The combined PSR for the postconstruction period is 80.3 percent.

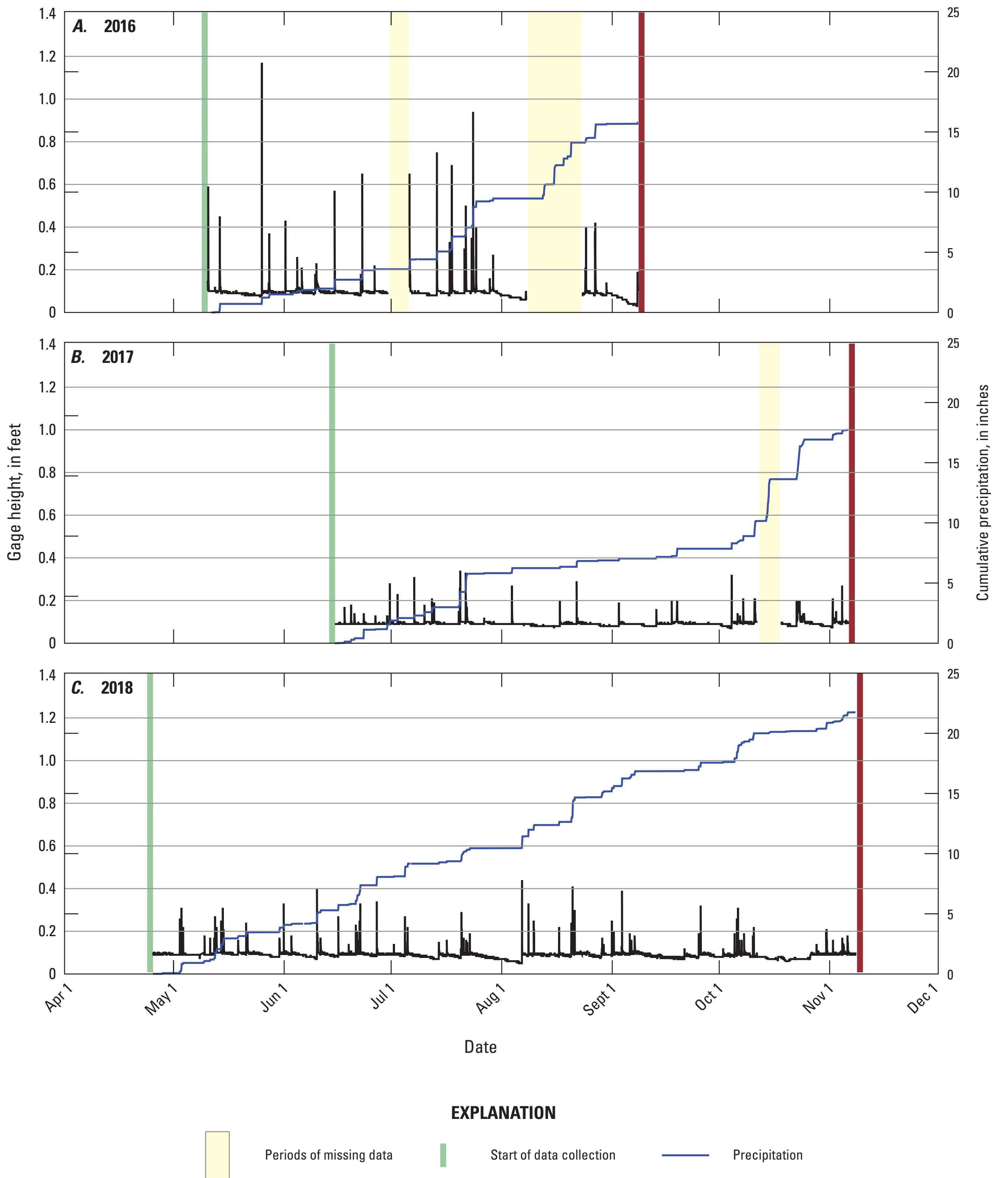

Figure 22. Plot of gage height in the drain with cumulative precipitation during the *A*, 2016 preconstruction, *B*, 2017, and *C*, 2018 postconstruction monitoring periods at Gary City Hall in Gary, Indiana.

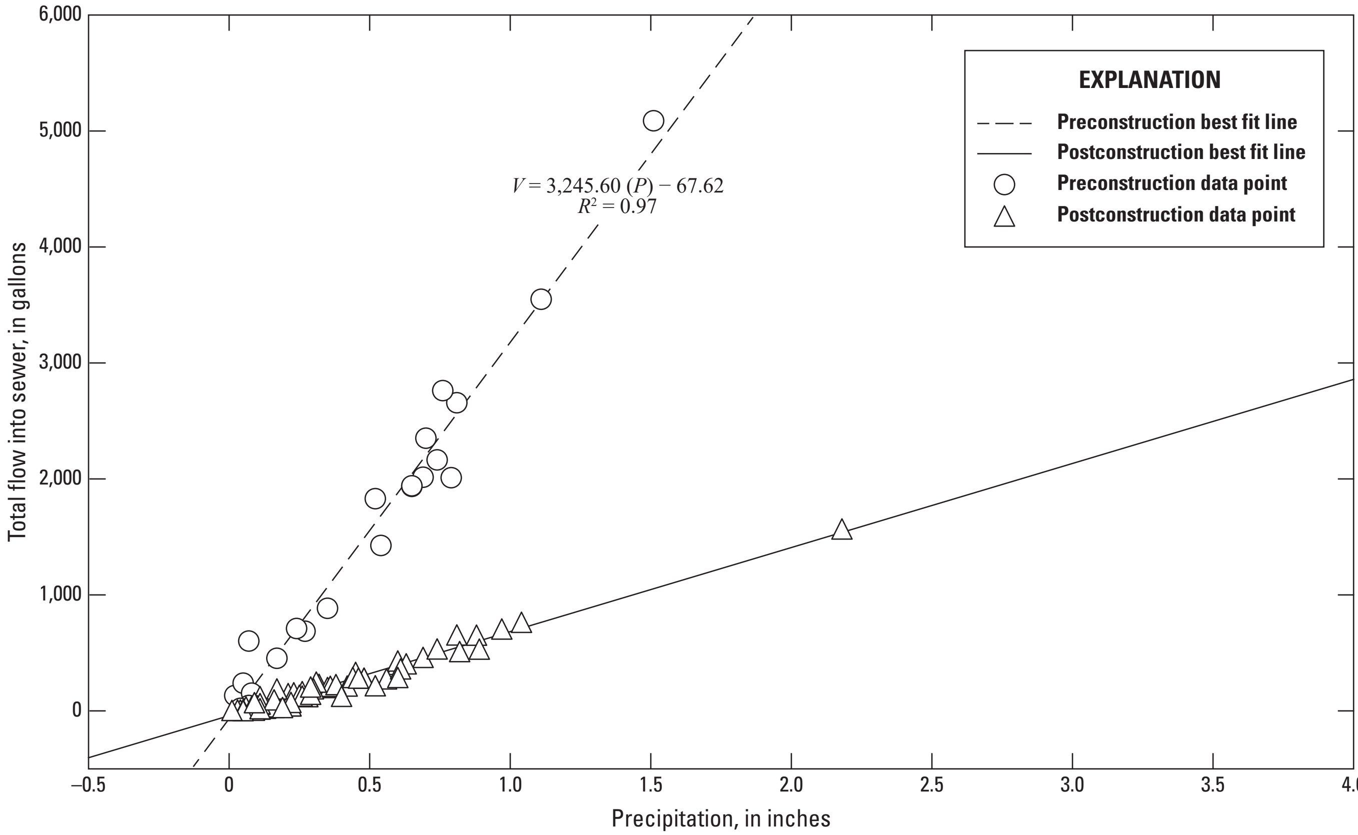

Figure 23. Plot of discharge to the sewer in relation to precipitation for individual precipitation events during the preconstruction and postconstruction monitored periods at Gary City Hall in Gary, Indiana. Lines were fit by linear regression to the data points from each period.

Water Budget Analysis

Water budgets were estimated from the measured data and from estimates based on measured data for the preconstruction and postconstruction monitoring periods at the Gary City Hall study area (2016–18). To better understand the fate of water that flowed into the rain garden, a separate water budget was computed specifically for the rain garden in 2017 and 2018.

Water Budgets for the Gary City Hall Green Infrastructure Study Area

Hydrologic measurements and estimates were used to develop the preconstruction and postconstruction water budgets for the Gary City Hall study area, excluding the rain garden area, and an individual water budget for the rain garden. Data were compiled for precipitation, the discharge from the parking lot drains to the storm sewer, and computed evapotranspiration (U.S. Geological Survey, 2020). Evaporation from impervious surfaces and recharge were estimated by using techniques described earlier in this report ("Monitoring and Estimation of Water-Budget Components"). Evaporation from paved surfaces was estimated to be 0.12 in. per storm, and that value was used to estimate evaporation totals for 17 storms in 2016, 27 storms in 2017, and 43 storms in 2018 (table 2).

Preconstruction and Postconstruction Water Budgets for the Study Area

There were six processes that removed precipitation or runoff input to the system from the study area (and the water budget) during the monitored parts of 2016–18, as identified in equation 4. The process that removed the most water from the water budgets in all 3 years was potential evapotranspiration (fig. 24; table 2). Potential evapotranspiration was estimated to remove 29 to 47 percent of the precipitation during 2016–18. The percentage was relatively consistent for all 3 years, although the area of green space increased somewhat with implementation of green infrastructure, and the monitored periods and corresponding weather were different.

The rain garden captured runoff from paved surfaces and removed 21 and 24 percent of the precipitation during 2017 and 2018, respectively. The rain garden capture (*Rg*) that appears in the water-budget equations for postconstruction

Table 2. Summary of water budget for the Gary City Hall study area in Gary, Indiana, for the monitored part of 2016–18.

[Percent (%) of total precipitation is given in parentheses. Letters in parentheses are variable names in the water-balance equations. eq., equation in the body of this report; NA, not applicable; ft^3, cubic foot]

Year	Water-balance equation	Period monitored (days)	Precipitation (*P*), ft^3 of water	Discharge to storm sewer from Massachusetts Street (Q_1), ft^3 of water and percent of total precipitation	Discharge to storm sewer from parking lot drain (Q_2), ft^3 of water and percent of total precipitation	Evapotranspiration (*ET*), ft^3 of water and percent of total precipitation	Evaporation from impermeable surfaces (*E*), ft^3 of water and percent of total precipitation	Groundwater recharge (*Re*),[a] ft^3 of water and percent of total precipitation	Rain garden capture (*Rg*), ft^3 of water and percent of total precipitation	Storage change and error ($\Delta S \pm e$), ft^3 of water and percent of total precipitation
2016	eq. 5	93	40,200	5,300 (13%)	4,900 (12%)	19,000 (47%)	4,400 (11%)	3,200 (8%)	NA	4,000 (10%)
2017	eq. 6	137	50,000	NA	1,000 (2%)	18,800 (38%)	7,900 (16%)	4,500 (9%)	10,700 (21%)	7,200 (14%)
2018	eq. 6	176	80,800	NA	1,600 (2%)	23,600 (29%)	12,500 (15%)	12,600 (16%)	19,700 (24%)	10,800 (13%)

[a]The mean groundwater recharge estimated using the episodic master recession method at wells CH–1 and CH–2. Assumes that recharge was equally distributed across the pervious area.

years (2017–18) is a lumped term that was not broken down into individual hydrologic components for the water budget of the entire Gary City Hall study area. In the following section, “Water Budget for the Gary City Hall Rain Garden,” the water budget for the rain garden is computed for the pertinent hydrologic processes.

During 2016, discharges to the storm sewer removed 13 and 12 percent of the total precipitation through the Massachusetts Street drain and parking lot drain, respectively, and 2 percent of the total precipitation during both 2017 and 2018 through the parking lot drains. The drainage area for the parking lot drain was greatly reduced and partially converted to grass during the installation of the green infrastructure, and the Massachusetts Street drain was removed in 2017 as part of the construction of the rain garden.

Groundwater recharge across the Gary City Hall green infrastructure area, taken as the mean of the recharge at wells CH–1 and CH–2 (table 3), removed from 8 to 16 percent of precipitation during the monitored parts of 2016–18 (table 2). Evaporation from paved surfaces removed 11 to 16 percent of the total precipitation falling on the study area during the monitored parts of 2016–18.

The storage of water onsite ranged from 10 to 14 percent of total precipitation. Storage (and error) at Gary City Hall was computed as the difference between the water inputs and outputs. The increase in recharge through time may be attributed to the construction of the rain garden in 2017 and the longer period of monitoring in 2018 that included April and May, when transpiration is less actively removing water from the system.

Water Budget for the Gary City Hall Rain Garden

Hydrologic measurements at the site were used to determine a water budget for the rain garden using equation 4 for the monitored periods of 2017 and 2018. Inputs to the water budget for the rain garden included direct precipitation onto the rain garden and runoff from the paved areas that constitute the drainage area for the rain garden. The paved drainage area to the rain garden was visually determined by onsite observations during precipitation events and totaled approximately 24,500 ft^2 (table 1).

Runoff coefficients, calculated by dividing the discharge measured at each flume for each storm event by the amount of precipitation falling in the drainage area, indicate that the flumes captured (on average) less than half of the total rainfall that fell on the paved surfaces (fig. 25*A*). Additionally, the differences between individual flumes indicate that some flumes capture a higher percentage of flow than others (fig. 25*B*). These values are lower than those typically associated with urbanized areas (0.50 to 0.95) and are more comparable to those listed for residential single family and suburban areas (0.25 to 0.50; California State Water Resources Control Board, 2022). The values may be lower than typical for urbanized areas because of the relatively small drainage area size and the site-specific conditions including (1) incomplete edging between the parking area and the rain garden that allowed water to enter the rain garden without being measured, (2) low-intensity or small total precipitation events that caused runoff into the rain garden that was less than the minimum stage required to quantify discharge, and (3) evaporation from paved surfaces. For all flumes except the north flume, the calculated runoff coefficient is higher in 2018 than 2017, indicating that the flumes captured a higher percentage of the total precipitation that fell in the catchment area in 2018 than 2017. The difference at the north flume may be because of

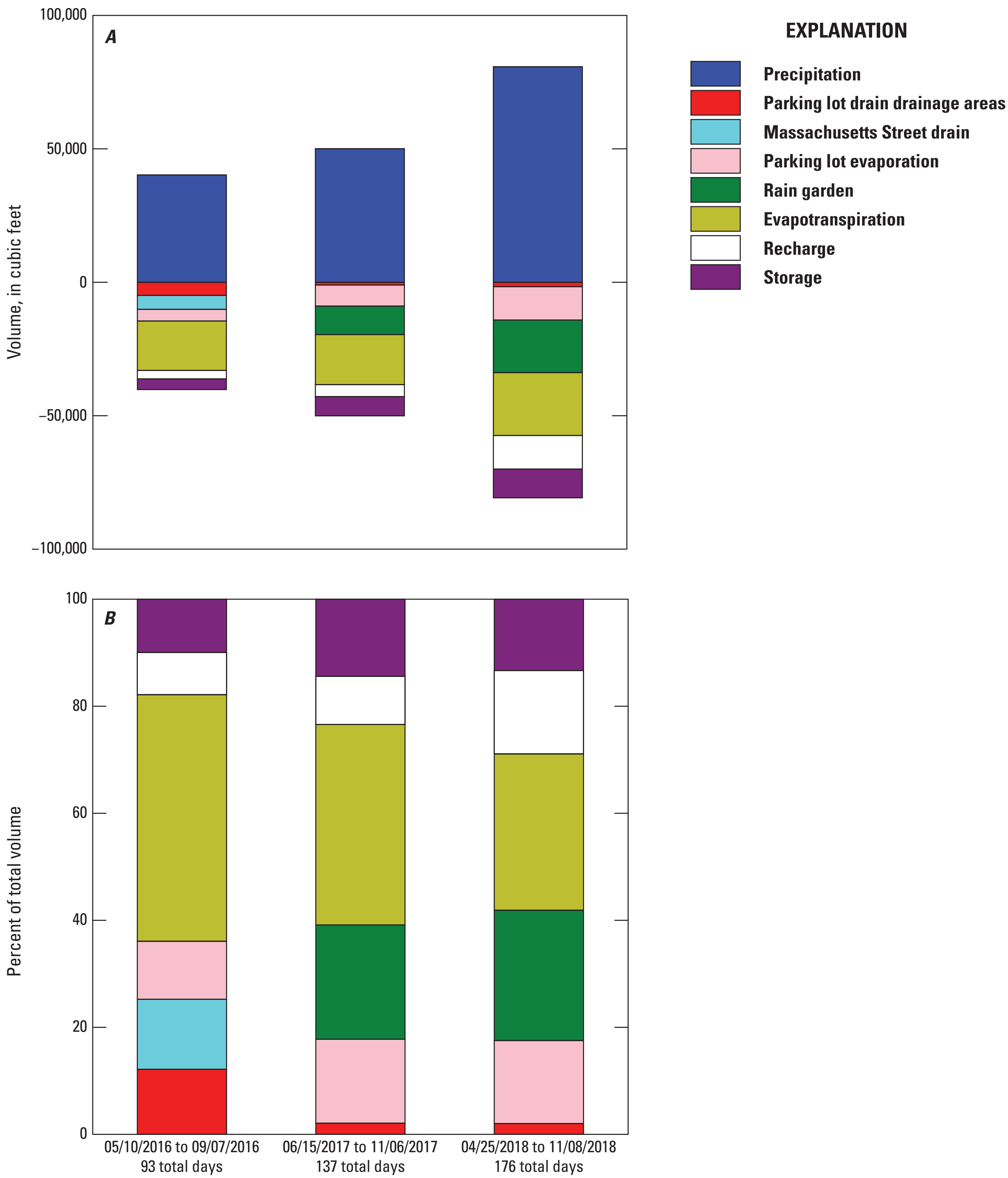

Figure 24. Plots showing the water budget in *A*, total volume and *B*, percent of total volume for the Gary City Hall study site (excluding the rain garden area) in Gary, Indiana, for the monitored periods in 2016–18. Negative values reflect volumes of water being removed from the water budget. Positive values reflect volumes of water being added to the water budget. Date format is month/day/year.

required repairs following the flume being dislodged during the winter of 2017 when the parking lot was plowed after a snowfall event.

The sums of water entering the rain garden from direct precipitation and runoff from pavement were approximately 15,100 and 26,800 ft^3 in 2017 and 2018, respectively. In 2017, 29 percent of the total water input to the rain garden was direct precipitation, and the remaining 71 percent was from runoff into the rain garden from paved surfaces. In 2018, about 26 percent of the total water input to the rain garden was direct precipitation, and the remaining 74 percent was runoff from paved surfaces (fig. 26; table 4). The total runoff into the rain garden from 35 precipitation events in 2017 was approximately 10,700 ft^3 (table 2), and the total runoff from 65 precipitation events in 2018 was approximately 19,700 ft^3 (tables 2 and 4). The rain garden captured 28 percent of the precipitation in the study area through direct precipitation or overland flow during the 2017 monitoring period and 31 percent during the 2018 monitoring period.

Hydrologic processes removing water from the rain garden water budget included discharges to the rain garden overflow (Q_3), estimated potential evapotranspiration in the rain garden (*ET*), and groundwater recharge (*Re*; eq. 7). In 2017 and 2018, evapotranspiration was the hydrologic process that removed the most water from the rain garden (31 and 22 percent, respectively), followed by groundwater recharge (13 and 19 percent, respectively). This relation is similar to the relation between the same properties for the entire study area (table 2). In the case of the rain garden, the ratio of the area available for *ET* to the rain garden catchment area is much smaller than the same ratio for the larger Gary City Hall study area and may explain the lower percentage of water removed by *ET*.

Recharge at the rain garden was computed by using processes described previously in this report (“Soil Moisture, Groundwater Levels, and Recharge”). In 2018, groundwater recharge was estimated to be 2.5–5 times higher at well CH–3, installed within the rain garden, than at other wells installed in other parts of the study area and in background locations (table 3). Because only water-level data for well CH–3 were available to estimate groundwater recharge in 2018, the relation of recharge rates estimated for wells CH–1 and CH–3 in 2018 were used to estimate the recharge rate for CH–3 in 2017; that was then used to estimate total recharge within the rain garden for the water budget. Groundwater levels fluctuated more in the rain garden (well CH–3) than at the other wells. The large quantities of water delivered to the rain garden during individual storms may force infiltration beyond the root zone to the water table, where the infiltrating water recharges the groundwater and is less available for plant transpiration; this may not be the case for the larger Gary City Hall study area where less water is estimated to be available for infiltration. The computed recharge for the rain garden assumes that only the area beneath the footprint of the vegetated garden had recharge; however, because of the highly permeable natural sediments, recharge resulting from infiltration into the rain garden likely affected a larger area that includes part of the subsurface beneath the larger Gary City Hall study area.

Discharges to the combined sewer through the rain garden overflow pipe removed less than 1 percent of the precipitation that fell on the rain garden catchment area in 2018; no flow was recorded through the rain garden overflow in 2017. The sewer discharge was the smallest quantity of water subtracted from the rain garden water budget. The relatively small amount of water discharged to the sewer through the overflow pipe may be attributed to the highly permeable natural soils and appropriate rain garden design and engineering.

Storage of water in the rain garden accounted for 56 and 59 percent of the water inputs in 2017 and 2018, respectively. Reservoirs for temporary storage could include the unsaturated zone beneath the rain garden and surrounding areas and the permeable pipe buried beneath the rain garden. Backwater conditions were observed at the eastern flumes leading to the rain garden from Massachusetts Street; these conditions would cause estimates of flow into the rain garden to be greater than actual flow, resulting in inflated estimated storage values (fig. 21*B*).

Table 3. Recharge at the Gary City Hall study area, Gary, Indiana, 2016–18.

[Recharge calculated by using precipitation and groundwater-level data measured at the site and analyzed with the episodic master recession method (Follette and others, 2022). ND, no data available; --, not applicable]

Monitoring well name	Recharge, in inches				
	2016	2017	2018	Site mean	Site median
BFPK	2.43	4.04	3.35	3.28	3.35
CH–1	2.17	3.83	10.39	5.46	3.83
CH–2	2.12	2.96	8.55	4.54	2.96
CH–3	ND	ND	15.17	15.17	15.17
GWPK	4.04	2.82	3.00	3.29	3.00
Annual mean	2.69	3.41	9.27	--	--
Annual median	2.30	3.39	8.55	--	--

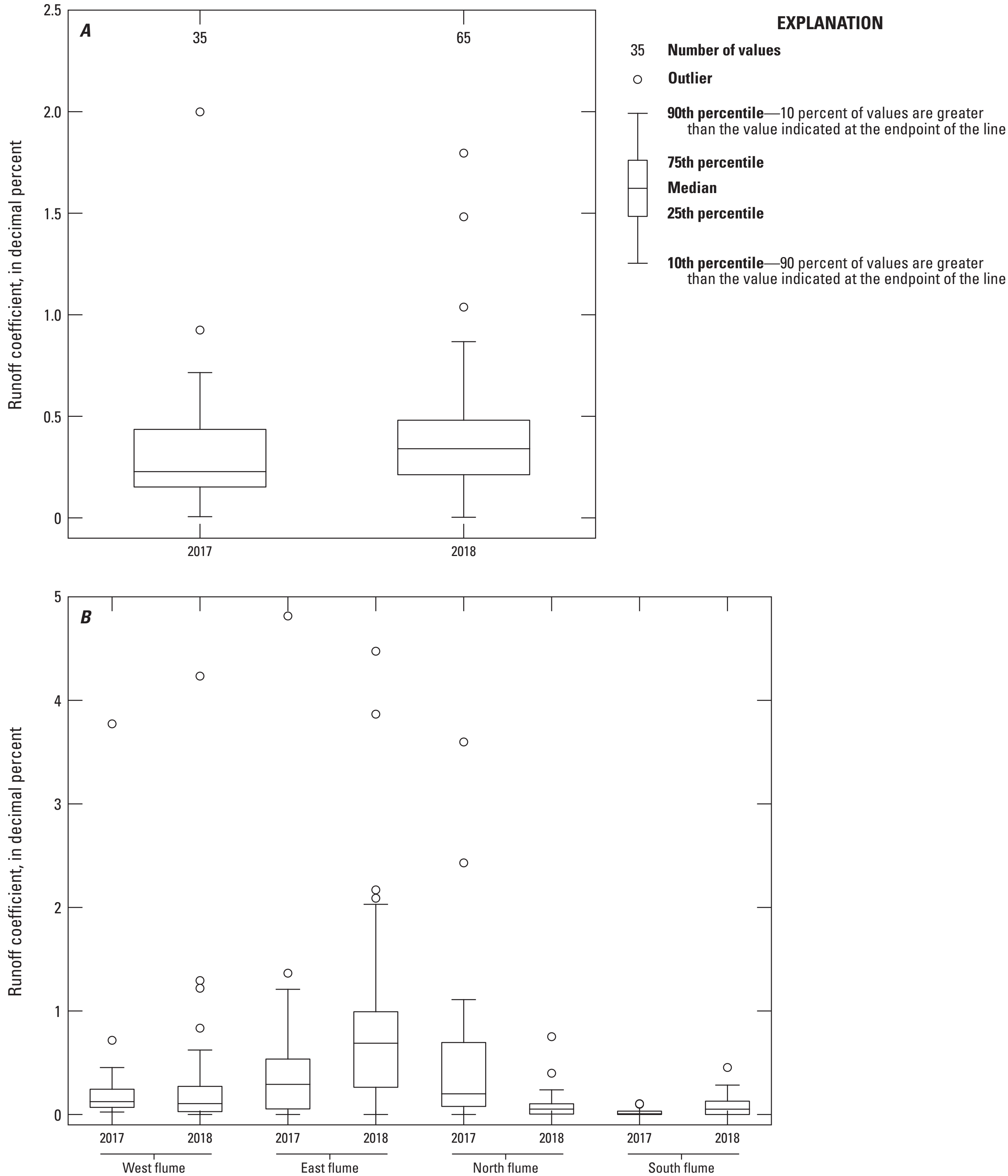

Figure 25. Box plots showing the percentage of *A*, total precipitation falling on paved surfaces in the rain garden drainage area that was measured by the flumes and, *B*, precipitation measured by each individual flume for the rain garden at Gary City Hall in Gary, Indiana.

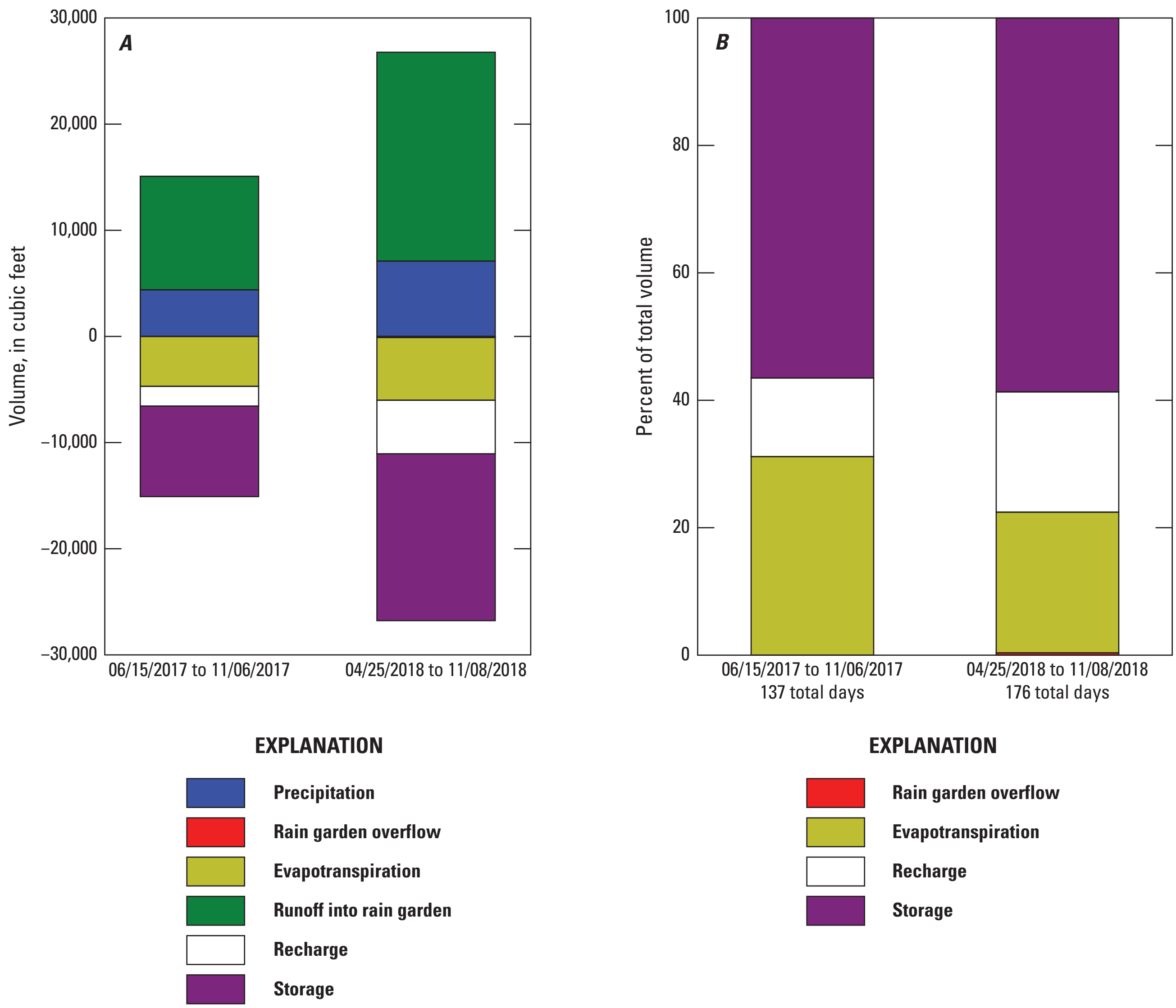

Figure 26. Plots showing the water budget in *A*, total volume and *B*, percent of total volume for the rain garden at the Gary City Hall study area in Gary, Indiana, for the monitored periods in 2017 and 2018. Negative values reflect volumes of water being removed from the water budget. Positive values reflect volumes of water being added to the water budget. Date format is month/date/year.

Limitations

The monitored period was unequal in duration from year to year, which is a consideration when comparing the annual water budgets. In addition, monitoring data were collected only during the warm-weather months of the year. The system understanding and relative percentages of water-budget components based on the data collected for this study may differ if data from the entire water year, including the cold-weather months, were included in the analyses.

Potential sources of errors in the water budget computations include but are not limited to the following:

1. *Application of empirical equations and estimation methods.*—The empirical methods used to compute evapotranspiration and groundwater recharge depend on the extent that the method's assumptions were met. In addition, PET in the rain garden was computed by using the Penman equation with the same parameters used for grass because parameters for the native species in the garden were unknown. The EMR method required subjective manual calibration. Evaporation from paved surfaces assumed that the amount of precipitation that fell before flow was initiated at flumes was equal to the amount of water left on the surface to evaporate after flow ceased. Some amount of direct precipitation was intercepted, retained on plants, and later evaporated. This quantity was not included in the water budget for the rain garden.

Table 4. Summary of water budget for the Gary City Hall rain garden in Gary, Indiana, for the monitored periods of 2017 and 2018.

[Percentages (%) are given in parentheses. Letters in parentheses are the variable names in the water-balance equation. eq., equation in the body of this report; ft^3, cubic foot]

Year	Water-balance equation	Period monitored (days)	Direct precipitation (*P*), ft^3 of water and percent of total inflow into rain garden	Rain garden capture (*Rg*), ft^3 of water and percent of total inflow into rain garden	Discharge to the rain garden overflow (Q_3), ft^3 of water and percent of direct precipitation and rain garden capture	Evapotranspiration (*ET*), ft^3 of water and percent of direct precipitation and rain garden capture	Groundwater recharge (*Re*), ft^3 of water and percent of direct precipitation and rain garden capture	Storage change and error ($\Delta S \pm e$), ft^3 of water and percent of direct precipitation and rain garden capture
2017	eq. 7	137	4,400 (29%)	10,700 (71%)	0 (0%)	4,700 (31%)	1,900 (13%)	8,500 (56%)
2018	eq. 7	176	7,100 (26%)	19,700 (74%)	100 (0.4%)	5,900 (22%)	5,100 (19%)	15,700 (59%)

2. *Using estimates of recharge from well CH–3 to calculate recharge for the entire area of the rain garden*.—Recharge is likely underestimated within the rain garden water budget. Infiltrating precipitation and runoff into the rain garden likely flows through the subsurface outside of the rain garden perimeter.

3. *Inaccuracy of instrument measurements during periods of extremely low and high precipitation and incomplete data records*.—Continuous data records for the monitored periods were largely complete, and measurement devices were regularly inspected for movement and calibrated. Some low-intensity rainfall events may not have generated runoff, and, as a result, that quantity of precipitation may not show up as evaporation from paved surfaces. During high-intensity rainfall events, the volume of water entering the rain garden may be underestimated at the flumes, especially those on the eastern side of the rain garden being inundated and producing backwater conditions or overtopping the edging funneling water to the flumes. It also is possible that runoff at unedged boundaries of the rain garden occurs before or after flow begins and ends at the flumes; this might introduce inaccuracy in the evaporation estimates.

4. *Sources or losses of water not included in the water budget*.—No sources or losses of water were intentionally ignored; however, some minor sources of water, such as leaky sewers, may have minor effects on the site hydrology and the interpreted water budget.

5. *Variable drainage area boundaries*.—Drainage area boundaries were visually identified during precipitation events. Some boundaries might change location during precipitation events with extreme intensity and duration and introduce inaccuracy into the water budget computations. All precipitation events were treated identically, and catchment areas remained constant.

Summary and Conclusions

The green infrastructure implemented at Gary City Hall nearly eliminated stormwater discharges to the sewer system, as most precipitation that fell at the study site was held in storage before being removed by evapotranspiration or groundwater recharge. The percent stormwater reduction during the combined postconstruction monitoring period was 80.3 percent. The estimated volume of stormwater discharged to the sewer system reduced in the postconstruction periods of monitoring was estimated as 2,900 and 5,300 ft^3 (21,400 and 39,300 gallons) in 2017 and 2018, respectively.

The quantities of water attributed to each of the variables in the water-budget equation indicate the following:

1. Discharge to the storm sewer declined from approximately 25 percent of the total precipitation measured at the site in 2016 to 2 percent of the total precipitation measured at the site for both 2017 and 2018 after installation of green infrastructure at Gary City Hall in 2017.

2. Median evaporation from the paved surfaces ranged from 0.10 to 0.13 inch during the monitored periods in 2017 and 2018.

3. Discharges to the combined sewer through the rain garden overflow pipe removed less than 1 percent of the precipitation that fell on the rain garden catchment area, the least quantity of water subtracted from the rain garden water budget.

4. Water entering the rain garden through overland flow from the parking lot or direct precipitation accounted for 28 and 31 percent of all precipitation falling in the study area during the monitored periods in 2017 and 2018, respectively.

5. Groundwater recharge in the rain garden, characterized by applying the EMR method to data collected at well CH–3, was estimated to be approximately 15 inches

in 2018, 2.5 to 5 times more than the recharge values estimated by the EMR method for monitoring wells in turf-covered areas elsewhere in the study area.

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Appendix 1. Monitoring Sites Used for Gary City Hall Green Infrastructure Evaluation

Table 1.1. Monitoring sites used in the evaluation of green infrastructure at Gary City Hall in Gary, Indiana, 2016–18.

[Inches in "Measurement type" column indicate depth of sensor below land surface. Date format is YYYY-MM-DD (year-month-day). USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; ft, foot; NWIS, National Water Information System; °, degree; ', minute; ″, second; ND, no data available; --, not applicable]

Site name	USGS site identifier	Latitude (NAD 83)	Longitude (NAD 83)	Land surface altitude (NAVD 88)	Sampling period used for this report
WELL BFPK-1 AT BUFFINGTON PARK IN GARY, IN	413558087200401	41°35′58.13″	87°20′04.24″	600.49	2016-05-10 to 2018-11-08
WELL CH-1 AT CITY HALL, GARY, IN	413610087201001	41°36′09.51″	87°20′09.62″	599.08	2016-05-10 to 2018-11-08
CITY HALL SOUTHEAST FLUME AT GARY, IN	413611087200901	41°36′11″	87°20′09″	598.08	2017-06-15 to 2018-11-08
CITY HALL RAIN GARDEN OVERFLOW AT GARY, IN	413611087200903	41°36′11″	87°20′09″	598.96	2017-06-15 to 2018-11-08
CITY HALL NORTH FLUME AT GARY, IN	413611087201001	41°36′11″	87°20′10″	598.96	2017-06-15 to 2018-11-08
CITY HALL SOUTH FLUME AT GARY, IN	413611087201002	41°36′11″	87°20′10″	598.74	2017-06-15 to 2018-11-08

Table 1.1. Monitoring sites used in the evaluation of green infrastructure at Gary City Hall in Gary, Indiana, 2016–18.—Continued

[Inches in “Measurement type” column indicate depth of sensor below land surface. Date format is YYYY-MM-DD (year-month-day). USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; ft, foot; NWIS, National Water Information System; °, degree; ', minute; ″, second; ND, no data available; --, not applicable]

Site name	Measurement type	Sampling depth (ft)	NWIS link
WELL BFPK-1 AT BUFFINGTON PARK IN GARY, IN	Groundwater level above NAVD 1988, ft	20.2	https://waterdata.usgs.gov/nwis/uv/?site_no=413558087200401
	Moisture content, soil, volumetric, fraction of total volume, [10 inches]	0.83	https://waterdata.usgs.gov/nwis/uv/?site_no=413558087200401
	Moisture content, soil, volumetric, fraction of total volume, [20 inches]	1.67	https://waterdata.usgs.gov/nwis/uv/?site_no=413558087200401
	Moisture content, soil, volumetric, fraction of total volume, [30 inches]	2.5	https://waterdata.usgs.gov/nwis/uv/?site_no=413558087200401
	Soil temperature, degrees Celsius, [10 inches]	0.83	https://waterdata.usgs.gov/nwis/uv/?site_no=413558087200401
	Soil temperature, degrees Celsius, [20 inches]	1.67	https://waterdata.usgs.gov/nwis/uv/?site_no=413558087200401
	Soil temperature, degrees Celsius, [30 inches]	2.5	https://waterdata.usgs.gov/nwis/uv/?site_no=413558087200401
WELL CH-1 AT CITY HALL, GARY, IN	Groundwater level above NAVD 1988, ft	20.3	https://waterdata.usgs.gov/nwis/uv/?site_no=413610087201001
	Moisture content, soil, volumetric, fraction of total volume, [10 inches]	0.83	https://waterdata.usgs.gov/nwis/uv/?site_no=413610087201001
	Moisture content, soil, volumetric, fraction of total volume, [20 inches]	1.67	https://waterdata.usgs.gov/nwis/uv/?site_no=413610087201001
	Moisture content, soil, volumetric, fraction of total volume, [30 inches]	2.5	https://waterdata.usgs.gov/nwis/uv/?site_no=413610087201001
	Soil temperature, degrees Celsius, [10 inches]	0.83	https://waterdata.usgs.gov/nwis/uv/?site_no=413610087201001
	Soil temperature, degrees Celsius, [20 inches]	1.67	https://waterdata.usgs.gov/nwis/uv/?site_no=413610087201001
	Soil temperature, degrees Celsius, [30 inches]	2.5	https://waterdata.usgs.gov/nwis/uv/?site_no=413610087201001
CITY HALL SOUTHEAST FLUME AT GARY, IN	Discharge, cubic feet per second	land surface	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087200901
	Gage height, feet	land surface	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087200901
CITY HALL RAIN GARDEN OVERFLOW AT GARY, IN	Discharge, cubic feet per second	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087200903
	Gage height, feet	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087200903
CITY HALL NORTH FLUME AT GARY, IN	Discharge from gage height	land surface	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201001
	Gage height, feet	land surface	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201001
CITY HALL SOUTH FLUME AT GARY, IN	Discharge from gage height	land surface	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201002
	Gage height, feet	land surface	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201002

Table 1.1. Monitoring sites used in the evaluation of green infrastructure at Gary City Hall in Gary, Indiana, 2016–18.—Continued

[Inches in “Measurement type” column indicate depth of sensor below land surface. Date format is YYYY-MM-DD (year-month-day). USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; ft, foot; NWIS, National Water Information System; °, degree; ', minute; ″, second; ND, no data available; --, not applicable]

Site name	USGS site identifier	Latitude (NAD 83)	Longitude (NAD 83)	Land surface altitude (NAVD 88)	Sampling period used for this report
WELL CH-3 AT CITY HALL, GARY, IN	413611087201004	41°36′11″	87°20′10″	598	2016-05-10 to 2018-11-08
CITY HALL WEST FLUME AT GARY, IN	413611087201101	41°36′11″	87°20′11″	599.19	2017-06-15 to 2018-11-08
CITY HALL WEST SUBDRAINAGE AT GARY, IN	413611087201102	41°36′11″	87°20′11″	ND	2017-08-15 to 2018-11-08
CITY HALL WEATHER STATION AT GARY, IN	413611087201301	41°36′11.06″	87°20′12.89″	599.22	2016-05-10 to 2018-11-08
CITY HALL NORTH-EAST FLUME AT GARY, IN	413612087200901	41°36′12″	87°20′09″	598.22	2017-06-15 to 2018-11-08
CITY HALL EAST SUBDRAINAGE AT GARY, IN	413612087200902	41°36′12″	87°20′09″	ND	2017-08-15 to 2018-11-08
CITY HALL DRAIN OUTFLOW AT GARY, IN	413612087201001	41°36′12.11″	87°20′09.57″	595.45	2016-05-10 to 2018-11-08
CITY HALL NORTH-EAST SUBDRAINAGE AT GARY, IN	413612087201002	41°36′12″	87°20′10″	ND	2017-08-15 to 2018-11-08
CITY HALL NORTH-WEST SUBDRAIN-AGE AT GARY, IN	413612087201201	41°36′12″	87°20′12″	ND	2017-08-15 to 2018-11-08

Table 1.1. Monitoring sites used in the evaluation of green infrastructure at Gary City Hall in Gary, Indiana, 2016–18.—Continued

[Inches in "Measurement type" column indicate depth of sensor below land surface. Date format is YYYY-MM-DD (year-month-day). USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; ft, foot; NWIS, National Water Information System; °, degree; ', minute; ″, second; ND, no data available; --, not applicable]

Site name	Measurement type	Sampling depth (ft)	NWIS link
WELL CH-3 AT CITY HALL, GARY, IN	Groundwater level	15.5	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201004
CITY HALL WEST FLUME AT GARY, IN	Discharge from gage height	land surface	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201101
	Gage height, feet	land surface	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201101
CITY HALL WEST SUBDRAINAGE AT GARY, IN	Gage height, feet	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201102
CITY HALL WEATHER STATION AT GARY, IN	Temperature, air, degrees Fahrenheit	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201301
	Wind speed, miles per hour	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201301
	Wind direction, degrees clockwise from true north	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201301
	Relative humidity, percent	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201301
	Potential evapotranspiration (PET), calculated by Penman method, millimeters per hour	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201301
	Precipitation, cumulative, inches	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201301
	Solar radiation (average flux density on horizontal surface during measurement interval), kilowatts per square meter	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201301
	Solar radiation (total flux density on horizontal surface during measurement interval), megajoules per square meter	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413611087201301
CITY HALL NORTH-EAST FLUME AT GARY, IN	Discharge, cubic feet per second	land surface	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087200901
	Gage height, feet	land surface	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087200901
CITY HALL EAST SUBDRAINAGE AT GARY, IN	Gage height, feet	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087200902
CITY HALL DRAIN OUTFLOW AT GARY, IN	Discharge, cubic feet per second	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087201001
	Gage height, feet	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087201001
CITY HALL NORTH-EAST SUBDRAINAGE AT GARY, IN	Gage height, feet	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087201002
CITY HALL NORTH-WEST SUBDRAINAGE AT GARY, IN	Gage height, feet	--	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087201201

Table 1.1. Monitoring sites used in the evaluation of green infrastructure at Gary City Hall in Gary, Indiana, 2016–18.—Continued

[Inches in “Measurement type” column indicate depth of sensor below land surface. Date format is YYYY-MM-DD (year-month-day). USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; ft, foot; NWIS, National Water Information System; °, degree; ', minute; ″, second; ND, no data available; --, not applicable]

Site name	USGS site identifier	Latitude (NAD 83)	Longitude (NAD 83)	Land surface altitude (NAVD 88)	Sampling period used for this report
WELL CH-2 AT CITY HALL, GARY, IN	413612087201301	41°36′11.84″	87°20′13.09″	ND	2016-05-10 to 2018-11-08
WELL GWPK AT GATE-WAY PARK IN GARY, IN	413615087201301	41°36′14.84″	87°20′12.86″	599.29	2016-05-10 to 2018-11-08

Table 1.1. Monitoring sites used in the evaluation of green infrastructure at Gary City Hall in Gary, Indiana, 2016–18.—Continued

[Inches in “Measurement type” column indicate depth of sensor below land surface. Date format is YYYY-MM-DD (year-month-day). USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; ft, foot; NWIS, National Water Information System; °, degree; ', minute; ″, second; ND, no data available; --, not applicable]

Site name	Measurement type	Sampling depth (ft)	NWIS link
WELL CH-2 AT CITY HALL, GARY, IN	Groundwater level above NAVD 1988, ft	20	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087201301
	Moisture content, soil, volumetric, fraction of total volume, [10 inches]	0.83	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087201301
	Moisture content, soil, volumetric, fraction of total volume, [20 inches]	1.67	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087201301
	Moisture content, soil, volumetric, fraction of total volume, [30 inches]	2.5	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087201301
	Soil temperature, degrees Celsius, [10 inches]	0.83	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087201301
	Soil temperature, degrees Celsius, [20 inches]	1.67	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087201301
	Soil temperature, degrees Celsius, [30 inches]	2.5	https://waterdata.usgs.gov/nwis/uv/?site_no=413612087201301
WELL GWPK AT GATEWAY PARK IN GARY, IN	Groundwater level above NAVD 1988, ft	20.1	https://waterdata.usgs.gov/nwis/uv/?site_no=413615087201301
	Moisture content, soil, volumetric, fraction of total volume, [10 inches]	0.83	https://waterdata.usgs.gov/nwis/uv/?site_no=413615087201301
	Moisture content, soil, volumetric, fraction of total volume, [20 inches]	1.67	https://waterdata.usgs.gov/nwis/uv/?site_no=413615087201301
	Moisture content, soil, volumetric, fraction of total volume, [30 inches]	2.5	https://waterdata.usgs.gov/nwis/uv/?site_no=413615087201301
	Soil temperature, degrees Celsius, [10 inches]	0.83	https://waterdata.usgs.gov/nwis/uv/?site_no=413615087201301
	Soil temperature, degrees Celsius, [20 inches]	1.67	https://waterdata.usgs.gov/nwis/uv/?site_no=413615087201301
	Soil temperature, degrees Celsius, [30 inches]	2.5	https://waterdata.usgs.gov/nwis/uv/?site_no=413615087201301

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