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Hydrologic Performance of Retrofit Rain Gardens in a Residential Neighborhood (Cleveland OH USA) with a Focus on Monitoring Methods

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Hydrologic Performance of Retrofit Rain Gardens in a Residential Neighborhood (Cleveland Ohio USA) with a Focus on Monitoring Methods

by

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Abstract

Green infrastructure refers to a range of urban stormwater management tools that can be flexibly implemented. These practices can aid in mitigating the negative impacts of runoff by increasing catchment detention capacity. We studied two engineered rain gardens in Cleveland OH that were designed to infiltrate and detain direct runoff volume generated from an adjacent roadway, and sheet flow from pervious areas of each catchment area. We also accounted for hydrologic interactions between the engineered and upslope basic (non-engineered) rain gardens. A whole water-cycle monitoring approach was employed to fully assess the role of green infrastructure interventions on performance as inflows captured, duration of outflow drainage (i.e., excess moisture), hydrologic losses (e.g., evapotranspiration), and groundwater table dynamics to accumulate warm-season stormflow data. The 75th Street South rain garden captured nearly 180,000 gallons of stormwater with a total duration of inflows of 308 hours. The duration of outflows in this 17-month period was 54 hours. This indicates that there isa outflow from the rain garden for only 17 percent of all rainfall-inflow events. Additional evidence indicates that these outflows were shallow and never approach surcharging the outflow pipe. Overall, the 75th Street South rain garden effectively contributed sufficient detention capacity, as the garden design ponding depth of 0.75 ft was not exceeded for any of the monitored storm events. Post-event shallow ponding (max. 0.4 ft) – an indicator of rooting zone saturation – persisted for less than a day, and for only 13 out of 138 possible events. Analysis of groundwater level data showed that the upslope basic rain gardens interacted with the downslope 75th Street South rain garden, and that the nature of this interaction shifted with growing versus senescent seasons.

The 75th Street North rain garden, which is downstream of the 75th Street South rain garden, came on line about 5 months after the 75th Street South rain garden. The 75th Street North rain garden came on line later in the project period, and for this rain garden within the shorter 12-month monitoring period, there was a cumulative total of more than 100,000 gallons of stormwater, over a period of 500 hours of inflow. There was ouflow from the 75th Street North rain garden for more than double (640 hours) the duration recorded for the 75th Street South rain garden. The 75th Street North rain garden outflow events typically had long recession times at very low flows. The 75th Street North rain garden was at the lowest point in a larger, vegetated catchment area, and experienced backflow (through the outflow pipe) from the combined sewer (CS) conveyance. These situational features enhanced subsurface runoff volume into the garden, and backflows from the CS contributed to an increased total duration of outflows.

The comprehensive, full water-cycle monitoring approach ensured qualification of important hydrologic processes that contribute to the overall effectiveness of these rain garden technologies. Due to the small difference in the invert elevations of the garden overflow pipe and its connection to the CS conveyance, we found that sewer flow can and does backup into the monitored outfall. This malfunction highlights the importance of properly siting and plumbing the engineered rain garden system.

We present an overview of rain garden monitoring practices and discuss the suitability and appropriateness of both passive low-cost, and research-grade monitoring strategies with regard to monitoring objectives; and provide example equipment-parts lists to aid in scaling level-of-effort and associated costs.

Key Words: Green infrastructure, stormwater management, wastewater management, combined sewers, sewershed, rain gardens, bioretention.

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Introduction

Much of the concern over stormwater comes from the quantity and quality of rainwater or snowmelt that flows over impervious surfaces such as roofs, parking lots, roads, and sidewalks. All cities have some degree of difficulty meeting the challenge of managing urban runoff. The density and concentration of impervious surfaces can produce a great deal of runoff, and this excess water volume is quickly and efficiently routed toward centralized sewer collection system inlets. Stormwater from separated storm systems has typically been routed directly to streams. However, either separated or combined sewer systems have finite volume capacity, and if this capacity is exceeded, the result is often local flooding, and combined sewer overflows (CSOs), respectively. Alternately, not only does excess stormwater volume and rainfall-derived inflow and infiltration (RDII) deplete system capacity, but its conveyance to the wastewater treatment plant also incurs an unecessary treatment burden.

A variety of practices known variously as best management practices (BMPs), green infrastructure (GI), low-impact development (LID), and stormwater control measures (SCMs; Fletcher et al., 2013) typically are used to regulate runoff production and routing in urban and suburban areas. These practices include but are not limited to; rain gardens, cisterns, rain barrels, and porous pavement. Importantly, each of these SCMs are scalable to balance stormwater management objectives with the amount of space that is available. SCMs modulate the local water cycle by creating intentional losses and by adding detention capacity to the catchment area. In tandem with grey infrastructures (pipes, pumps, ditches, and detention ponds), SCMs may aid in controlling the volume of stormwater routed into the sewer system, and lessen the likelihood of CSOs, sanitary sewer overflows (SSOs), and other sewer system malfunctions. These SCMs are designed to reduce or delay peak flows of stormwater runoff by enhancing evapotranspiration and more generally, by retaining, detaining, and infiltrating water across the landscape. These SCMs may also improve stormwater quality by pollutant removal and transformation, and through the mechanisms of settling, filtration, and the enhancement of beneficial biogeochemical processes (Hunt et al., 2008; Hatt et al., 2009).

One type of SCM technology is the rain garden, also referred to as a biodetention basin. A rain garden integrates plant and soil processes to improve landscape-level stormwater detention through intentional hydrologic losses. The flow into and out of the rain garden is a function of many internal hydrologic processes (e.g., inputs, losses, transfers) that regulate water movement through each SCM and that affect system performance. These hydrologic losses include: infiltration (the movement of water into soil), redistribution (the diffusion of soil water throughout the soil matrix), percolation to groundwater, and evapotranspiration, which is the combination of direct evaporation from the ground surface; and if the surface is vegetated, transpiration through drawing up of soil water through plant roots, and release of this moisture to the atmosphere through leaf stomata.

Once SCMs are implemented, there is often no follow-up monitoring that would otherwise lead to certification of effectiveness. This dearth of data impacts our understanding of the efficacy of GI as a management strategy, and its broader implementation toward control of stormwater volume. As a note to the reader, we will use performance and effectiveness as equivalent terms to describe how well the system achieves its objectives over a continuum of rainfall forcing and changing antecedent conditions. Monitoring the hydraulic characteristics of SCM features is important to understand how water moves through under differently-sized storm events, to identify design flaws or maintenance issues, and to overall document effectiveness of the design. For example, Dumouchelle and Darner (2014) monitored infiltration and redistribution of soil moisture in the lower garden of a two-rain garden network (Cincinnati OH; Shuster et al., 2017) with sensors based on time-domain reflectometry. A time series of soil moisture at each of several depths was used to visualize the movement of water over the course of rainfall events. These data were used as a feedback to identify and improve the function of the rain garden. This quantitative information pointed out significant, but relatively simple modifications to the rain garden. After implmentation of these fixes, the detention capacity in the rain garden was increased, and without causing undesirable ponding.

The use of these SCMs in cities like Cleveland OH is intended to reduce direct stormwater runoff and the release of untreated septic and stormwater directly to numerous low-order streams, the Cuyahoga River, and ultimately, Lake Erie (Figure 1). The need for a changing approach to stormwater control in Cleveland has a basis in an economically-driven transformation of land use. This transformation began in 2007 with the emergence of the sub-prime mortgage and foreclosure crisis. Subsequent devaluation of residential properties led to wholesale abandonment, and when the condition of these structures was compromised, citizens and city officials worked in concert to demolish these structures. For example, Slavic Village, an urban neighborhood on the near southeast side of Cleveland employed demolition to control blight, and at present, more than one-third of its land area is in vacant lots, with some streets almost entirely vacant (Figure 1). Aside from the social, cultural, and economic tradeoffs and impacts of wholesale demolition, the demolition process can produce vacant lots that are backfilled with impermeable materials (e.g., clayey soils), and are net producers of stormwater runoff. By recognizing the potential, and positive impact that an environmentally-sound demolition may have on air, water, and soil, U.S. Environmental Protection Agency (U.S. EPA) Region 5 developed guidance as demolition bid specifications (U.S. Environmental Protection Agency, 2013). Yet, the present stock of vacant lots are limited to retrofit strategies to improve their hydrologic function and utility. For example, retrofit of vacant lots with rain gardens transform the vacant lot into a net absorber of rainfall and upstream runoff volume. This new hydrologic setting can then prevent runoff from forming, concentrating, and ultimately overwhelming local sewer systems.

Through a cooperative arrangement (interagency agreement 14-95831101-5), the U.S. EPA Office of Research and Development and the U.S. Geological Survey applied whole water-cycle monitoring to quantify the overall hydrologic impact of retrofit SCM interventions at the neighborhood scale. The Slavic Village area of Cleveland, because of its application of SCMs, was especially well-suited for this type of monitoring. In order to leverage existing vacant landscapes toward beneficial reuse, the Slavic Village Community Development Corporation petitioned the Northeast Ohio Regional Sewer District (NEORSD) to be one of their SCM pilot communities; NEORSD subsequently implemented three engineered rain gardens.

In this study, engineered rain gardens include features such as; curb-cut inlets, mulched root zone soil, a gravel drainage layer with internal drainage, an overflow to sewer system, and decorative plantings. Two engineered rain gardens were installed along the east side of East 75th Street and the third was installed on an elevated area of East 80th Street (Figure 2). Basic rain gardens include features such as shallow excavation, improved soils, intentional plantings, though no engineered features such as curb cuts, nor drainage and conveyance of overflow or excess soil moisture to the sewer system. Nine basic rain gardens were interspersed on vacant lots throughout the neighborhood; these were installed by the Cleveland Botanical Garden. The USGS installed 30 wells, two weather stations, and instrumented the two rain gardens on East 75th Street for volumetric inflows and durational outflows to the sewer system. This report presents information to quantify hydrologic performance of two of the engineered rain gardens set in former vacant areas of Slavic Village and impacts to the overall groundwater system from all SCMs. The report also presents the monitoring approach used to quantify hydrologic performance. In particular, we describe how this monitoring system was built to achieve specific objectives to make sound conclusions about how this complex hydrologic system repsonds to changing conditions (rainfall pattern, antecedent moisture conditions, etc.). We go on to describe a range of monitoring techniques, from the simplest and most passive, to research-grade, automated systems. This information is intended to build practitioner awareness of the different monitoring technologies and how each is appropriate for whichever level of complexity that specific project objectives may call for.

Methods

Site Description and Geology

The site is in the Slavic Village area of Cleveland, Ohio (Figure 1). The land use is predominantly residential with lot sizes of less than 1/6 acre. Impervious paved and rooftop areas that are directly-connected to sewers are common. Geologic and soils makeup near the easternmost part of the study area consists of shallow bedrock at less than 10 ft below land surface overlain by unconsolidated lake bed sediments and then by urban fill. Four wells in close proximity to each other (CU-35, CU-36, CU-38, and CU-39) each intersect shallow bedrock at less than 10 ft (Figure 2). The bedrock lithology encountered by these wells is described as Late Devonian age Berea Sandstone and Bedford Shale and Early Mississppian age sandstone and shale of the Cuyahoga Formation (Pavey and others, 2000). Bedrock is overlain by unconsolidated material of the Wisconsinan glaciation.This material includes till at the bedrock surface overlain by silt and clay with interbedded layers of fine sand or gravel. The composition of strata transitions in the downslope, west-northwest direction, as the top of bedrock elevation drops into the Cuyahoga River valley. In that direction, the lake bed sediments are thicker, and are overlain with more recent urban fill. The geology at the western edge of the study area is Devonian age Ohio Shale overlain by up to 290 ft of valley-fill Wisconsinan glaciation sand. Overall, there is nearly 50 ft of surface elevation change across the study area from a high at well CU-49 to a low at well CU-31 (Figure 1). The geologic stack map (Figure 1) was developed from interpolated soil core or well log records (Pavey and others, 2000). Yet, the core taken in the installation of well CU-31 was composed prediminantly of sands interbedded with silt loams, and indicated that the start of the sandier

Devonian formation is actually eastward of the previously mapped formations. Given the spatial variability of these deposits and their layering, it is important to take and assess soil cores to confirm or correct mapped soils-geology. This approach improves accuracy of site charcterization compared to using heavily-interpolated maps, and informs qualified decisions about surface and subsurface lithology features that may impact the performance of SCMs in urban systes that rely on infiltration and drainage for their proper function.

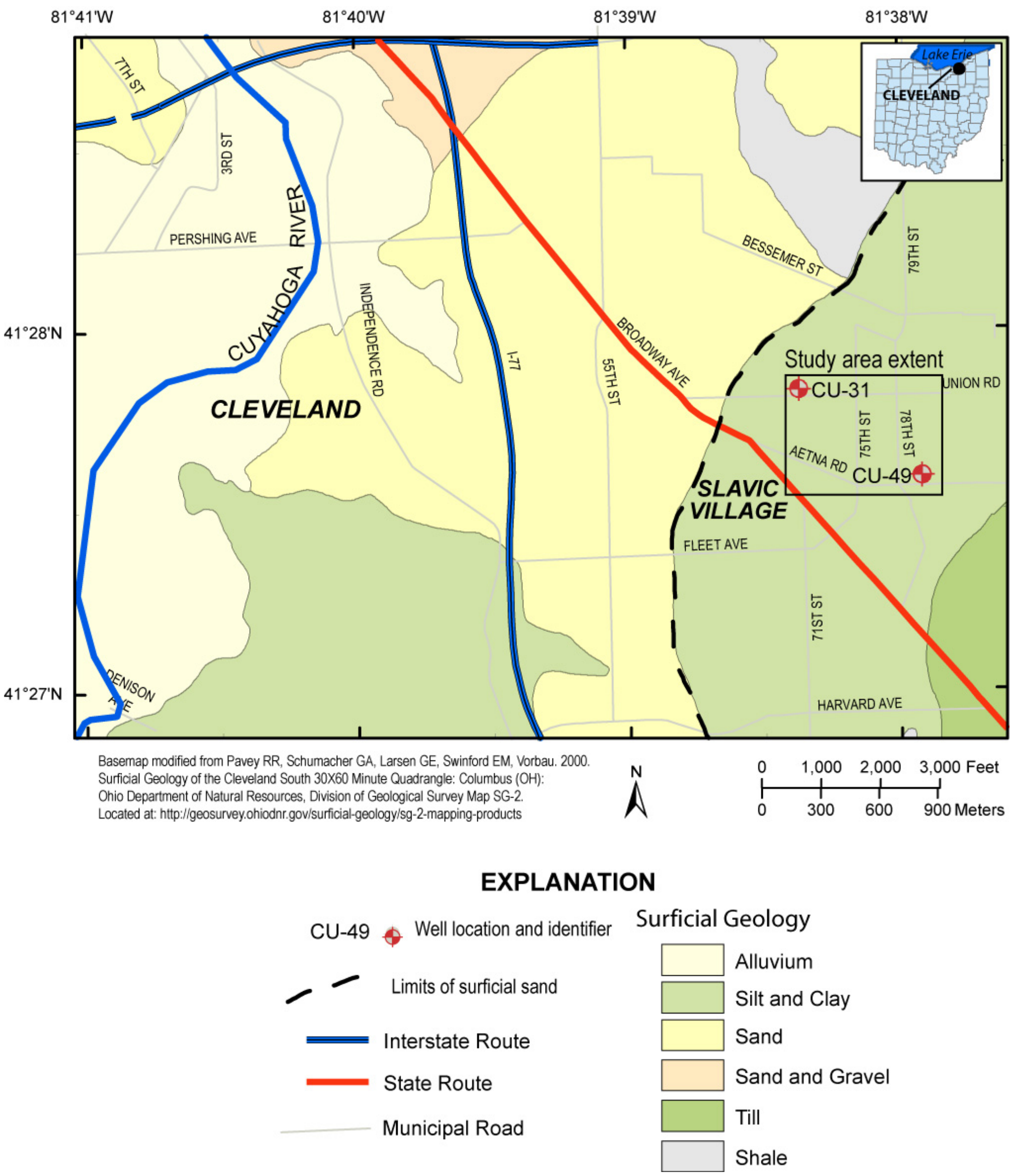


Figure 1. Study site in the context of underlying surficial geology.

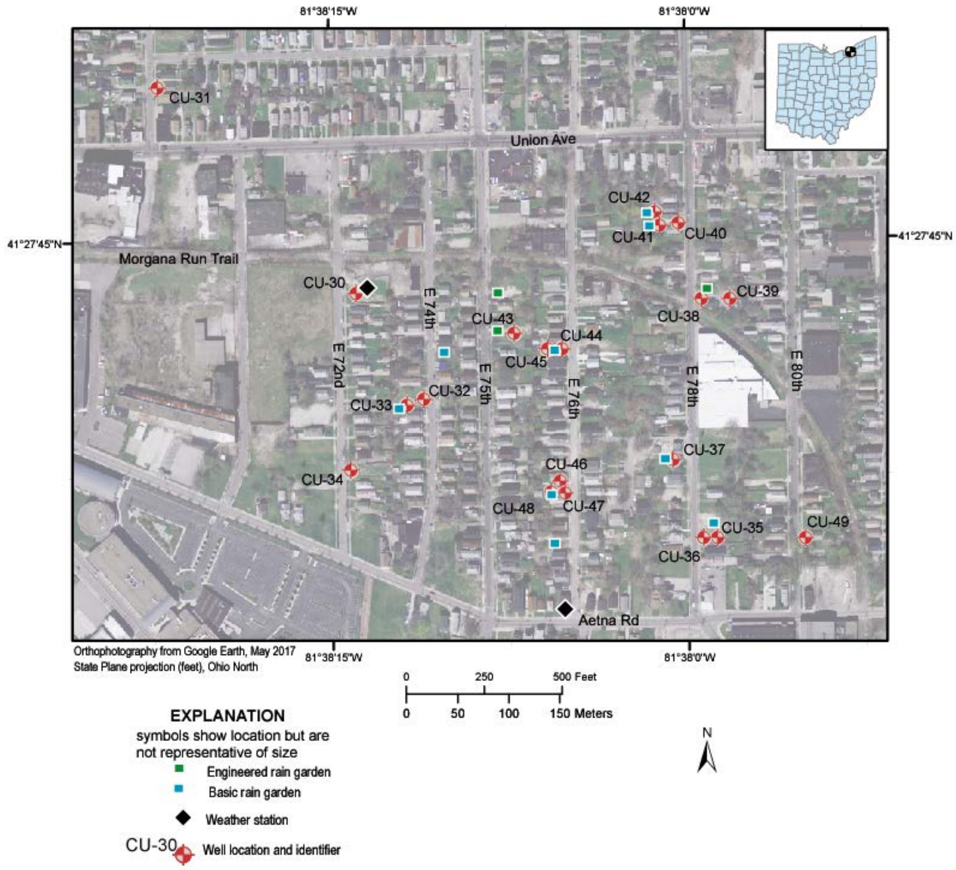


Figure 2. Study area with groundwater well locations.

Instrumentation was installed in September of 2013 prior to SCM installation to start collection of a baseline record using two weather stations to cover the catchment area, twenty groundwater wells installed in a grid with transects bounded by East 70th Street on the west, East 80th Street on the east, Union Avenue on the north and Aetna Road on the south, and flow monitoring in a large sewer interceptor pipe running beneath/astride and along Union Avenue that drains septic and storm flows from this neighborhood. Figure 2 shows the location of 20 shallow groundwater wells, 2 weather stations, and 2 engineered rain gardens that have runoff measurement instrumentation (75th Street North and South). Along with detailed soil surveys (from 72nd Street east to 80th Street) in 2011, a topographic survey was conducted along each of 72nd and 75th Streets to delineate drainage areas in this neighborhood area.

Soil Hydrology

For at least four locations in each rain garden, we eastimated rain garden infiltration rate with measurements of near-saturated surface hydraulic conductivity [K_{unsat}] were made with tension infiltrometers run at a suction head of 2 cm (Mini-Disk Infiltrometers; Decagon Devices, Pullman, WA). This unsaturated measurement technique served to exclude high variation in saturated hydraulic conductivity (K_{sat}) due to structural cracks and other macroporous sinks for flow, and emphasized the measurement of matrix flow into surface soils. Separate measures were made for organic-mulch and mineral soil surfaces in the basic rain gardens; the mulch layer in engineered gardens was for the most part washed aside by 2016, eliminating the need for separate measurements. K_{unsat} was calculated according to manufacturer-recommended methods. Soil texture class (e.g., silt loam) was determined by feel-test (Natural Resources Conservation Service, 2018). The saturated hydraulic conductivity of sub-soil horizons was measured in both basic and the engineered 75th Street South rain gardens with a compact constant head permeameter (CCHP or Amoozemeter; Ksat, Inc., Raleigh, NC). Water flux data collected from the CCHP was used to calculate K_{sat} via Eq. 1:

$$K_{sat} = AQ \qquad [1]$$

where K_{sat} is the subsurface hydraulic conductivity, A is a constant based on the radius and head of water in the borehole, and Q is the steady-state rate of water flow into the borehole. The method treats the equilibrium outflow of water from the borehole in an assumed quasi-spheroidal geometry, and transforms this outflow to a value of K_{sat}. We take this K_{sat} value as a proxy measure for drainage.

Meteorology

The weather station (model ET107; Campbell Scientific; Logan UT) on 72nd Street was installed in an open field August 2011, and the weather station on 76th Street was installed in a corner vacant lot December 2012. This arrangement of weather monitoring was done to account for the potential impact of residential structures on the meteorology of the overall site. The weather station on 72nd Street is in a field with clearance free from structures, while the weather station on 76th Street is next to the road with residences on three sides. Data were recorded at 5- or 60-minute intervals, stored on the data logger, and transmitted regularly to the NWIS database, and near real-time data can be accessed online using the NWIS web interface. Meteorological data available from each weather station included: 5-minute interval precipitation, 60-minute interval air temperature; barometric pressure; solar radiation; relative humidity; and wind speed and direction, all of which were integrated to calculate hourly reference evapotranspiration (ET_O) using the ASCE Standardized Reference Evapotranspiration equation (Penman-Monteith method; Monteith, 1964).

The weather stations were customarily checked every 6 to 8 weeks for proper function, and full calibration checks and maintenance of the instrumentation were done twice a year (spring, fall), according to project specific QA/QC specifications. The instrument used to measure precipitation was an unheated tipping bucket. During the late fall and winter, precipitation data were checked against air temperature data. For periods when the air temperature was below freezing, precipitation data were flagged and disregarded. For warm-season events, tipping bucket rain gages are known to under-report precipitation during high-intensity rainfall greater than about 1 inch per hour (U.S. Geological Survey, 2006). However, the vast majority of rainfall events considered for this study had an average rainfall intensity of less than 1 inch per hour. As per good monitoring practice, the rain gage should be kept in the same location for the duration of the study and properly maintained. All monitoring data are accessible on the NWIS Web interface (U.S. Geological Survey, 2016) and for individual sites at the following URLs:

https://nwis.waterdata.usgs.gov/oh/nwis/uv/?cb_00045=on&format=gif_default&site_no=412743081381400&period=&begin_date=2012-10-01&end_date=2016-09-30

https://nwis.waterdata.usgs.gov/oh/nwis/uv/?cb_00045=on&format=gif_default&site_no=412733081380500&period=&begin_date=2012-10-01&end_date=2016-09-30

Rain Garden Design

The Northeast Ohio Regional Sewer District (NEORSD) contracted for design and installation of three engineered rain gardens, and the Cleveland Botanical Garden (CBG) installed nine minimally-engineered (basic) rain gardens in the Slavic Village neighborhood (Figures 2-4). The general objective of the engineered rain gardens was to demonstrate that parcel-level rain gardens could absorb and otherwise redistribute anticipated runoff volume from directly-connected impervious area (e.g., streets, driveways, sidewalks) through curb-cuts, runoff from the immediate surrounding drainage area, and direct rainfall catch. The engineered rain gardens each have sub-surface perforated pipes to remove excess soil moisture in the root zone during saturating rainfall events. These engineered rain gardens contain two media layers: 1) an uppermost biosoil layer composed of an engineered sandy loam soil amended with compost, and 2) an aggregate base layer designed for stormwater storage (Figure 3). In general, the design for both 75th Street engineered rain gardens consisted of 1 ft of gravel covered by 2-3 ft of engineered soil, with subsurface perforated drainage tile connected to a combined sewer system (CSS) through the legacy residential sanitary service lateral. Due to poor contractor selection of soils (clayey fill), the soil in both engineered rain gardens was also replaced during the spring of 2015 and the rain gardens were replanted. Water flow into the basic rain gardens was limited to direct rainfall catch and runoff from surrounding landscapes. This limitation on potential inflow that improved stormwater detention and abatement was due to city-level administrative constraints that disallowed a curb-cut entry to the basic rain gardens. The basic rain gardens were assessed for soil hydrology several times over the course of the study, and were the focus of a U.S. EPA and Ohio State University study on pollinator activity in these basic rain gardens (M. Spring, 2018).

The 75th Street South rain garden was built with an area of 530 ft^2, and design plans indicated that the 75th Street South rain garden receives water from approximately 0.9 acres or about 39,000 ft^2 (Figure 3a). U.S. EPA delineated impervious surface coverage with Google Earth Pro tools and determined that the directly-connected impervious area (DCIA) was 19,000 ft^2, which is about half of the NEORSD estimate of approximately 39,000 ft^2, for the design standard. The 75th Street South rain garden outflow is in a 6-inch diameter pipe that is 8 ft underground, where it connects directly to the legacy residential sewer lateral (also at 8 ft of depth), which is partially blocked by roots and stones. The underdrains are commonly used to drain the rooting zone of excess soil moisture.

The 75th Street North rain garden is downstream of the 75th Street South rain garden, has an area of 415 ft^2, and receives runoff from a larger (1.1 acre) catchment area composed of largely grassed meadow sloped down and inward at its perimeter (Figure 3b). U.S. EPA delineated impervious surface coverage with Google Earth Pro tools and determined that the directly-connected impervious area (DCIA) was 11,000 ft^2. With regard to actual monitored contributions to 75th Street North rain garden inflow, the drainage area receives flow generated from the section of the street downstream from the 75th Street South rain garden curb cut inlet. This flow is composed of sheet flow along the curb that bypassed (either due to shallow street flow, or some proportion of deeper, high flows that could overwhelm the 75th Street South rain garden inlet) the 75th Street South rain garden curb cut inlet; and in addition, direct rainfall, and overland sheet flow from the surrounding meadow areas. As in the 75th Street South rain garden, the 75th Street North rain garden subsurface perforated drain tile is connected to a legacy residential sewer lateral that is connected to the CSS at a depth of about 8 ft. The North legacy lateral is 12 inches in diameter and the South legacy lateral is 6 inches in diameter. The North subsurface perforated underdrain is 6 inches in diameter and ends in a valve (that remained fully open for the entirety of the study) that connects to the 12-inch diameter legacy residential lateral in an overflow structure. Surveys of the North rain garden indicate that the elevation inverts for the rain garden outflow and the legacy lateral are similar, so circumstances are such that flow may be exchanged in both directions between the rain garden and CSS.

There were also nine basic rain gardens in the study area developed by the CBG (Figure 4b). The driving concept behind these minimally-engineered, basic rain gardens was to use minimal financial and resource inputs to maximize infiltration, drainage, and erosion control through improvements in both surface soils and re-vegetation (Chaffin and others, 2016), primarily with Common Yarrow (*Achillea millefolium*). These practices were assessed for soil texture, infiltration, drainage only, and there was no continuous monitoring conducted for any of these sites. Basic rain gardens received direct rainfall, and varying amounts of unmonitored sheet flow from adjacent vacant and residential lots. By 2016, one site had been reclaimed by the local community development corporation, leaving 8 basic rain gardens for the remainder of the study, the most pertinent being the basic garden located upslope of the 75th Street South engineered rain garden.

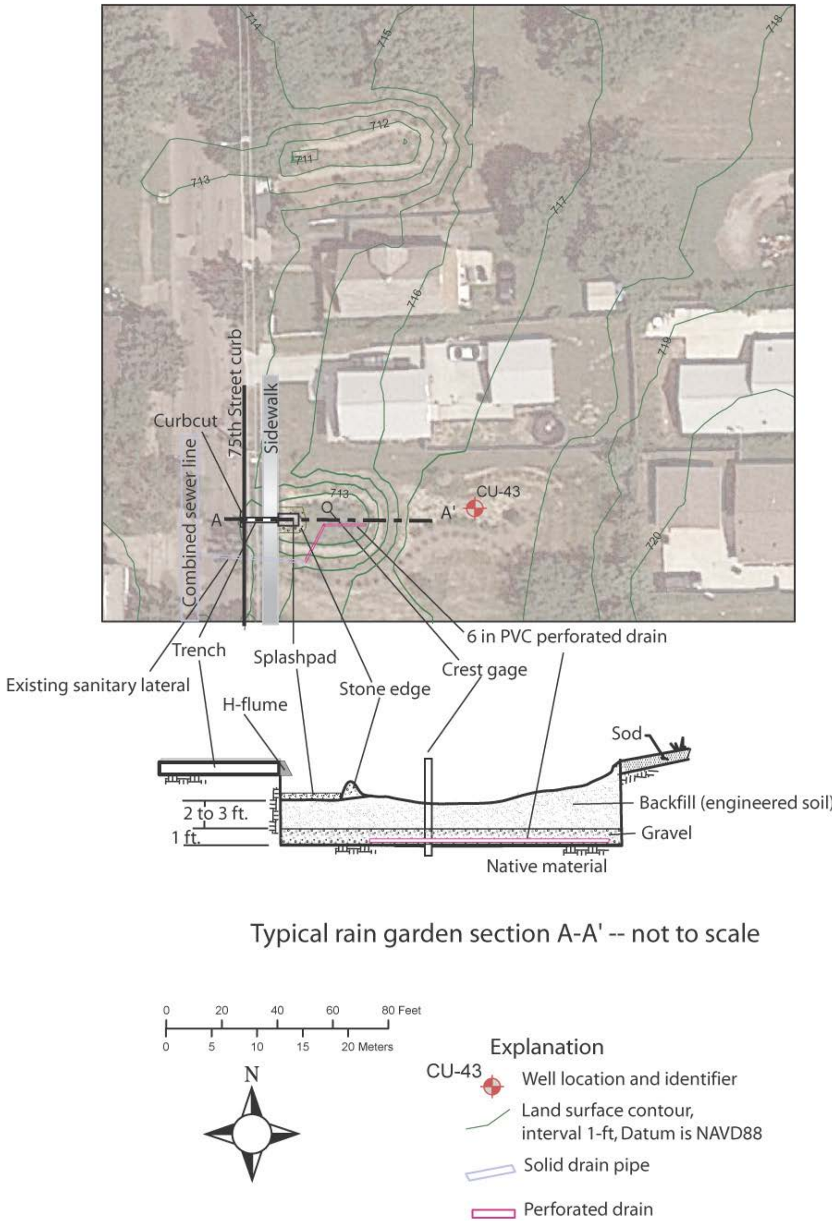


Figure 3a. Schematic of 75th Street South rain garden.

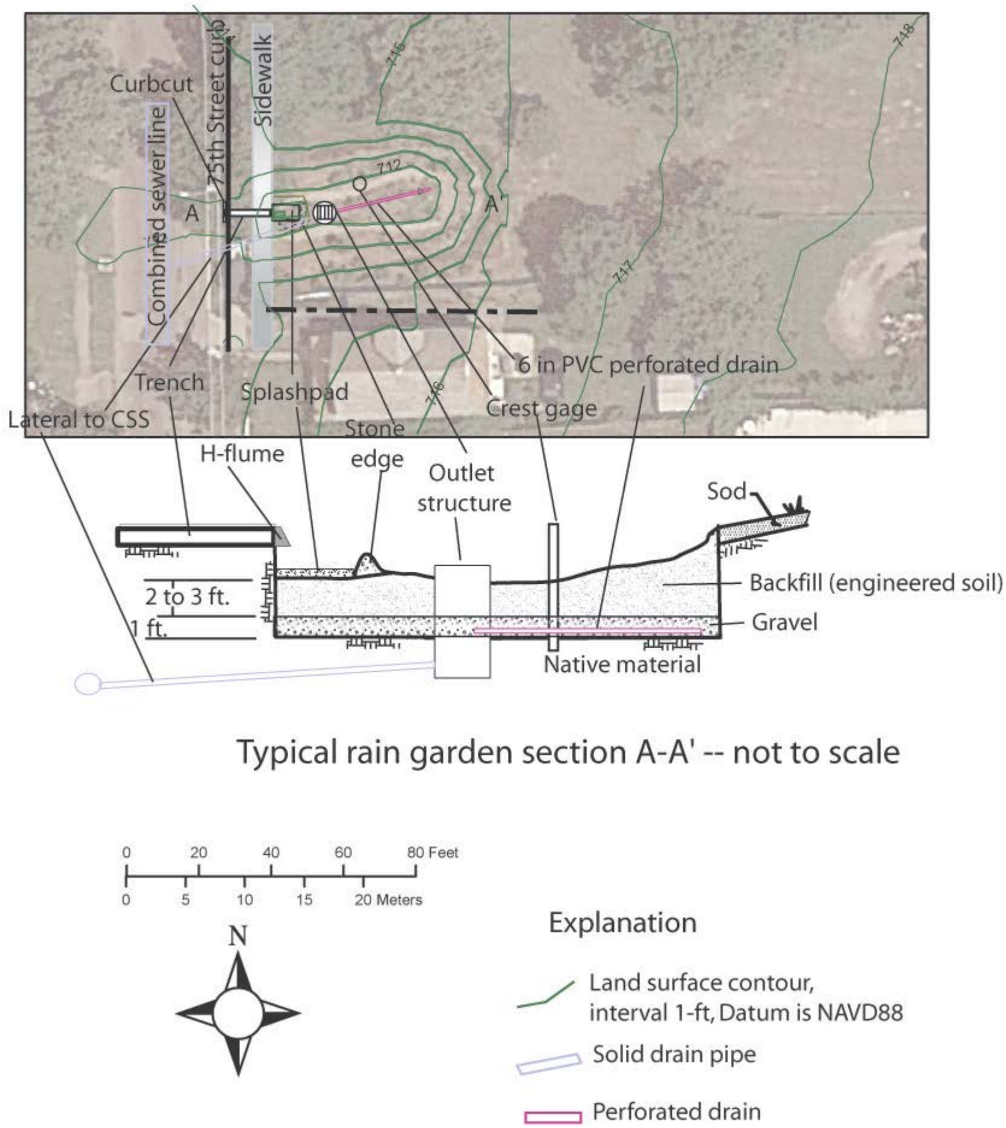


Figure 3b. Schematic of 75th Street North rain garden.

Figure 4a. An engineered rain garden in the Slavic Village neighborhood study area.

Figure 4b. A basic rain garden in the Slavic Village neighborhood study area.

Rain Garden Instrumentation

Instrumentation at these two engineered rain gardens was installed to document the quantity of water flowing into each rain garden, maximum level and duration of ponding in each rain garden, and their impact on groundwater table dynamics. Due to physical constraints, measurement of outflows from the rain gardens was limited to recording the duration of outflows, rather than the volume of discharge at a given time interval. Instrumentation (separated out as sub-systems) for each of the NEORSD installations on 75th Street is detailed in the Appendix, along with approximate costs. In brief, a calibrated 0.5 ft H-flume was employed to convey and measure flow into the rain garden. The depth of water in the flume was determined with an Ott CBS bubbler/pressure transducer; each water depth measurement was taken, then recorded at two-minute intervals with a Campbell Scientific CR800 or CR1000 datalogger. To determine the timing and the duration of ponding, a crest-stage gage (CSG) was installed at the low point in each rain garden to passively record the maximum ponding depth (peak stage). The CSG consists of a 2-inch diameter galvanized pipe with vented cap on top and measuring point pins and holes at the bottom. Inside the pipe is a fixed cedar wood stick (rod) with a charge of powdered cork at the bottom. Affixed at the bottom of the wooden rod was a non-vented pressure transducer (Schlumberger, or equivalent Diver-type sensor) set to record water depth and temperature every 5 minutes, which was changed to a 15-minute interval, February 2017 to save on battery life. Runoff events that produce ponding in the rain garden suspend and float the cork inside the pipe, where it then consequently sticks to the wooden rod, and on recession of flow (stage), leaves a clear line of cork marking the maximum stage achieved during the ponding event. During a subsequent field visit, the top cap is unscrewed, the wooden rod is removed, and the cork line(s) are measured from the bottom of the stick, and can be used to cross-check and calibrate the barometrically-corrected pressure data from the pressure transducer. All monitoring data are accessible on the NWIS Web interface (U.S. Geological Survey, 2016) and for individual sites at the following URLs:

https://nwis.waterdata.usgs.gov/oh/nwis/uv/?cb_00060=on&format=gif_default&site_no=412743081380801&period=&begin_date=2012-10-01&end_date=2016-09-30

https://nwis.waterdata.usgs.gov/oh/nwis/uv/?cb_00060=on&format=gif_default&site_no=412742081380801&period=&begin_date=2012-10-01&end_date=2016-09-30

Groundwater

Due to their proximity to NEORSD GI in Slavic Village, these wells monitor the impact of the SCM interventions on water table dynamics. Groundwater wells are differentiated by name, latitude and longitude, elevation, and some information on the initial hole excavation and well depth (Figure 2). In August and September 2013, the USGS installed 20 two-inch diameter wells in Slavic Village (Table 1). Four wells were placed as “regional” controls to monitor water levels at the water table outside the area expected to be influenced by the rain garden installations. The remaining 16 wells were placed on or near lots that were expected to be used as treatment or control sites for the study. In two areas (near wells CU-46, CU-47, CU-48 and CU-40, CU-41, CU-42) multiple lots were available and wells were installed with one well approximately up gradient, one well approximately down gradient, and one well on a control vacant lot that did not receive any management inputs. Data collection started in September 2013 and was ongoing through 2017 with minor exceptions in the record for various reasons including: calibration of the instrumentation, well development, or equipment malfunction. Well CU-38 was destroyed during construction of one of the NEORSD engineered rain gardens; the groundwater level data record for that well ends on 8/27/2014.

Table 1. Characteristics of groundwater wells in study area. All wells are 2-inch inside diameter with 0.010-inch slot width screens. Well CU-38 was destroyed by demolition operations, early in the study period.

Well identification	USGS Station identifier and hyperlink URLs	Total depth, below land surface	Screen interval, feet below land surface		Land Surface elevation, feet above NAVD88
		feet	Top	Bottom	feet
CU-30	412743081381401	20.47	10.0	19.7	708.43
CU-31	412750081382200	19.39	9.2	19.2	695.80
CU-32	412740081381100	14.93	4.5	14.2	712.12
CU-33	412740081381200	14.27	4.6	14.3	712.43
CU-34	412738081381400	19.94	9.7	19.4	709.97
CU-35	412735081375900	9.31	4.2	9.1	742.48
CU-36	412735081375901	6.38	4.2	6.2	741.82
CU-37	412738081380100	12.31	7.0	12.1	740.63
CU-38	412743081375900	N/A	N/A	N/A	N/A
CU-39	412743081375800	9.45	4.6	8.7	741.25
CU-40	412745081380000	15.27	5.4	15.1	729.25
CU-41	412745081380100	16.06	6.1	15.8	727.20
CU-42	412746081380100	17.03	6.7	16.4	725.30
CU-43	412742081380700	15.81	5.6	15.3	717.54
CU-44	412742081380500	11.80	4.7	11.2	720.77
CU-45	412742081380600	11.87	5.2	11.7	720.99
CU-46	412737081380500	11.81	6.9	11.5	729.50
CU-47	412737081380501	12.67	6.1	11.3	731.93
CU-48	412737081380600	10.45	4.4	9.6	728.81
CU-49	412735081375500	27.4	16.8	26.5	744.45

Data collected at each site includes hourly water level and water temperature. The instrumentation used to collect water levels are non-vented pressure transducers, so the raw data must be corrected for fluctuations in barometric pressure. This is done as a post-processed routine and barometric pressure collected at the weather station on E. 72nd Street is used. Wells CU-49 and CU-47 have different type instrumentation that records water level, water temperature, and specific conductance.

Wells were instrumented with a Schlumberger or Van Essen Diver (Mukilteo WA, USA) non-vented pressure transducer and set to record hourly pressure and temperature. To compensate the absolute pressure for changes in barometric pressure, a baro-Diver was installed in the weather station on 72nd Street. While reviewing the compensated water-level data to determine ponding depth in the rain gardens it was discovered that the temperature compensation in the baro-Diver was not adequate and the baro-Diver was moved to well CU-31 in August 2015. With the baro-Diver in well CU-31, near the surface where it could not be submergered, the fluctuations in barometric pressure could be recorded with minimal interference from temperature changes. The temperature compensation does not appreciably change the water level analysis for groundwater (where the thermal regime is relatively constant), but determining the start and end times of the ponding and overflows using a baro-Diver correction is more challenging due to its mounting in the midst of free air space, and thus subject to diurnal variation in the daily heating and cooling cycle. Data collection frequency for the baro-Diver was hourly from September 2013 to March 2016, at which time it was changed to a 15-minute interval to match other sensors installed at that time.

All sensors installed in the wells were set to record hourly pressure and temperature. Data were downloaded during each field trip, and as indicate above, compensated for barometric pressure prior to entry into into the USGS NWIS database. Temperature data from sensors were used to compensate for sensor response. Because comparison temperatures were not periodically measured in the wells with an independent calibrated thermometer, the precision and accuracy of the transducer-measured temperatures could not be verified and therefore the data were not approved for public release in NWIS. Water level check measurements were made during each field trip and used to correct the time series data. During each field trip a water column profile was conducted by placing a sensor at the top of the water column to record water temperature and specific conductance. The sensor was then lowered to the middle and bottom of the water column where it was allowed to stabilize before recording.

Several wells were instrumented with sensors to measure specific conductance during the study period. In September of 2013 wells CU-49 and CU-47 were instrumented with secondary sensors (In-Situ Aqua Troll 100) to collect hourly specific conductance. The secondary sensor in well CU-47 was moved to well CU-43 in February 2016. In June 2016 the Diver in well CU-47 was replaced with a CTD-Diver (which records pressure, temperature, and specific conductance) so there is a gap in the specific conductance record from February to June 2016. The Diver and Troll in well CU-49 were replaced in March 2017 with a CTD-Diver. The Divers in wells CU-30, CU-31, CU-43, CU-44, CU-45, and CU-47 were replaced with CTD-Divers in June 2016. All data are stored in NWIS, and some of it is available through the web interface (U.S. Geological Survey, 2016). Specifically, well CU-43 is on the same lot as the 75th Street South rain garden (street address 3559 East 75th St.); wells CU-38 and CU-39 are in the vicinity of the East 78th Street basic rain garden. Well CU-39 was recovered after construction and has been re-developed and cleaned but well CU-38 may have been destroyed during construction and has not been recovered. Details and illustration of transects, specific monitoring areas, and example data are given in Figures 5a-d.

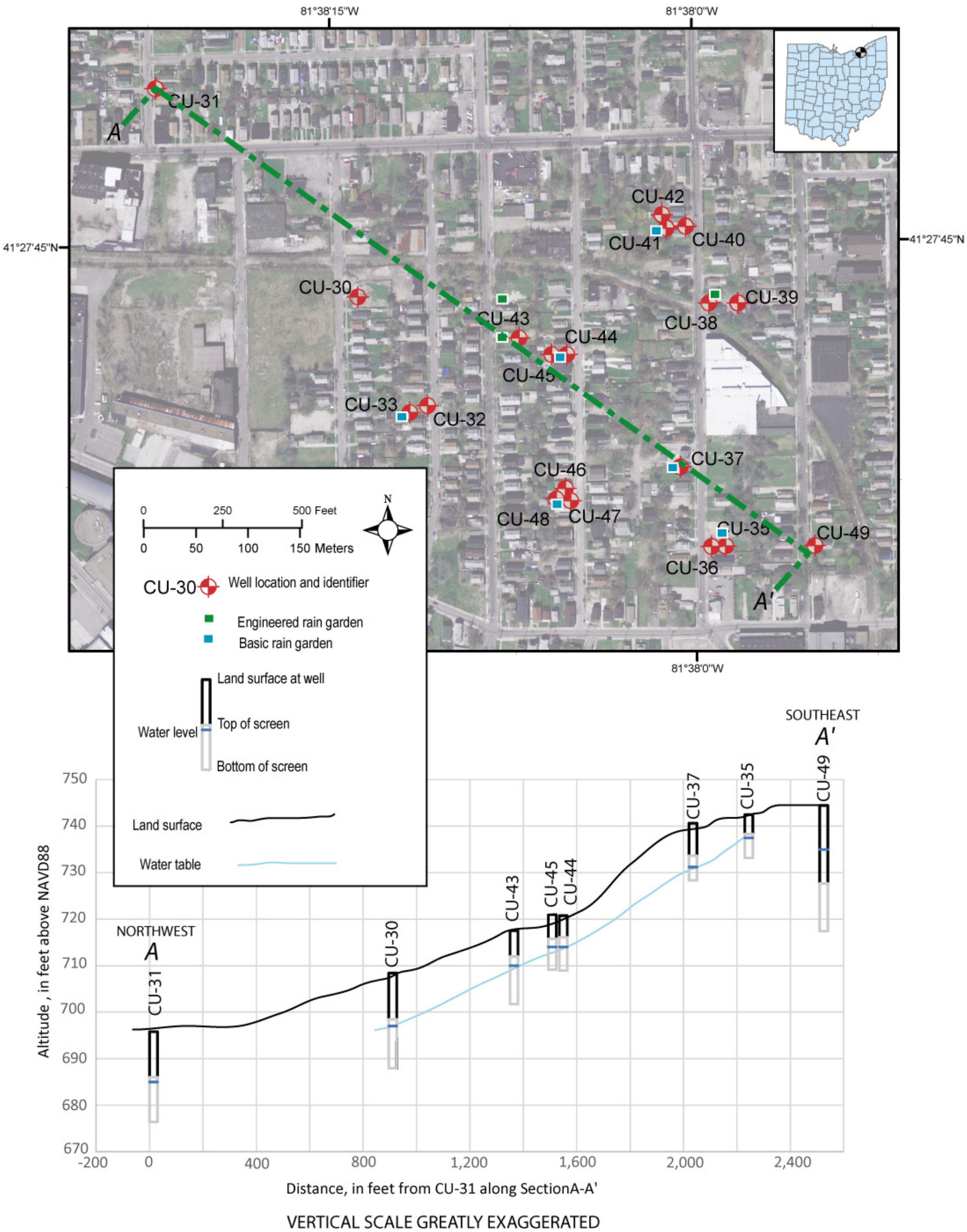


Figure 5a. Groundwater levels along a transect from well CU-31 to well CU-49 at the Slavic Village neighborhood, Cleveland, Ohio. Water levels shown are the median daily maximum depth below land surface for the period September 2013 through October 2016.

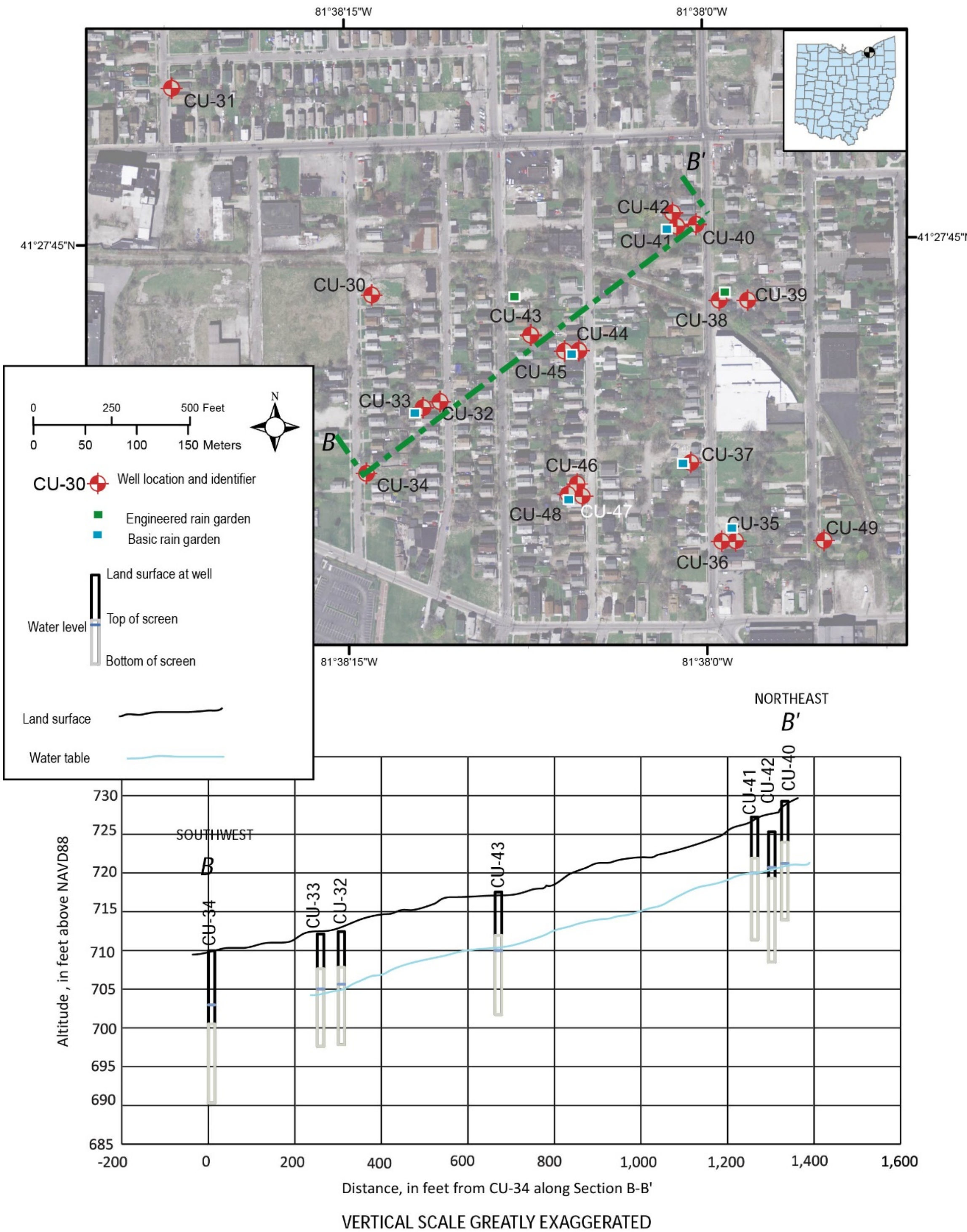


Figure 5b. Groundwater levels along a transect from well CU-34 to well CU-40 at the Slavic Village neighborhood, Cleveland, Ohio. Water levels shown are the median daily maximum depth below land surface for the period September 2013 through October 2016.

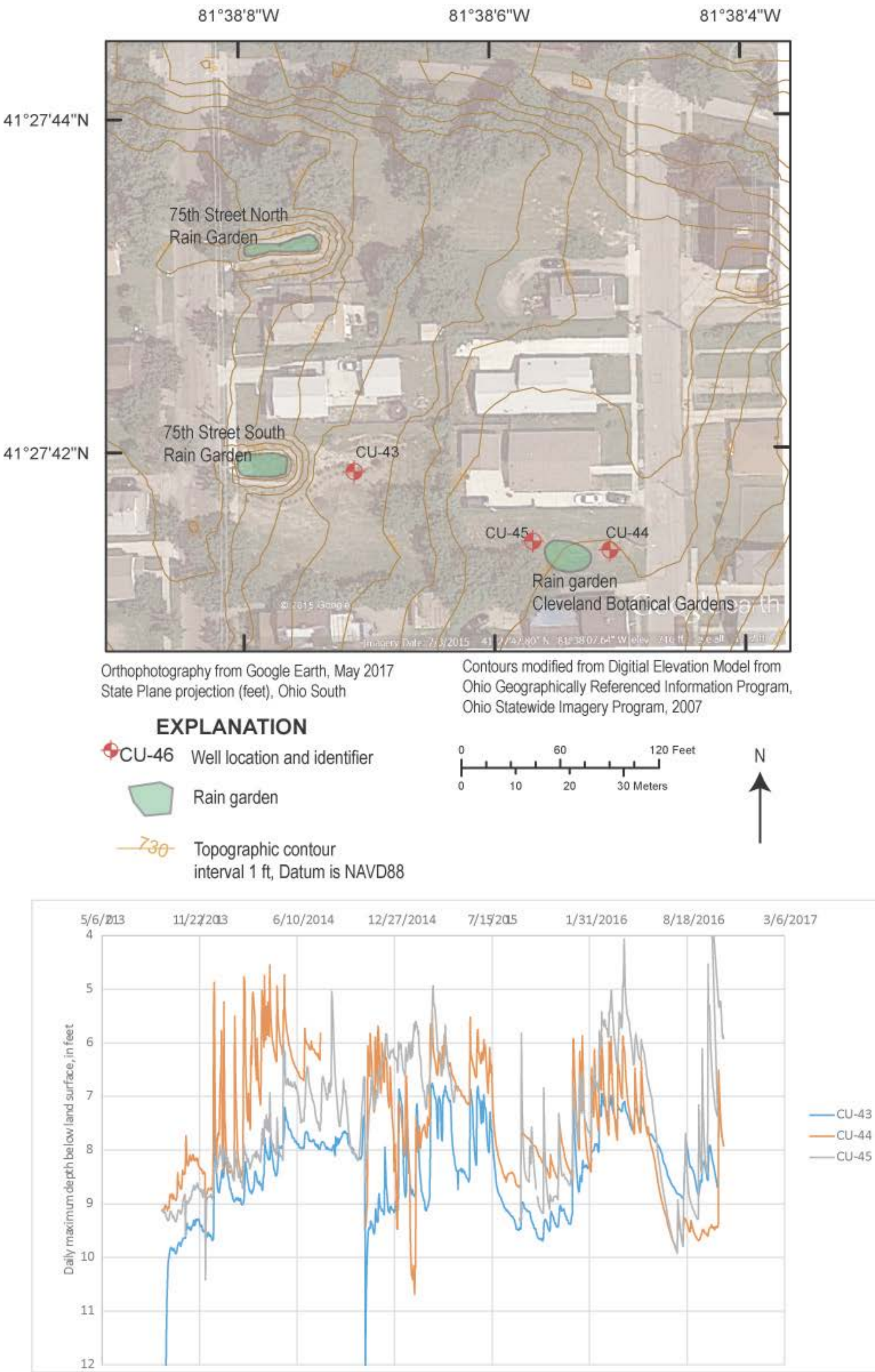


Figure 5c. Piezometer network and rain gardens along between East 75th Street and East 76th Street. Water levels indicate seasonal influence of the basic rain garden, and subsurface flow to the west, just upslope from the 75th Street South engineered rain garden.

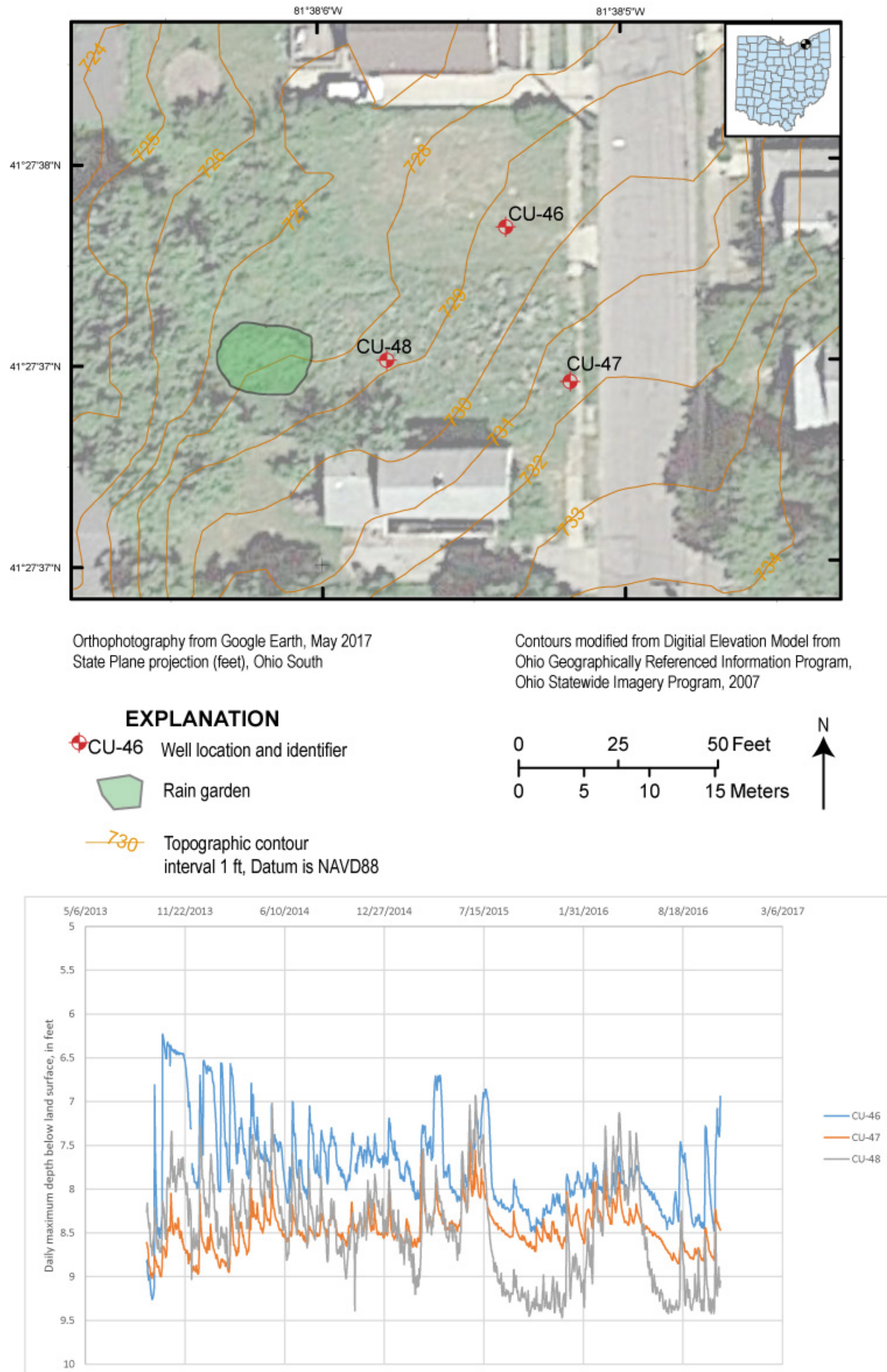
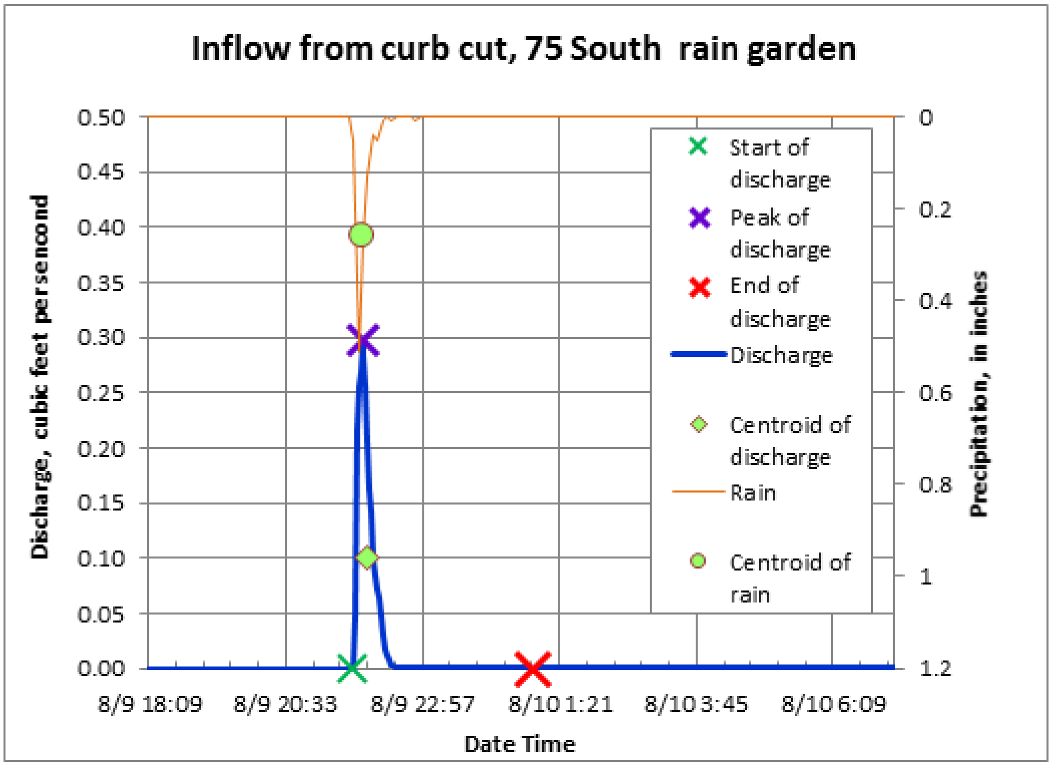


Figure 5d. Piezometer network along East 80th. Street tracks the plane of the groundwater surface, which may indicate subsurface drainage from the street and right-of-way to the basic rain garden.

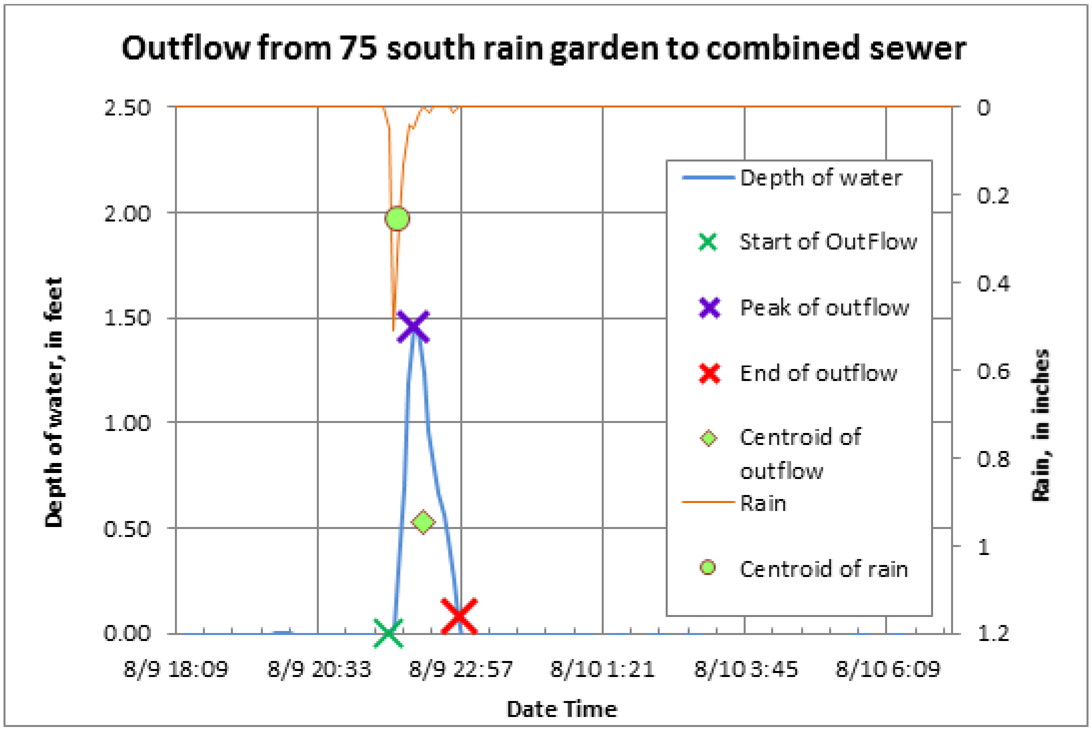
Data Analysis

A spreadsheet macro program was used to plot a storm hyetograph and analyze the rainfall event hydrograph (Figures 6a and 6b). Start and end times for a precipitation event were used to determine start and end times for discharge from each flow monitoring point and to determine total flow and centroid for both precipitation and flow. Both cold and warm season storm event data were included in the analysis. Cold season conditions can influence system hydrology due to freeze-thaw cycles that affect low-flow measurements in the flumes. Snow accumulations can generate runoff with varying lag times and diffuse routing, affecting the size and yield of the drainage area, and ultimately, the apparent estimated amount of water reaching the rain garden or the flume. Based on air temperature data and inflows measured at the North rain garden flume, events falling in the period between 12/23/2015 through 01/16/2016, and coincident with air temperatures below freezing were discarded, and the record was adjusted to reflect these conditions. The estimate of directly connected impervious area (DCIA) was used as the drainage area to convert rainfall depth to a volume of water. For this paper rainfall volume (ft^3) was defined as DCIA (ft^2) multiplied by rainfall depth (converted from inches to feet). This maximum possible runoff volume was used to determine the runoff ratio for each event. The basis of our monitoring effort was inflow monitoring through the curb-cut, defined as volume of inflow (ft^3). The ratio of volume of inflow to rainfall volume is defined as the runoff ratio for the event. Therefore, a runoff ratio greater than one would indicate that more water flowed into the rain garden than actually fell in the catchment. The runoff ratio values for each event were used as a quality assurance check to identify events with measurement error, or an indication that the contributing area for some storms may have measured additional volume as direct rainfall onto the rain garden, and overland flow volume from the landscape upslope and surrounding the rain garden.



Rain start	**8/9/2016 21:45**	
Rain end	8/9/2016 22:50	
Rain duration	1.2	hours
Total depth of rain	1.07	inches
Flume start	8/9/2016 21:44	
Flume end	8/10/2016 0:54	
Flume flow duration	3.2	hours
Volume of inflow	315 (2,350)	cubic feet (gallons)
Start time lag	-1	minutes
Centroid time lag	5	minutes

Figure 6a. Example analysis for a short-duration August 2016 storm event as inflow to the 75th Street South rain garden. Two quality control flags are provided by this analysis: 1) the start lag time indicates the flume flow started about 1 minute before the tipping bucket indicated rain; and 2) the centroid lag time indicates that the centroid of the flume flow is after the centroid of the precipitation.



Rain start	**8/9/2016 21:45**	
Rain end	8/9/2016 22:50	
Rain duration	1.2	hours
Total depth of rain	1.07	inches
Outflow start	8/9/2016 21:45	
Outflow end	8/9/2016 22:55	
Outflow duration	1.2	hours
Start time lag	0	minutes
Centroid time lag	25	minutes

Figure 6b. Outflow analysis from 75th Street South rain garden. In this outflow event (same as that analyzed in Figure 6a) note that the start times can overlap. This is because the flume flow data have a collection frequency of 2 minutes while the pressure transducer used in the outflow has a data frequency of 5 minutes.

Results and Discussion

75th Street South Rain Garden

Monitoring for this rain garden started on 5/15/2015 and ended 10/31/2016, which translates to 1.46 years. Rainfall event total depth ranged from 0.02 to 4.45 inches for a total study period depth of 65.44 inches, which would be slightly higher than the long-term average annual rainfall depth of ~ 39 inches. In this period, this rainfall record was composed of a total of 183 monitored rain events that produced measurable inflow, and 23 rain events that either did not produce measureable flow, or had data that was not sufficient to identify measureable flow. The 23 events lacking measureable flow were not considered in the analysis. Over this monitoring period, the total volume of inflow was 179,600 gallons. Overland runoff that may have contributed run-on into the garden and direct precipitation onto the rain garden were qualitatively and proportionally insignificant inflows into the rain garden system. The rain garden is designed to quickly move water into the gravel storage zone, where some proportion of this flux is intercepted by the perforated drain tile network and routed to the combined sewer. Despite the best monitoring resources and hydrometry, event outflow hydrology and hydraulics were not directly measurable. The project was not permitted (nor could afford) to excavate a 9'- deep manhole-access pit to install and maintain a weir and flow metering in the 4" outflow pipe that linked the rain garden overflow drainage to the CSS. However, we could make partial assessments of this highly-constrained quantitative data to identify the hydrologic processes that drive rain garden outflow response. Outflow behavior in the sub-period 3/24/2016 through 10/31/2016 included 85 rain events ranging in depth from 0.02 to 1.70 inches for a total depth of 27.02 inches. This rainfall pattern generated outflow from the rain garden for 26 events. The total duration of outflows in this sub-period was 54 hours, which is about one-sixth of the total duration of inflows of 308 hours. According to regular, qualitative observation in the outflow pipe, the majority of these outflows were very small. This indicated that the rain garden internally cycled a substantial amount of inflows. Based on non-zero measured drainage rates from 2011, we estimate that water saturates the gravel-subsoil interface and eventually infiltrates deeper – and into native soils – to an existing water table. In addition, subsurface runoff can be intercepted by one of the "French drains" that surround every underground utility in the area and thereby these subsurface flows are diverted offsite.

Evapotranspiration (ET) losses are applicable to both rain gardens (Table 2). One part of this ET loss involves plant transpiration, in which root zone soil moisture is removed as climate demand for moisture during the growing season. Hardwood mulch applied for weed control likely minimized or otherwise reduced the other part of ET losses as evaporation. Therefore, transpiration in warm-season months was the predominant and higher ET loss (Table 2).

Table 2. Cumulative monthly evapotranspiration rates in units of inches calculated for each of two weather stations in the Slavic Village neighborhood, Cleveland, Ohio. Blank spaces indicate incomplete records where a given month had missing daily data.

	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	72nd	76th	72nd	76th	72nd	76th	72nd	76th	72nd	76th	72nd	76th	72nd	76th	72nd	76th	72nd	76th	72nd	76th	72nd	76th	72nd	76th
2011	--	--	--	--	--	--	--	--	--	--	--	--	--	--	6.3		2.8		2.2		1.9		0.9	
2012	1.0	--	1.4	--	3.6	--	4.4	--	6.2	--	6.9	--	7.9	--	4.2	--	3.9	--	2.4	--	1.4	--	0.8	--
2013	0.4	0.9	0.5	0.9	1.0	1.8	2.3	3.6	4.4	6.7	4.3	5.2	4.4	5.4	--	5.2	--	3.8	--	2.3	--	1.4	--	0.7
2014	--	0.7	--	0.9	--	1.8	4.3	4.0	5.5	5.3	6.2	5.9	6.3	5.7	5.2	5.4	3.9	3.8	2.6	2.3	1.8	1.4	1.1	0.9
2015	0.7	0.6	0.9	0.8	2.4	2.2	4.2	3.8	5.9	5.5	5.1	4.9	6.5	6.2	6.1	5.8	4.3	4.3	3.1	2.8	2.4	2.1	1.3	1.1
2016	1.3	1.0	1.9	1.5	3.2	2.8	3.6	3.6	5.4	5.2	7.4	7.0	7.0	6.5	6.1	5.8	4.4	4.3	--	2.9	--	--	--	--

Although we observed that the rain garden had overall high capacity for inflows, and a high measured infiltration rate of nearly 2 inches per hour (9.2 ± 2.2 cm hr^{-1}), some rainfall events were of sufficient total depth, intensity, or both to saturate the rain garden system, which led to transient ponding. A crest-stage gage (CSG) was operated from 8/13/2015 to 9/21/2016 (at which point, we found that the CSG had been vandalized) through a total of 138 rain events ranging in depth from 0.02 to 1.85 inches, for a total rainfall accumulation of 31.77 inches. In this period, the pressure transducer in the CSG registered standing water on 13 occasions, with a maximum ponding depth of about 0.4 ft, and a total duration of ponding of about 22.5 hours. As a note on the application of this sensing technology, the CSG sensor is limited in its ability to detect transient shallow ponding, which may not be of practical importance. The zero point on the CSG which is in the middle of instrumented rain gardens is about 0.1 ft above the garden surface invert. This arrangement would detect only inundating events where the garden surface is saturated, and depression storage volume is filled.

75th Street North Rain Garden

Monitoring for the 75th Street North rain garden started just after its completion on 8/18/2015 and ended on 10/31/2016. The total rainfall recorded was 45.79 inches, and rainfall depths ranged from 0.02 to 1.85 inches (less than the depth ascribed to a typical 2-year rainfall event for this area), which suggests that this later overlapping monitoring period (with regard to the South rain garden) was closer to the Cleveland average annual rainfall of ~39 inches. This rainfall record was comprised of 158 events, of which 126 produced measurable flow. In this period, the amount of flow into the rain garden through the curb cut totaled 104,000 gallons. Based on direct observation during storm events, canopy cover and other factors prevented overland runoff or direct precipitation onto the rain garden from accounting for anything more than minor contributions.

As is the case for the 75th Street South rain garden, the 75th Street North rain garden had an underdrain system to limit the time period in which the root zone was saturated. Starting on 10/15/2015 and ending 10/31/2016, a total of 137 rain events ranging from 0.02 to 1.85 inches for a total rainfall depth of 41.54 inches were recorded, 88 of which caused outflow from the 75th Street North rain garden.

The total duration of outflow was longer at 640 hours than inflow duration, which was 500 hours. These outflow events categorically had very low flows over long recession times. There was ouflow from the 75th Street North rain garden for more than double the duration recorded for the 75th Street South rain garden. The 75th Street North rain garden outflow events typically had long recession times at very low flows. The 75th Street North rain garden was located at the lowest point in a larger, vegetated catchment area, and experienced backflow (through the outflow pipe) from the combined sewer (CS) conveyance. These situational features enhanced subsurface runoff volume into the garden, and backflows from the CS both contributed to an increased total duration of outflows. Furthermore, our assessment of CS backup into the monitored outfall started with a septic odor that was noted after storm events. This confirmed that flow-surcharge hydraulic conditions in the combined sewer collection and conveyance system were sufficient to cause pipe flows to back up into the rain garden outflow pipe. This complicates interpretation of rain garden effectiveness (as we could not differentiate the direction of flow, only by sewage smell on the rain garden side), and has implications for microbial contamination of the rain garden gravel storage and rooting zones.

The design ponding depth of 0.75 ft was never exceeded in the 75th Street North rain garden. Only events with either the largest total depth, or the most intense events resulted in water (minimally) ponding at the surface of the rain garden. As in the 75th Street South rain garden, the CSG was placed near the middle of the 75th Street North rain garden. Data from the pressure transducer in the CSG showed that ponding depth did not exceed 0.1 ft, which was also the zero point on the CSG (i.e., ~ 0.1 ft above the bottom of the rain garden). Because the raingarden surface was not perfectly flat, we concluded that there may have been patchy, localized ponding (i.e., less than 0.1 foot) as transient depression storage, which remained below the threshold of detection, and thus not recorded in the time series data. The overall absence of extensive and frequent ponding indicated that the rain garden quickly and completely infiltrated runoff volume.

Groundwater

Groundwater levels near the basic rain gardens, specifically those east and upslope of the 75th Street South rain garden, indicated that the basic rain gardens collected and infiltrated run-on and direct rainfall, which drained downward and elevated the water table as per downslope well records. The basic rain gardens were intentional patches of enhanced infiltration, and so the areas around and downslope of these basic gardens would be wetter in the subsurface. Although the basic rain gardens were not monitored, we observed a post-event rise in groundwater levels for wells downslope of a basic garden. Well CU-43, upslope of the 75th Street South rain garden, correspondingly registered for all events, a clear, post-event rise in the groundwater table (see maps in Figure 5, a-d).

The infiltration process and antecedent moisture conditions played significant roles in regulating rain garden detention capacity. At the onset of rainfall, the densely vegetated basic rain gardens abstracted the full rainfall depth, and thus prevented runoff formation. The infiltration process in the basic gardens would have been sequential based on differences in infiltration rate through first the surface organic-mulch layer (infiltration rate = 0.3 inch per hour; n = 30), then proceeded through the silt loam backfill soil (infiltration rate = 1.8 inches per hour, n = 30). The measured infiltration rate may have decreased due to wetting of the organic particles followed by swelling of these same particles, which would serve to temporarily restrict flow, at least up until saturation. However, once water infiltrated below this thin organic layer, flow would have been comparatively unimpeded (at almost 2 inches per hour), until it reached a restrictive subsoil layer at 1 ft depth, where the saturated hydraulic conductivity (i.e., drainage rate) averaged 0.1 inch per hour (n = 8); suggesting a finer soil texture with a potentially more compact structure. Soil water may have run downslope toward the 75th Street South rain garden as shallow subsurface flow along this restrictive subsoil layer. This sequence of near-surface hydrologic processes contributed to subsurface runoff, raising groundwater levels in the well downslope of at least one basic rain garden, and this drainage volume consequently contributed to a rise in the water level of the well that is upslope of the 75th Street South rain garden. Because the drainage rate of the restrictive subsoil layer was non-zero, deeper percolation would be predicted to proceed over the longer recession period.

In terms of seasonal shifts, we found that the gradient measured between wells CU-44 and CU-45 changes direction from warm-season to the fall and winter months when the remaining vegetation and rain garden flora become senescent and evapotranspiration losses decline. The switching primarily involved the extant landscape and subsurface conditions around the basic rain garden that is upslope of the 75th Street South rain garden. We speculate that the lack of inflows from a curb-cut lead to overall less catchment area for this rain garden, there is little DCIA, and infiltration of rainfall is limited to the narrow right-of-way. These factors would explain a less active water table response to events in well CU-44, which is just upslope from this basic rain garden. The basic garden is built on the foundation of demolition backfill, which creates a flow discontinuity. Any subsurface flow would travel under the backfill material, and along the impermeable sub-grade at a depth of 12-14 ft, largely below the rooting depth of vegetation and otherwise independent of seasonal changes in transpiration. However, the rooting zone of the extensive vegetated area downslope of this basic rain garden will act to intercept any enhanced level of soil moisture and transpire this during the growing season. These transpiration losses would then be curtailed in the senescent season. Taken in the aggregate, these factors may explain the observed switching behavior among wells CU-44 and CU-45.

Monitoring approach, a follow-up discussion

The present study monitored the whole water cycle at the catchment level, with a rain garden intervention. This approach improved our understanding of what hydrologic characteristics rain gardens contribute to stormwater management and how they affect the hydrology of the landscape. Properly designed monitoring data infrastructure can then be used to identify “bottlenecks” in system functions, and quantify efficiency gains from improvements on the rain gardens. As in other studies, improvements in a rain garden efficiency, such as the need for minor changes to a rain garden underdrain, would never have been documented or identified without high-quality flow and water level data before and after the change. As an example, if the objective is to develop an event-specific record of whether a basic rain garden succeeded or failed to absorb flows from a storm event, then a suitable dataset could be derived from a largely passive monitoring arrangement that measures direct rainfall and the height of water. In this case, the arrangement would consist of a CSG and an attached rain gage that measures total rainfall (which could be a calibrated jar, or an inexpensive cumulative rain gage, as in Figure 7). It is important to consider any local constraints on rainfall catch, and situate the rain gage where there is no canopy cover.

Figure 7. Passive rain gage measures the cumulative depth of rainfall, and can be mounted to the top of a suitably located crest-stage gage.

We provide a parts list and approximate costs in the Appendix. The CSG is installed in the low-point or middle of the rain garden (which is usually slightly depressed), and a mark on the CSG pipe or stick is made, corresponding to the top edge of the rain garden. If water level goes over the top edge, then this indicates that the rain garden overtopped during a rainfall event. Each storm event produces paired data: total rainfall event depth, and peak stage. If the rainfall event forces peak stage over the top edge of the rain garden, then this indicates that the rain garden was not able to detain all of the stormwater runoff inflow, and the event caused a rain garden failure. The data chart could look like the one presented in Table 3.

Table 3. Event date and data pairs form a hypothetical record of rain garden performance. In this illustrative example, data in blue highlight may be an inundating event (few rain gardens are designed for this amount of rainfall). Data highlighted in blue show a series of closely-spaced rainfall events. Rain garden failure on the last event in this series may indicate that the garden has not had enough time to recover before the next event, or could also indicate that the garden is not draining as fast as it should, and requires inspection and maintenance.

Date of event	Rainfall depth (inches)	Was crest-stage gage height more than garden depth?
6/12/2017	0.5	N
6/22/2017	1.5	Y
7/5/2017	1	N
7/14/2017	**3.5**	**Y**
7/18/2017	**0.75**	**N**
7/19/2017	**0.5**	**N**
7/20/2017	**0.5**	**Y**

As the tally of rainfall depth and stage height grows over time, whomever is operating the rain garden has at their disposal a consistent record of rain garden detention performance. This record may be useful in showing good faith toward reporting requirements required by funding agencies, local sewer district (e.g., to obtain credits against sewer bills), or just knowing that the rain garden meets design objectives and produces some return on investment. At the next level of monitoring engagement, if the operator wishes to chart how fast the water level in the rain garden declines after a storm (drawdown rate), or the extent of ponding from a particular storm intensity or magnitude, a pressure transducer can be placed in the CSG. In this way, water-level data (with time-date stamp) are accumulated, explicitly recording the drawdown rate, the duration of ponding, and all of this throughout serial storm events over time. It should be noted that drift in pressure transducer readings can make it difficult to discern smaller ponding events (one or two inches of depth) or the completion of drawdown, denoting when ponding has ended. Because the pressure transducer readings need to be adjusted for barometric pressure, and the barometric pressure sensor is sensitive to fluctuation in temperature, some effort needs to be made to stabilize abient temperature around the monitoring devices. One possible fix may be to use PVC instead of steel pipes as the crest stage gage housing, and to set the whole assembly below land surface, which would help keep temperature fluctuations to a minimum.

This example of increased monitoring engagement illustrates that as the monitoring system becomes more complex, there are tradeoffs in level-of-effort, and the number of different issues that must be recorded and managed. To obtain a meaningful event water balance, inflow for each event must be accurately measured and recorded as a continuous time series. A higher level-of-effort is required in order to collect accurate rainfall and evapotranspiration data. Most sewer districts have an established local rainfall monitoring network. However, a local rainfall monitoring network must be maintained so that rainfall data are of known quality and consistency. For site-level rainfall and evapotranspiration monitoring, several commercially available meteorologic stations are capable of measuring rainfall along with other constituent parameters that are used to calculate reference potential evapotranspiration at an hourly time step. Through this overview, this study provided practitioners and users some impression of the range of steps that contribute to a structured monitoring process, and the relative effort and costs associated with different levels of engagement with this process.

Engineered rain gardens tend to include underdrains, which serve to maintain the root zone soil water content below saturation, and assist the rain garden in draining (i.e., drawing down) between rainfall events. The underdrain either daylights drainage flow to the local landscape, or is routed directly to a sewer system or a drainage field. Drainage from the rain garden directed to a sewer system can be considered return flow. This return flow may be delayed by some amount of time, but the local sewer district would benefit from knowing the specifics of how the rain garden may still be contributing stormwater volume as inflow and infiltration to sewer system conveyances. As we have shown herein with the Slavic Village rain gardens, outflow pipe monitoring was challenging, and because of complicated hydraulic characteristics, was limited to quantifying the time duration of outflows. Despite this limitation, outflow duration data can be used, such as, by comparison with inflow duration data collected over time, to build a weight-of-evidence assessment of rain garden effectiveness.

Conclusions

We studied two engineered rain gardens (Cleveland OH) designed to infiltrate and detain direct runoff from an adjacent roadway, and sheet flow from directly connected areas around the rain gardens. A whole water-cycle monitoring approach was employed to fully assess the role of green infrastructure interventions on detention performance, hydrologic losses including evapotranspiration, and groundwater table dynamics that indicate deeper infiltration losses. Overall rain garden detention effectiveness was evaluated by comparing the cumulative periods of event inflows and outflows within and among each garden. Both gardens provided considerable additional detention capacity to this small sewershed, thus preventing or delaying some proportion of event stormwater from directly entering into the local combined sewer system. For the sub-period 3/24/2016 through 10/31/2016, the total duration of inflows was 308 hours, total flow into the rain garden through the curb cut was 179,600 gallons, and duration of outflows in this period was 54 hours. According to regular, qualitative observation in the outflow pipe, the majority of these outflows were very small. This suggested that the 75th Street South rain garden internally cycled and detained the greater proportion of inflow volume. Post-event shallow ponding (max. 0.4 ft) – an indicator of root zone saturation – was observed to persist for less than a day, and for only 13 out of 138 possible events. For the 75th Street North rain garden, a cumulative (14-month) total of 104,000 gallons flowed into the rain garden. During the sub-period of 10/15/2015 through 10/31/2016 there were 500 hours of recorded inflow, with 640 hours of outflow. One reason for this observation is that the vast majority of outflow events had long recession times, which were at very low flows. Due to the small difference in the invert elevations of the garden overflow pipe and its connection of the combined sewer conveyance, we found that sewer flow can and does backup into the monitored outfall. The potential for bi-directional flow has implications for best practices to place a rain garden for optimal drainage (i.e., invert of pipe relative to the rain garden profile elevation), and to mitigate against undesirable backups of septic flows into the rain garden.

Our results suggest that both rain gardens have additional available capacity. This data could be used to calibrate a model of rain garden response, wherein more sources (i.e., more inflow volume) versus bioretention capacity could be simulated to better understand tradeoffs in stormwater management strategies. Experience from the whole water-cycle monitoring approach and its associated research questions indicated a range of possible simplified approaches to address rain garden design issues; these were addressed through an overview of the comparative suitability of passive, low-cost to research-grade monitoring strategies, provide parts lists, and their suitability to address different monitoring objectives and design questions.

For any future rain gardens, placement in areas overlying the sandier, better drained, and overall more permeable deposits along the eastern boundary would be recommended. The soil core taken for the installation of well CU-31 was composed prediminantly of sands interbedded with silt loams and indicated that the start of the sandier Devonian formation is actually eastward of the mapped formations. Overall, it is important to take and assess soil cores to confirm the accuracy of previously mapped soils-geology, and reveal actual soil conditions. This improvement in accuracy over heavily-interpolated maps would inform qualified decisions about landscape features that may impact on the hydrologic performance of green infrastructure techniques, which principally rely on infiltration and drainage for their proper function.

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Appendix

Crest-Stage Gage

Part	Approx. price	Notes, Dimensions
Length of pipe threaded both ends, 2 inch galvanized	$25	10-foot section for $45, cut in half and rethreaded
Vented cap	$5	
Bottom cap	$14	
Cork	$11	one-pound bag
Screen	$2	$5.50 per square foot. Minimum order of 19 square feet is $105, and that would put in a few hundred crest-stage gages
Clamps/Stake	$34	Two ea. of 6-inch crest-stage gage pipe clamps at $17 each
Cedar Stick	$5	
Miscellaneous hardware, stainless steel nuts, bolts, washers	$15	1 box of SS screws (100 count) $13, L-brackets for bottom of stick, bolts to mount clamps to something
Optional		
Transducer for continuous data, water level and temperature	$575	Van Essen (or, Schlumberger) Divers or equivalent
Barometric pressure logger to compensate non-vented water level data	$450	Baro-Diver from Van Essen
Transducer for continuous data including Specific Conductance, temperature, and water level	$2,000	CTD-Diver from Van Essen
Cable to download data from pressure transducer	$250	

Instrumenting a curb-cut for inflow measurements, using a flume

Part	Approx. price	Notes
Data logger	$1,500	Campbell Scientific CR-850 or equivalent
Stage sensor	$2,000	Prefer bubblers to reduce risk of lost data due to freezing. Example sensors are the OTT-CBS, Waterlog H-3553, or the Sutron Constant Flow Bubbler.
H-flume with approach section	$1,850	Recent quote for 0.5 ft H-flume at $1,750 and 0.75 ft H-flume at $1,900. Includes detached stilling well, approach section, staff plates. Cost could be much higher, $4000 for 2 ft h-flume, $4 to $10K if it needs to be in a manhole
Environmental enclosure	$450	Varies but a good size is 24"x24"x10" in stainless steel.
Solar recharged power system	$850	$850 includes 90 W solar panel, battery, breaker, and charge controller. If not using modem or camera can probably go cheaper with 20 or 30 watt system
Modem	$740	Sierra Wireless RV50 ($560) plus antenna, mount, cables (Campbell Scientific)
Posts to mount enclosure	$75	Metal fence posts, 2" diameter
Monthly service fee for modem	$15-$40	This varies greatly depending on the carrier, data package, and how much of the data allowance is used.
Optional		
Sensor for water temperature and specific conductance	$490	Campbell Scientific CS547, Specific Conductance, temperature
Soil moisture sensor	$216	Campbell Scientific CS655
Precipitation data	$1,400	$400 for TE525WS or $1400 for the TB4 (Campbell Scientific)
SC32-B		Cable to talk to CSIO port on logger, not required but helpful to have when using a modem

Shallow piezometer to monitor groundwater

Part	Approx. price	Notes
Drive point. 1-foot length, 10 slot stainless steel screen	$75	$75 when ordering a dozen or more. Would probably cost more to just order 1 or 2
Length of pipe threaded both ends, 2 inch galvanized	$45	10-foot section
Vented cap (HIF)	$5	
Optional gear		
Transducer for continuous data, water level and temperature	$575	Many manufacturers out there but we have been using Van Essen (or, Schlumberger) Divers
Barometric pressure logger to compensate non-vented water level data	$450	Baro-Diver from Van Essen
Transducer for continuous data including Specific Conductance, temperature, and water level	$2,000	CTD-Diver from Van Essen
Cable to download transducer	$250	
Need to develop the well, add water to the well, surge it with a piece of 1-inch PVC pipe with a cap, then clean out the water. Repeat until screen is clean	$50	

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