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Hydrologic impacts of sewershed-scale green infrastructure retrofits: Outcomes of a four-year paired watershed monitoring study

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ABSTRACT

Cities across the world are implementing green infrastructure (GI) retrofits to manage stormwater, but limited research has been performed to quantify the hydrologic impact of these efforts at the watershed-scale. To fill this knowledge gap, this study aimed to monitor and evaluate the impact of GI stormwater control measures (SCMs) on sewershed-scale runoff hydrology across multiple treatment sewersheds with varying GI implementation. A paired watershed approach was applied in which a control (i.e., no GI), and three treatment sewersheds (208 bioretention cells and 8,400 m^2 of permeable pavement in total) were monitored from 2016 to 2019 in Columbus, Ohio, USA. Further infrastructure changes, such as lining sanitary sewer laterals to prevent infiltration and inflow of stormwater, were anticipated to counterbalance the hydrologic improvements provided by the GI retrofits by routing more stormwater to the storm sewers. Significant decreases in runoff depths and peak flow rates (35–62% and 40–58% respectively) and increases in lag-to-peak (6–64%) were observed in the treatment sewersheds following the installation of GI retrofits. Compared to the control sewershed, the treatment sewersheds had slight increases (1–3 mm) in runoff thresholds and lower runoff coefficients post-GI. Following additional infrastructure changes, increases in volume and rate of flows were observed, but hydrologic indicators did not significantly differ from pre-GI levels (i.e., no net impact of the overall project on runoff hydrology). These responses indicated that sewershed-scale GI implementation successfully mitigated peak flow rates; however, the additional infrastructure improvement projects appear to have neutralized volume reductions by routing additional stormwater to the GI. Results confirm the impacts of sewershed-scale GI retrofits; however, research investigating the optimization of GI retrofit location, climate change impacts, and GI design, construction, and maintenance to maximize benefits of distributed SCMs in urban areas should be further explored.

1. Introduction

The continued growth of urban areas (United Nations, Department of Economic and Social Affairs, and Population Division., 2019) leads to the construction of impermeable surfaces (e.g., roads, buildings, etc.) that inhibit infiltration into soils which, coupled with reductions in interception and evapotranspiration following the removal of vegetation, results in increased runoff volumes conveyed at higher flow rates to receiving waters (Shuster et al., 2005). Historically, sewer networks were employed to quickly drain runoff from cities (Vietz et al. 2016). While this reduced localized flooding, it compounded effects on downstream communities and severely degraded water quality (Booth et al. 2016; Walsh et al. 2005). These hydrologic shifts result in impacts to channel cross-sections, bed forms, and the sediment transport dynamic equilibrium (Booth and Jackson 1997; Davis 2008; Wilby, 2007).

The negative effects of urbanization on surface waters led to regulations and standards for stormwater management in the US (US EPA 1972). Stormwater control measures (SCMs), such as wet and dry ponds, were some of the first catchment-scale systems recognized in the US to reliably detain stormwater, with the primary goal of flood mitigation

Abbreviations: BRC, Bioretention Cell; GI, Green Infrastructure; PP, Permeable Pavement; SCM, Stormwater Control Measure; AI^2, All- Infrastructure Improvements.

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(National Research Council, 2009). Detention-based SCMs are often large and centrally located within a catchment to facilitate complete capture and release of flows from design storm events, making them a good fit for developed areas with larger parcels of available land (Hale 2016). SCMs have since evolved to take up less space and provide improved stormwater quality by treating the first flush of pollution (Peter et al. 2020) using processes including as filtration, sorption, plant uptake, and microbially-mediated breakdown of pollutants. Studies documenting the effectiveness of SCMs vary in scale, from analyzing single SCMs (Kadlec et al. 2020; Mallin et al. 2002; Schwartz et al., 2017) to connected networks of SCMs managing runoff from a catchment (Gagrani et al. 2014; Loperfido et al. 2014; Walsh et al. 2016).

Hydrologic benefits at the individual SCM scale include decreased runoff volumes and flow rates; however, several studies identified the need for proper construction and continued maintenance of SCMs to promote long term hydrological benefits (e.g., Emerson et al. 2010; Erickson et al 2010; Flynn et al 2012; Merriman and Hunt 2014). Of the research investigating SCMs at the catchment scale, observed hydrologic impacts varied and were often a function of the location and density of SCMs installed. Greater runoff reductions tended to result from more densely installed SCMs to treat a greater portion of the impervious cover of a catchment (Goff and Gentry 2006; Loperfido et al. 2014; Meierdiercks et al. 2010). Goff and Gentry (2006) also found that the directly connected impervious area, which are impervious surfaces directly connected to the sewer and drainage system (Boyd et al. 1993), and the shape of the watershed influence the efficacy of SCMs to reducing peak flow rates. This was further corroborated by Bell et al. (2016) who found within 16 watersheds that total imperviousness of a catchment was the best predictor of hydrologic response with SCM related metrics (i.e., type, number, etc.) being ancillary predictors. Challenges in reliably discerning hydrologic benefits of SCMs at the sewershed scale were reviewed by Jefferson et al. (2017), who found that differences generated by watershed characteristics, such as capacitance or prior land use, often led to greater variability in hydrologic performance across otherwise similar SCM installations. This finding was highlighted by the results of 23 included empirically monitored studies where detention and infiltration based SCMs often did not discernably change sewershed scale hydrology (Jefferson et al. 2017).

When the Clean Water Act (CWA) amendments of 1990 were released, sanitary sewer overflows (SSOs) and storm sewer discharges became regulated under the National Pollutant Discharge Elimination System (NPDES) (US EPA, 2014). In response, cities such as Philadelphia, New York City, Seattle, and Columbus, Ohio created multi-faceted, long-term control plans for SSOs, combining traditional sewer infrastructure improvements with Low Impact Development (LID; Hopkins et al., 2018). Traditional sewer infrastructure improvements often limit flow pathways that may have arisen over time such as replacing old (or failing) sewer pipe or sealing cracks along sanitary sewer laterals, resulting in less inflow and infiltration (I/I) into storm and sanitary sewers (Bocarro et al. 2007). A central tenet of LID is the disconnection of impervious surfaces to limit the detrimental effects associated with parking lots, rooftops, and roads on receiving waters and mimic predevelopment hydrology (Fletcher et al. 2015, Walsh et al. 2005). Several studies have documented the effectiveness of downspout disconnection, which releases water to pervious areas where subsequent infiltration can lead to reduced stormwater flows (Taguchi et al. 2019). In contrast, redirecting downspouts to storm sewers as well as sump pump installations within residential and commercial developments can reduce I/I and increase the total stormwater flows when directed directly into the storm sewer or streetside SCMs. Another set of practices commonly implemented to achieve LID goals focuses on decentralized, infiltration based SCMs, also known as Green Infrastructure (GI).

GI SCMs, such as bioretention cells (BRCs), permeable pavement (PP), bioswales, etc., temporarily detain stormwater before releasing it at reduced rates or permanently abstracting stormwater through exfiltration into native soils, evapotranspiration, or other pathways which divert runoff from the storm sewer, thus decreasing the volume and flashiness of flows in the receiving stream. BRCs are planted, depressional areas with sandy soil media optimized for infiltration that have been shown by numerous studies to reduce runoff at the site-scale (e.g., Hunt et al, 2008; Mangangka et al., 2015; Winston et al, 2016a). PP, which may consist of interlocking brick pavers or a highly porous concrete/asphalt, allow stormwater to infiltrate the pavement and, depending on design and site conditions, infiltrate into the underlying soil (Scholz and Grabowiecki, 2007; Tirpak et al. 2021).

Field research into the hydrological performance of BRCs and PP often focuses on one or two SCMs treating a small drainage area (e.g., Collins et al., 2008; Hunt et al., 2006, 2008; Jayakaran et al., 2019; Mangangka et al., 2015; Winston et al., 2016a,b). Wide variability in GI performance exists in the literature, including runoff volume mitigation (35–98%) and peak flow mitigation (40–99%) (Collins et al. 2008; Davis, 2008; DeBusk and Wynn 2011; Hunt et al. 2012; Schlea et al. 2014; Winston et al., 2015). Variability in GI performance is related to site and design characteristics, such as directly connected impervious area, surface to drainage area ratio, presence of underdrains, and ponding and media depths (Hunt et al. 2012; Li et al. 2009), with proper maintenance being crucial to long-term function (Bean et al. 2007; Winston et al. 2016b; Simpson et al. 2021). Variability in reported hydrologic mitigation can also be attributed to SCM design specifications, which are based on capturing a design water quality volume (e.g., retaining runoff from the 90th percentile event on-site) and allowing runoff from larger events to bypass treatment.

In contrast to other SCMs, few studies, particularly field monitoring efforts, have been performed to-date which demonstrate the effectiveness of GI when implemented at the catchment or sewershed scale (Li et al. 2017; Jefferson et al. 2017), a selection of these studies have been summarized in Table 1. While previous sewershed-scale GI field studies have often focused on BRC retrofits, three studies monitored new developments where GI was included (Hood et al. 2007; Loperfido et al. 2014; Woznicki et al. 2018), and three featured rain gardens (shallower BRCs without underdrains connecting to the storm sewer system) and rain barrels as opposed to BRCs or PPs (Burns et al. 2016; Jarden et al 2016; Mayer et al., 2012). Significant reductions in runoff volumes (33–80%) were observed from GI sewersheds compared to control sewersheds with traditional drainage infrastructure (Table 1). Additionally, GI was found to significantly reduce peak flow rates by 20–40% and increase lag-to-peak times (Table 1). Some studies found significant differences in GI SCM performance as a function of storm depth, with better reductions occurring for smaller, lower intensity storm events (Table 1, Hood et al. 2007; Loperfido et al. 2014; Woznicki et al. 2018). Jarden et al. (2016) observed limited hydrologic benefits (i.e., 30% reduction in runoff volume) at the sub-catchment scale, which was attributed to the placement, design, and construction of retrofitted practices within the sewersheds. Mayer et al. (2012) did not observe significance from ANOVAs within their before-after-control-impact study, but noted significant, small effects and impacts at a neighborhood scale when modeled with a reduced-versus-full model test. This was due to the placement within parcels, diversion of runoff from disconnected impervious surfaces, and proximity to other impervious surfaces (Mayer et al., 2012). Uncalibrated modeling of these types of GI networks is also relatively common in practice and the literature (Damodaram et al., 2010; Moriasi et al. 2012; Jefferson et al. 2017), of which the accuracy is highly related to the underlying model assumptions.

Paired watershed studies are a standard approach to evaluate the statistical significance of management changes implemented the sewershed-scale (Table 1) where two or more watersheds are monitored before and after the management change is implemented (Clausen and Spooner 1993). GI (or other modifications) are added at a discrete moment in time to a treatment watershed, while the control watershed is unchanged, to determine the impacts on hydrology following the change (Loftis et al. 2001).

Table 1
Summary of a collection of previous studies on sewershed or catchment scale hydrological benefits of GI SCMs.

Study	Location	Sewershed Area (ha)	Type of GI	Retrofit or New Construction	Statistical Analyses	Key Findings
(Barr Engineering, 2006)	Burnsville, MN	2.1	17 BRCs	Retrofit	Paired watershed, regression	80% volume reduction over 48 storm events in 2008
(Bedan and Clausen, 2009) (Hood et al. 2007)	Waterford, CT	1.7	10 BRCs, PP	New Construction	Paired watershed, regression, ANCOVA	Larger reductions in peak flow rate and volume observed for smaller rain events, but reductions were still observed for large events from GI watershed
(Loperfido et al., 2014; Pennino et al., 2016) (Hopkins et al. 2020)	Washington DC Metro	111–770	1 catchment: 73 distributed SCMs ranging between BRCs, bioswales and infiltration trenches, catchments: 17–43 centralized, detention facilities	New Construction	Streamflow analysis, piece-wise regression	Comparisons of distributed GI SCMs to centralized SCMs yielded differences in baseflow and stormflow stream levels. Distributed GI had more storage utilized in smaller (<10 mm) storm events, centralized SCMs performed better during larger storm events.
(Page et al., 2015a,b)	Wilmington, NC	0.53	1 BRC, 4 PP Parking Stalls, 1 Tree Filter	Retrofit	Paired watershed, linear regression, ANOVA, ANCOVA	GI significantly impacted peak flow rate, runoff threshold, runoff coefficient, lag-to-peak and runoff depths
(Jarden et al. 2016)	Parma, OH	6.0–11.7	23 BRCs, 30 Rain gardens, 58 Rain barrels	Retrofit	Before-after-control-impact comparisons	Street subcatchments with smaller lot sizes (and implementation based on voluntary resident participation) resulted in 33% peak flow and 40% volume reductions. Voluntary GI can make substantial differences, design and construction can be an influence short and long term
(Burns et al. 2016) (Walsh et al. 2015)	Melbourne, Victoria, Australia	450	SCMs installed on 237 private and 58 public properties including rainwater harvesting and/or BRCs	Retrofit	Paired watershed	Storm events resulting in highly polluted runoff volumes were significantly reduced and a more natural hydrological regime was observed
(Mayer et al., 2012; Shuster and Rhea, 2013)	Cincinnati, OH	180	83 Rain gardens, 176 Rain barrels	Retrofit	Before-after-control-impact comparisons, ANOVA	No significant effects found at catchment scale. Reduced-versus-full model test indicated significant effects from the treatment; small effects were detected at the neighborhood scale.
(UNH Stormwater Center, & City of Dover, 2017)	Berry Brook, Dover, NH	75	14 BRCs, 2 sub-surface gravel filters, infiltration trench, 3 catch basins	Retrofit	Before-and-after comparisons, linear regression, change in NRCS Curve Number	Direct runoff decreased from similar precipitation events post-implementation, manifested as a decrease in curve number
(Woznicki et al. 2018)	Montgomery County, MD	5.25	3 streets of connected vegetated swales	New Construction	Paired Watershed	GI significantly improved the hydrological response compared to traditional stormwater controls; very effective for meeting small storm reduction goal

To address the need to enhance the scientific understanding of large-scale retrofitted GI performance, the paired-watershed approach was used to compare stormwater discharges from three treatment sewersheds (10.5, 47.7, and 61.3 ha) with an adjacent control sewershed (111.5 ha) in the Clintonville neighborhood of Columbus, Ohio, USA. Previous studies on GI retrofits included<20 BRCs installed in a 75 ha or smaller drainage area (Table 1). In contrast, the sewersheds herein were retrofitted with 208 BRCs and over 8,400 m^2 of PP in 232 ha of existing residential development. Furthermore, additional infrastructure improvements such as sanitary sewer lateral lining and downspout redirections were also completed. Runoff depth, peak flow rate and runoff thresholds from the sewersheds were monitored and compared in three distinct periods: 1) pre-GI, 2) post-GI, and 3) post-All Infrastructure Improvements (Post-AI^2) following the completion sanitary sewer lateral lining, sump pump installation, and downspout disconnection. It was hypothesized that runoff volumes and peak flow rates for the treatment sewersheds would 1) decrease from the pre-GI to post-GI periods due to GI implementation and 2) remain from pre-GI to post-AI^2 periods due other sewershed modifications in the post-AI^2 period which increase total flows into the storm sewer system. Results from this study can inform the impacts of large-scale GI retrofit and assist communities in understanding the potential effects of multiple stages of infrastructure retrofits on sewershed hydrology.

2. Methods

2.1. Site descriptions and experimental design

Blueprint Columbus is an effort by the City of Columbus, Ohio to improve sewer infrastructure and reduce SSO occurrences and volumes. The project targets four changes to existing infrastructure: (1) lining of sanitary sewer laterals to reduce infiltration and inflow of stormwater, (2) installation of sump pumps, (3) redirection of downspouts to GI, and (4) GI retrofits. Though the approach will target numerous neighborhoods throughout Columbus, the first phase of Blueprint Columbus activities was implemented in the Clintonville neighborhood, a 1500 ha residential area with a population of 30,000 located 16 km north of downtown. The City's goal for Blueprint Columbus was to have no net change in runoff hydrology compared to pre-project levels.

Four storm sewer outfalls draining separate portions of the Clintonville neighborhood were instrumented to measure runoff hydrology from 2016 to 2019. In the Blenheim-Glencoe (BG), Indian Springs (IS), and Cooke-Glenmont (CG) sewersheds, GI was retrofitted into the existing residential neighborhoods beginning in 2017 (Fig. 1). The Beechwold (BW) sewershed received minimal infrastructure retrofits and served as the experimental control. Existing land uses in each sewershed were predominately small single-family residential lots (CG: 100%, BG: 89%, IS: 75%, and BW: 96%). The remaining area in the BG and BW sewersheds was institutional (e.g., churches and schools; Fig. 2). The remaining area in the IS sewershed was institutional (17.4%) and

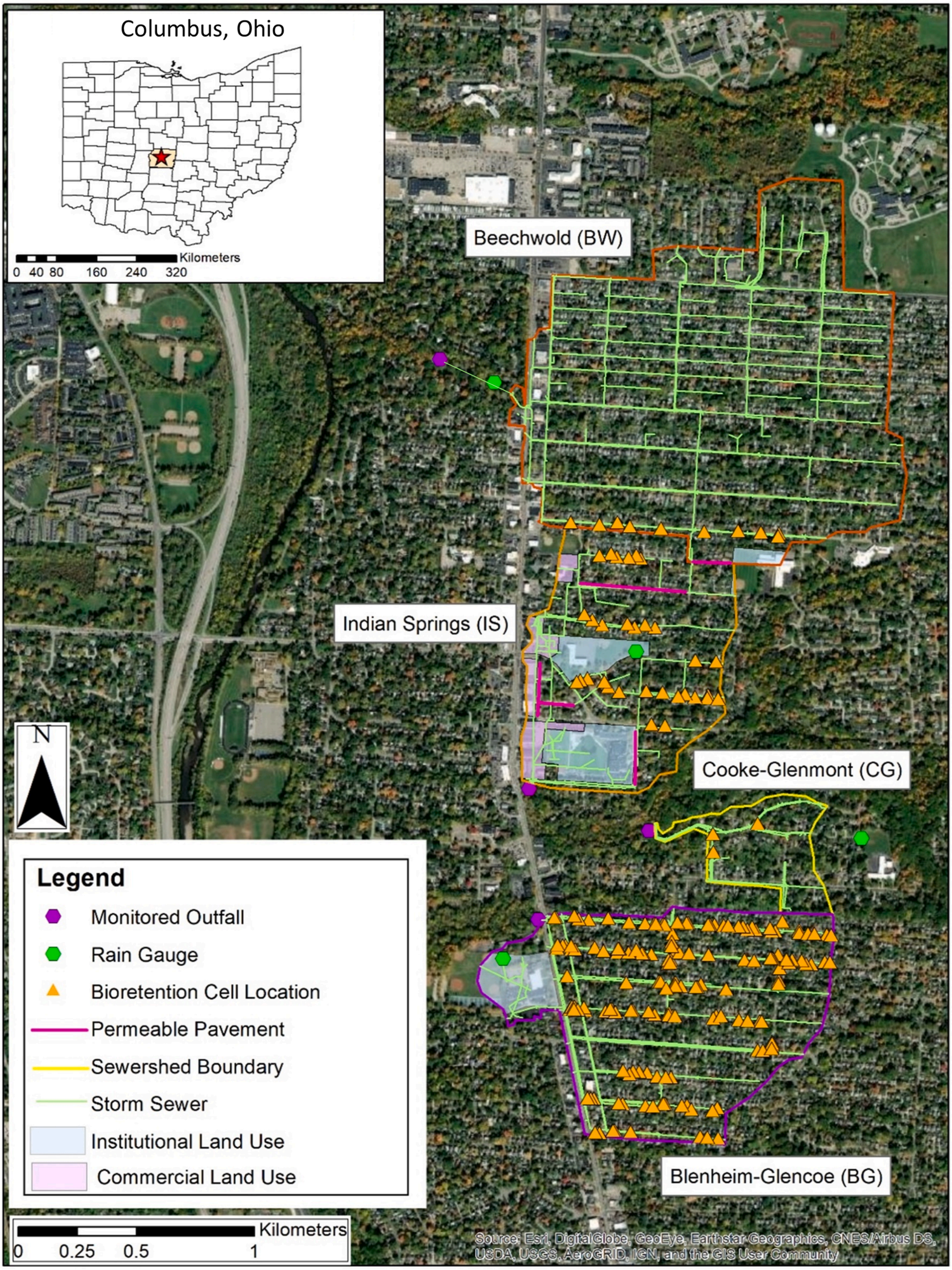

Fig. 1. Sewersheds with locations of GI, monitored outfalls, and rain gauges in the Clintonville neighborhood of Columbus, Ohio. Commercial and institutional land uses were delineated while the remainder of each sewershed was small lot single-family residential.

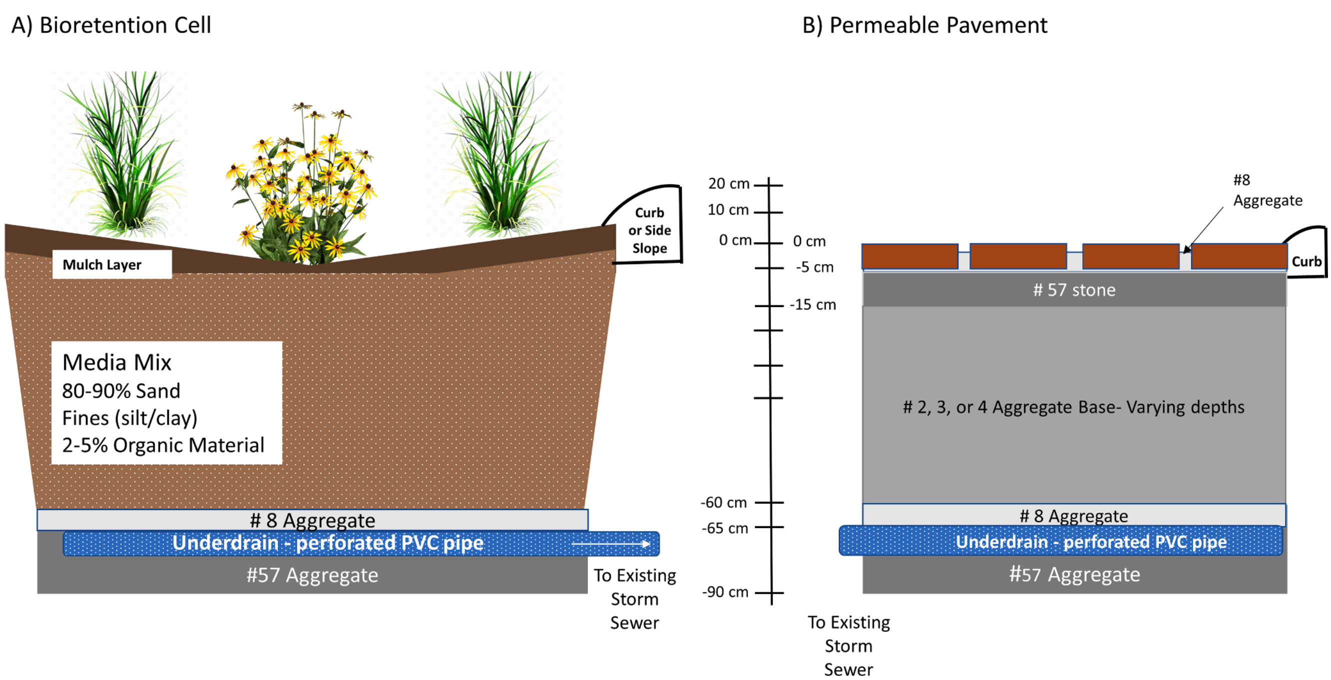

Fig. 2. Typical cross-sectional designs for BRC (A) and PP (B) within study areas. The PP aggregate base depth varied as needed to accommodate existing infrastructure. Some BRCs had more gradual side slopes, while others had curbs or stone walls to meet ponding depth requirements of 20 cm.

commercial (7.6%). Native soils in the project areas were mapped as Cardington and Bennington silt loam soils (Hydrologic Soil Group C) with hydraulic conductivities ranging from 1.2 to 5.2 mm/h (NRCS 2020).

Between 2017 and 2019, a total of 437 BRCs and five PP streets were retrofitted in Clintonville. Of the 437 BRCs, 208 were installed in the three treatment sewersheds and four of the five PP installations (6,000 m^2) were located exclusively in IS (Table 2, Fig. 2). Ten BRCs and one PP cul-du-sac (2,400 m^2) were installed in the southern boundary of the BW sewershed, which treated only 2% of the sewershed area. Despite the construction of these BRCs, it was determined that BW could still serve as a control sewershed for the study because no significant differences in runoff hydrology were detected prior to and following the installation of the GI (see Section 3.1). In contrast, GI treated 23–44% of the treatment sewershed areas.

The surface area and added storage volumes of GI were highly varied, due to some being installed in existing vegetated areas receiving runoff from larger areas and others installed along residential streets treating relatively small areas (Table 2). While BG was larger in sewershed area (~61 ha), the BRCs were much smaller in surface area (mean 12.5 m^2) than those in CG (mean 145 m^2). All of the BRCs were installed in city-owned easements (either behind or in front of the curb) or along roads with the exception of CG where two (>200 m^2) regional BRCs were constructed to replace city-owned green spaces. The BRCs were designed to store a 19 mm storm event in their surface storage zone (The City of Columbus, 2017). Despite multiple firms contributing to GI design in different project areas, the cross sections of the BRCs and PPs were similar across all treatment sewersheds (Fig. 2). Due to the low infiltration rates of native soils, all GI featured an underdrain (10–20 cm perforated PVC) surrounded by approximately 20 cm of ASTM No. 8 or No. 57 aggregate (The City of Columbus, 2017, Fig. 2). Media blends were sourced similarly across the BRCs used in the project, all were high sand content mixtures (80–90%) with a loamy sand classification and between 2 and 5% organic material by weight (The City of Columbus,

Table 2
Characteristics of the monitored Blueprint sewersheds and retrofitted GI. The surface storage volumes were calculated from GIS analysis of as-built surveys of a representative number of the BRCs (approx. half in each sewershed) in 2019–2020. The City of Columbus began installing downspout disconnections, and lateral linings in BG after the time period evaluated in this study (2016–2019).

Sewershed	Area (ha)	Land Use	Sewershed Impervious-ness (%)	Sewershed Area Treated by GI (%)	No. of GI Types	Total surface storage volume (m^2)	Homes with Discon-nected Downspouts	No. of Sanitary Sewer Laterals Lined	No. of Sump Pumps Installed
Beechwold (Control, BW)	111.5	Residential, Institutional	38.2	2	10 BRCs 1 street of PP 2,400 m^2	8.4	0	0	0
Indian Springs (IS)	47.8	Residential, Commercial, Institutional	40.3	23	32 BRCs 4 streets of PP 6,000 m^2	89.4	349	447	61
Cooke-Glenmont (CG)	11.5	Residential	30.9	31	3 BRCs	188	60	75	22
Blenheim-Glencoe (BG)	61.3	Residential, Institutional	44.5	44	163 BRCs	145.4	Started 2020	Started 2020	159

2017, Fig. 2). BRCs were planted with native plant species (mostly consisting of forbs and grasses) across the three sewersheds with plant coverage at the time of as-built surveys varying from 15 to 80% depending on the growing season and time since initial planting. While underdrains were utilized, IWS zones were not utilized in design; similarly, if designs featured flow limiting devices (e.g., ball valve), they were not utilized to create an IWS zone in the media profile.

2.2. Data collection

Tipping bucket (0.25 mm resolution, Davis Rain Collector) and standard rain gauges were located near the sampled storm sewer outfalls in areas free of overhead obstructions (Fig. 1). Gauges were secured to 2-m tall wooden posts and rainfall data were recorded on HOBO pendant loggers at 1-minute intervals (Onset Computer Corporation, Bourne, Massachusetts).

Monitoring began at each storm sewer outfall in June 2016. Either Teledyne ISCO 6712 or 3700 series automated samplers were used with

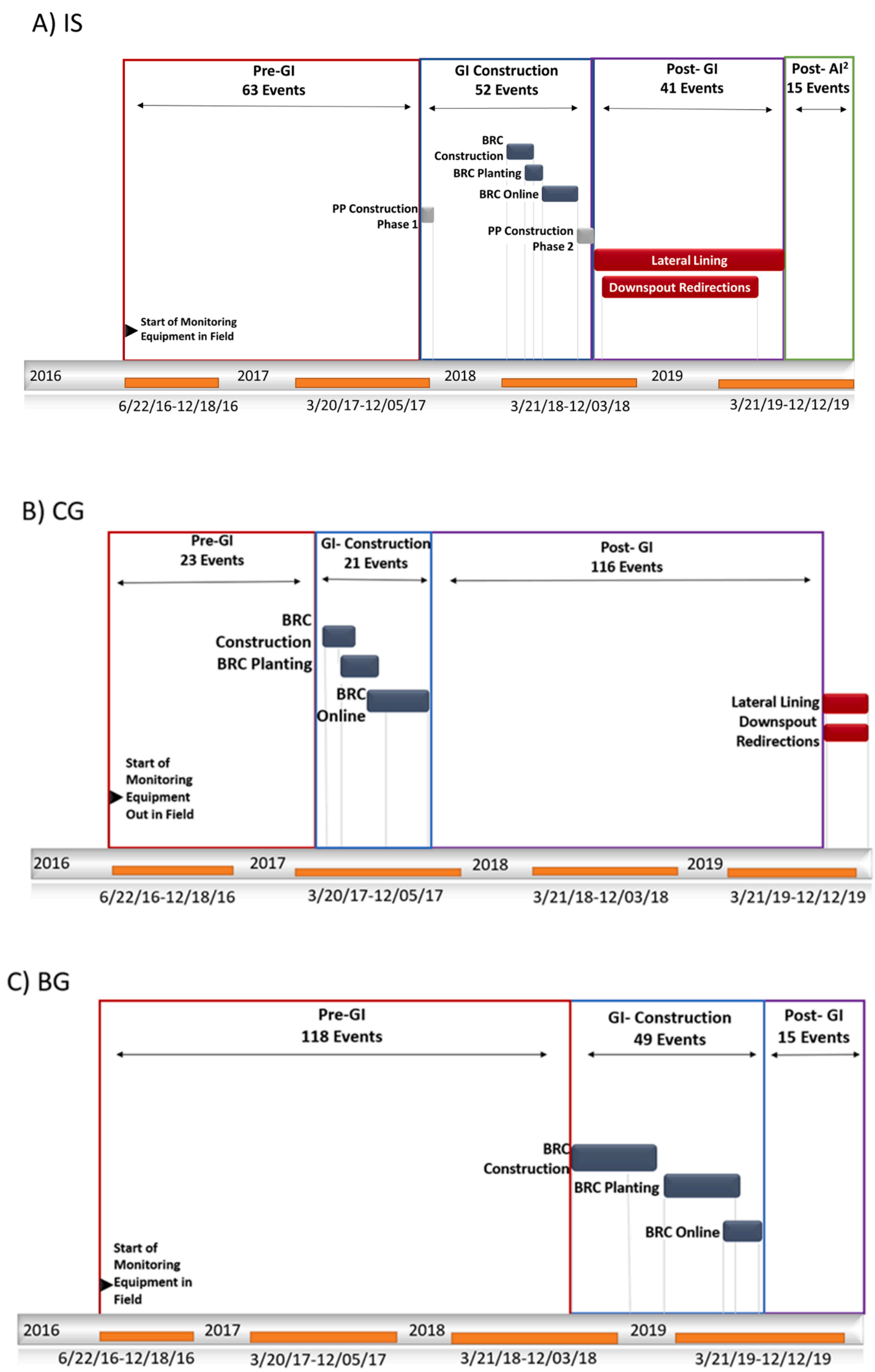

Fig. 3. Timeline of Blueprint Columbus project phases for the treatment sewersheds. Monitoring periods are indicated in orange (monitoring equipment was removed during winter months). GI construction events are shown in blue while construction of remaining infrastructure improvements is shown in red. The number of monitored storm events in each project period is specified at the top of each time period.

area velocity sensors attached to the bottom of each pipe, which measure velocity using the Doppler effect and water level using a pressure transducer. Sites were visited after events>5 mm of precipitation occurred to recalibrate the stage measurement, monitor battery usage, and perform preventative maintenance such as clearing debris upstream of the area velocity sensor or refreshing desiccant to remove excess moisture. Sites were decommissioned in the winter months (late December- early March) to protect the equipment from freezing temperatures.

Hydrologic data were collected by the area velocity sensors and stored on a 1-minute interval to the automated samplers; data were downloaded and managed in Flowlink version 5.1 (Teledyne ISCO, Lincoln, Nebraska). Except for CG, all storm sewers had baseflow during inter-event periods. Separation of wet weather events from baseflow was completed using the USGS local minima method (Sloto and Crouse, 1996), wherein for each hydrograph the lowest discharges are connected linearly to estimate baseflow.

2.3. Project Timeline

Blueprint Columbus was implemented in Clintonville in two phases: (1) the GI construction phase, and (2) the All-Infrastructure Improvements (AI^2) phase consisting of downspout redirections, and sanitary sewer lateral lining (Fig. 3). Sump pumps were installed on a rolling basis in each sewershed with the majority installed in 2018 for IS and 2019 for CG and BG. Sump pump installations are expected to continue through 2021. The GI construction phase encompassed the three periods: construction, planting, and establishment. During the establishment phase, runoff was routed away from the BRC inlets to provide a period for plant roots to become established. The construction phases (of both GI and AI^2 phases) were omitted from the analysis for CG and BG due to the use of flow diversions around constructed SCMs as construction throughout the sewershed continued to limit excess sediment accumulation. Unlike the other treatment sewersheds, the AI^2 construction phase in IS began immediately after the GI construction phase. Therefore, the Post-GI retrofit period for IS included the AI^2 construction phase (Fig. 3), during which the inlets of the GI were temporarily blocked while construction was occurring nearby. Construction in IS was fully completed at the end of August 2019, at which point the Post-AI^2 period began.

2.4. Data analysis

A modified paired watershed approach was used to account for GI construction which occurred over several months instead of at a single change point. The hydrological responses of the three treatment sewersheds were compared to the control sewershed in a pair-wise fashion to account for differences implemented between time periods (i.e., pre- vs. post-GI or pre- vs. post-AI^2, Fig. 3). The Kruskal-Wallis test was used to test for significant differences in precipitation characteristics (i.e., rainfall depth, peak 5-minute rainfall intensity, and the number of storms exceeding the 19 mm event depth used to design the BRCs) between project periods (Kruskal and Wallis, 1952). Each rainfall event was separated by a minimum antecedent dry period of six hours and minimum depth of 2.5 mm. Measured runoff volume was normalized by sewershed area to determine the runoff depth for each storm. Other flow metrics obtained for each storm event included area-normalized peak flow rate, lag-to-peak (defined as the time between the start of rainfall and the time of peak discharge), and flow duration.

Kruskal-Wallis tests comparing pre-GI to post-GI periods for BW were completed to determine whether it was a suitable control since it had 2% of its 111 ha sewershed treated by 10 BRCs (Fig. 3). No significant differences were observed for runoff depths, peak flow rates and lag-to-peak among pre- and post-GI periods ($p > 0.19$ for all comparisons). Similar to Smith (2020), these comparisons confirmed that BW was an appropriate control for this study.

Linear regression and analysis of covariance (ANCOVA) were used to examine hydrological changes in the monitored sewersheds across the project periods (i.e., Pre-GI, Post-GI, and Post-AI^2; Fig. 3). Linear regression models comparing runoff to rainfall depth were used to determine how the runoff thresholds and runoff coefficients changed over project periods. The runoff threshold (RO_T), the rainfall depth at which incipient runoff was generated, was determined as the x-intercept for each runoff depth versus rainfall plot. The runoff coefficient (C_R) was defined as the quotient of total runoff depth to total rainfall depth.

ANCOVA analyses were used to control for variation in rainfall over different periods; data collected at the BW sewershed outfall used as the covariate and plotted against hydrologic data from each treatment sewershed. Analyses were conducted to determine significance in the change in responses (slope) and intercepts of the regression equations between project periods. Percent reductions of runoff depth and peak flow rate as well as percent increases in lag-to-peak were calculated through a ratio of least square means (Eq. 1, Clausen and Spooner, 1993; Page et al., 2015a,b) where LSM_{Post} reflects the Post-GI or Post-AI^2 LSM and LSM_{Pre} equals the Pre-GI LSM for that sewershed. All data were log transformed as needed to meet the normality assumptions as determined by the Shapiro-Wilk test (Shapiro and Wilk, 1972).

$$\%\,Difference = \left(\frac{10^{LSM_{Post}}}{10^{LSM_{Pre}}} - 1\right) \times 100$$

2.5. Simulated storm testing

Despite having the same bioretention media, differences in hydraulic function during rain events were visually observed between individual BRCs. Thus, to determine an estimated field infiltration rate (IFR) of the BRC media, 10 simulated storm tests were performed at six different BRCs in the treatment sewersheds. The tests consisted of a known volume of water (1.5 m^3) applied via gravity to each BRC from a tank to determine single event performance where both the inlet and underdrain outlet were monitored using methods similar to Schlea et al (2014). Briefly, inflow and outflow hydrographs were determined through the use of a water meter (inflow) or graduated pan (outflow) from which volumes, peak flow rates, and lag times were calculated. Using these measured data, field IFR (cm/hr) was determined by taking the volume into the BRC (V_{in}, m^3) and dividing it by the BRC surface area (A_{BRC}. m^2) and the time for the entire volume to infiltrate the media layer (T_{in}, hr) using Eq. (2). These field-derived IFR values may be lower than the actual IFR of the media as complete wetting of BRC area likely did not occur during testing.

$$\text{IFR} = \frac{V_{in}}{A_{BRC} \times T_{in}} \tag{2}$$

3. Results and discussion

3.1. Monitored rainfall events

Between 119 and 142 rainfall events were observed in the sewersheds during the 42-month monitoring period (June 2016 - December 2019, Table 4). No significant differences in rainfall characteristics were observed across monitored sewersheds, likely due to the proximity (maximum distance of 2 km) of the rain gauges and sewersheds. The monitored rainfall events across the control sewershed observed depths ranging between 3.3 and 47.2 mm (5th-95th percentiles), this range was similar across the treatment sewersheds. The return periods for these storm events ranged from<1-year to the 2-year for the median rainfall duration (6 hr) observed during the study.

No significant differences in rainfall depths were observed across the project periods. Significantly lower peak 5-minute rainfall intensities occurred in the post-GI and post-AI^2 periods compared to pre-GI periods for each sewershed (BG: $p < 0.01$, CG: $p < 0.018$, and IS: $p < 0.004$, Table 3).

Table 3
Rainfall characteristics observed in the treatment sewersheds for each project period. Statistically significant differences determined using the Kruskal-Wallis test, of median rainfall depths and peak 5-minute intensities are denoted with a * (for $p < 0.05$). The 19 mm threshold is the GI design event.

	IS			**CG**		**BG**	
Project-Period	Pre-GI	Post-GI	Post-AI^2	Pre-GI	Post-GI	Pre-GI	Post-GI
# of Monitored Events	63	41	15	26	116	118	15
Median Rainfall Depth (mm)	10.7	11.4	8.9	7.4	10.2	11.7	5.8
Median Peak 5-min Intensity (mm/hr)	13.7	12.2	7.6*	19.1	13.7	19.8	8.4
Median ADP (days)	3.2	3.7	3.3	3.1	2.9	3.1	4.5
Median Rainfall Duration (hr)	5.0	6.2	7.8	4.4	6.0	5.5	5.9
# Storm Events > 19 mm	19	11	5	5	31	30	2

3.2. Changes in runoff depth and volume

3.2.1. Rainfall and runoff regressions

Runoff depth was positively correlated to rainfall depth in each sewershed ($0.51 < R^2 < 0.98$; Figs. 4–6). Similar runoff generation patterns were observed pre-GI for BG and IS (slopes of 0.36 and 0.37, respectively, Figs. 4 and 6). While BG had greater total imperviousness compared to IS (44.3% and 40% respectively; Table 2), the large areas of connected imperviousness in IS, attributable in part to the institutional and commercial land uses, were likely contributors to greater similarities in overall runoff generation (Lim and Welty, 2017; Pappas et al. 2008; Schuster et al. 2005). The shallowest pre-GI rainfall-runoff linear regression slope was observed in CG (Fig. 5), which is characterized by relatively low-density residential land use and had the lowest imperviousness. Similar results were reported by Hood et al. (2007), who observed slopes of 0.21 and 0.37 for regressions between rainfall and runoff depths from two residential developments in Connecticut. Other primarily residential urban catchments around the world have been characterized with slopes ranging from 0.33 in France to 0.58 in Italy (Boyd et al. 1993) and 0.36–0.61 in Minnesota (Ebrahimian et al. 2016). Similar to the Minnesota study, higher regression slopes were correlated to greater connected imperviousness within the sewersheds pre-GI (Ebrahimian et al. 2016).

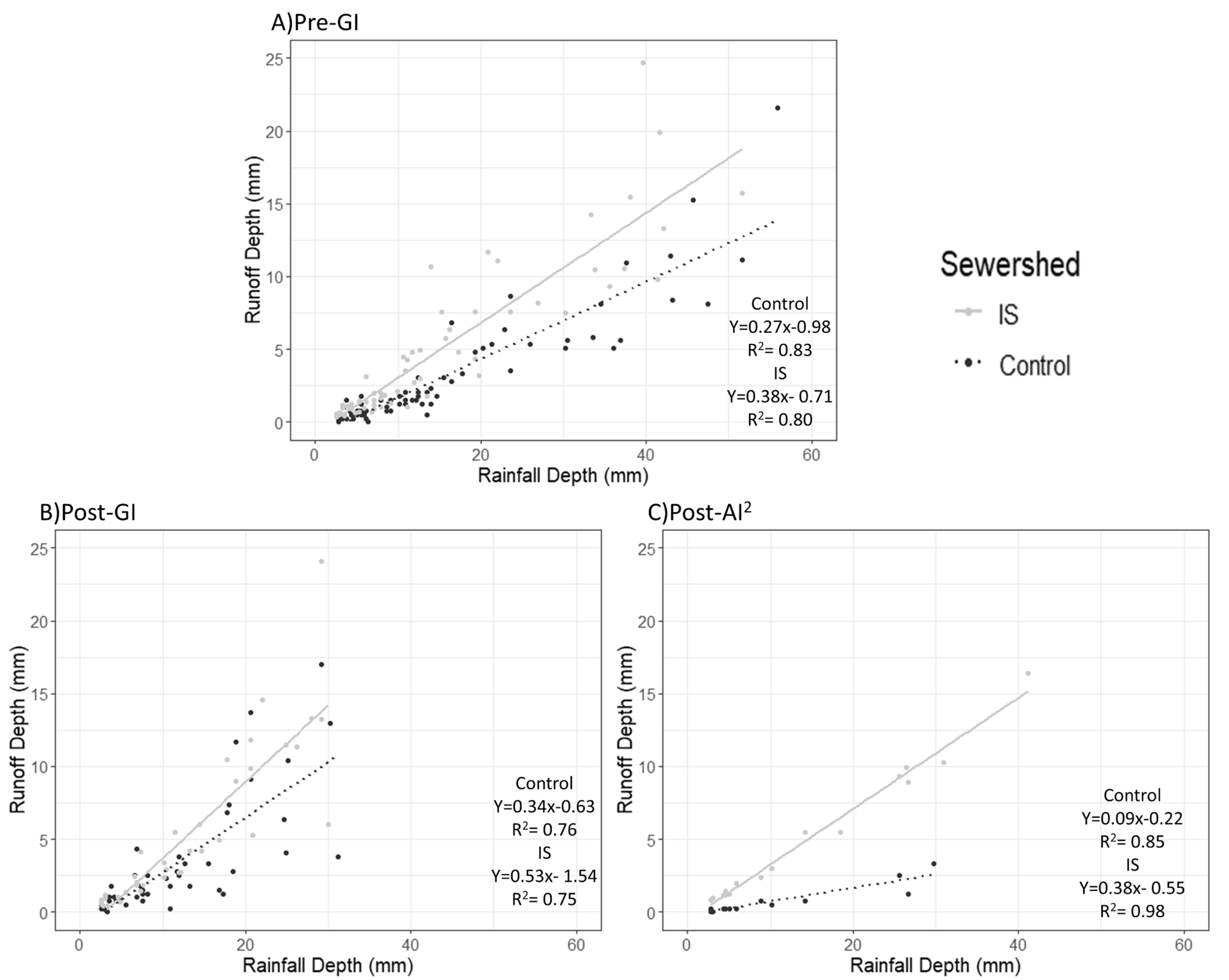

Fig. 4. Runoff depth (mm) versus rainfall (mm) depth in IS and control during the various project periods. Plots show comparisons between IS and the control sewershed across pre-GI, post-GI and post-AI^2 project periods, respectively. The control sewershed data is presented with black points with dotted trend lines and the treatment sewershed data and trend lines are presented in grey.

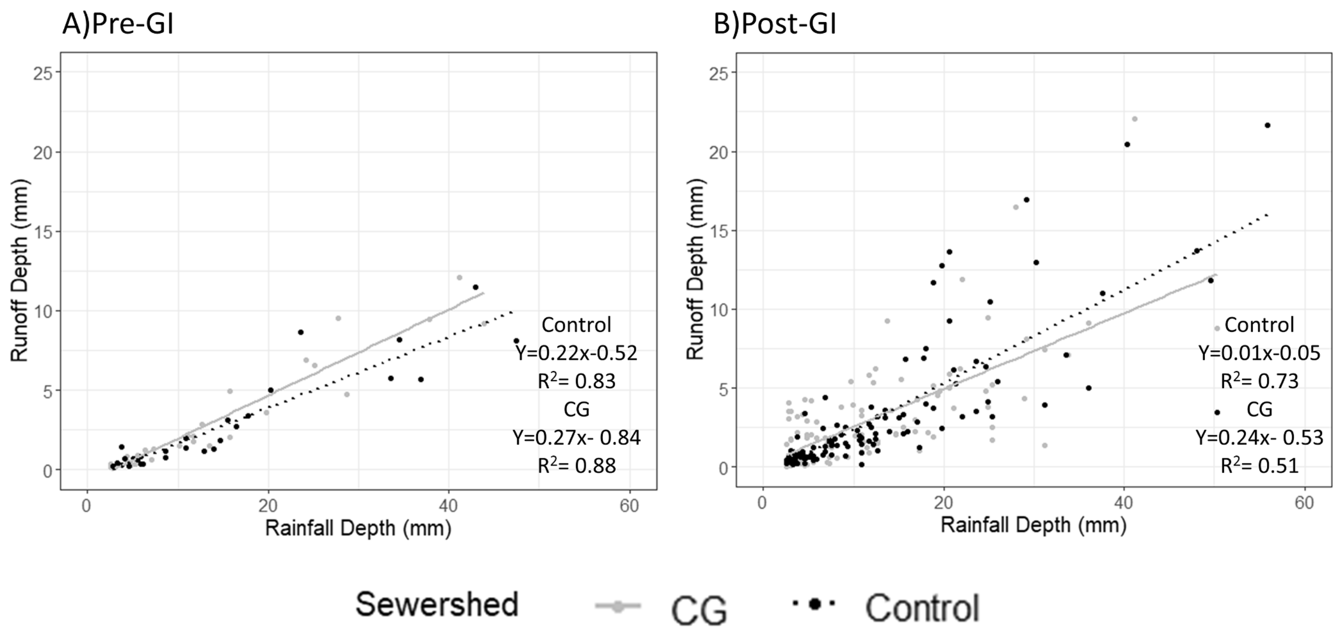

Fig. 5. Runoff depth (mm) versus rainfall (mm) depth in CG and control across project periods. A compares CG and the control across pre-GI and B compares across post-GI periods. The control sewershed data is always presented with black points with dotted linear regressions and the treatment sewershed data and linear regression are presented in grey.

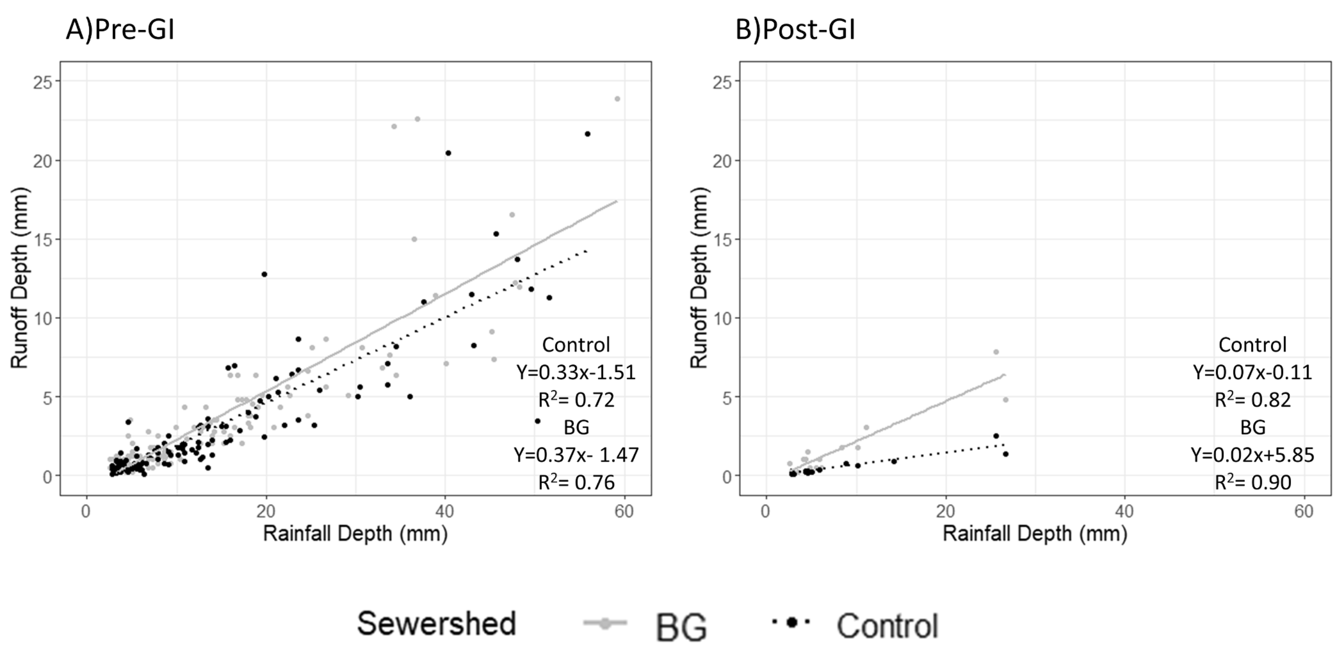

Fig. 6. Runoff depth (mm) versus rainfall (mm) depth in BG and control across project periods. A compares BG with the control across pre-GI and B compares across post-GI periods. The control sewershed data is always presented with black points with dotted linear regressions and the treatment sewershed data and linear regression are presented in grey.

Regression slopes were observed to decrease for all treatment sewersheds in the post-GI period compared to pre-GI, with BG exhibiting the greatest decrease (0.36 to 0.02) followed by CG (0.27 to 0.23, Fig. 4,5, and 6). These results indicate that the amount of runoff generated in each sewershed decreased following the installation of GI. Regression slopes at IS increased between the pre-GI (0.37) and post-GI (0.53) periods (Fig. 4), likely due to the ongoing construction efforts to improve other infrastructure which occurred during the period. Further, these activities coincided with the use of temporary sediment controls to block flow from entering the BRCs and added additional stormwater into the sewer system through sanitary sewer lateral lining (i.e., reducing infiltration and inflow of stormwater into the sanitary sewer). At IS post-AI^2, the slope decreased to 0.38 (Fig. 4C), nearly equaling the pre-GI phase and indicating that once construction was completed, the GI was able to mitigate the additional stormwater inputs, resulting in modest changes to catchment-scale hydrology.

Results of comparisons of runoff depth between treatment and control sewersheds using linear regression with rainfall as a covariant are presented in Fig. 7. Statistical significance in this model would indicate that the hydrologic response in the treatment sewersheds was significantly different than responses observed in the control over the same period. The regression equations, and median values for each of the

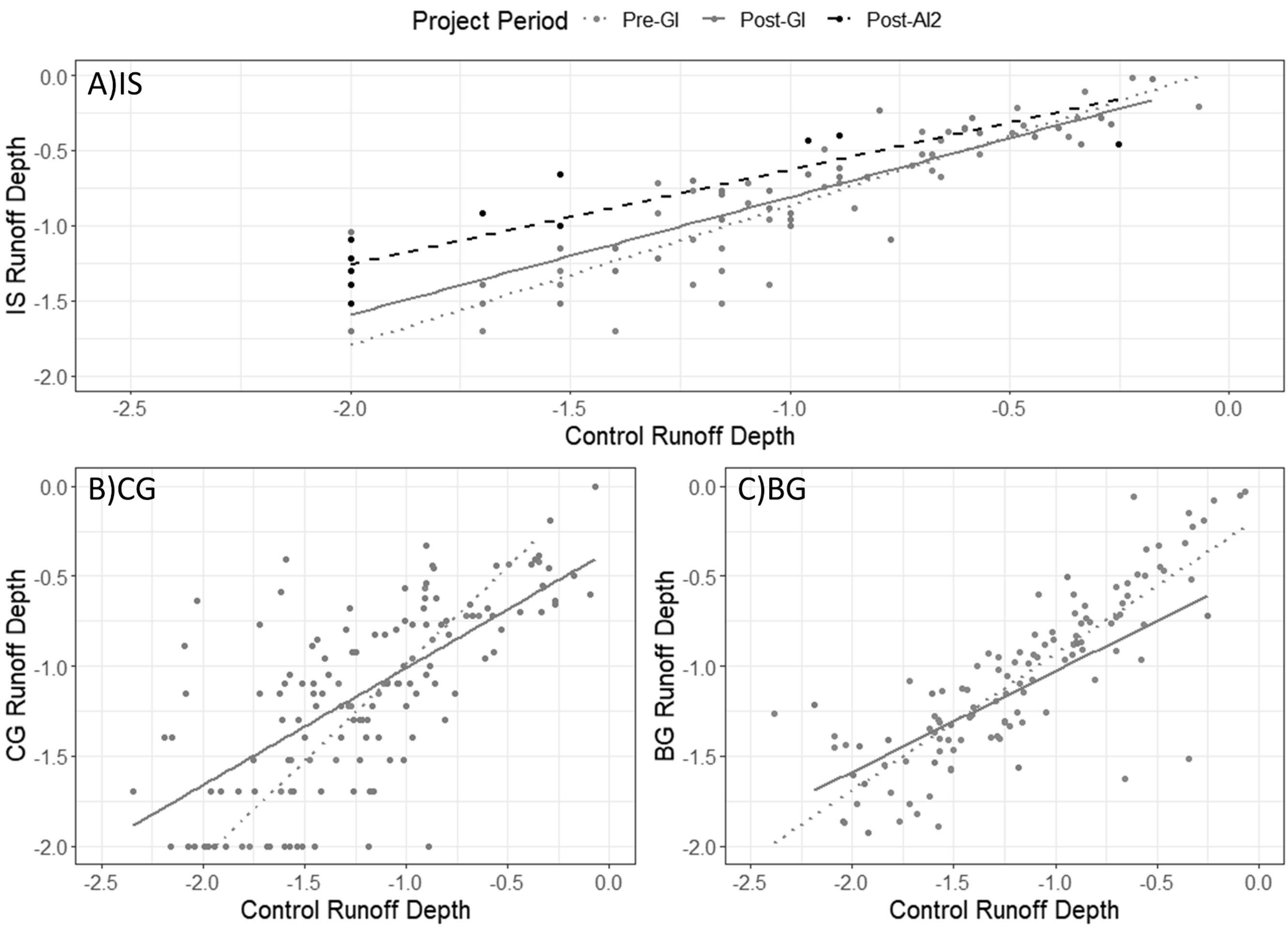

Fig. 7. ANCOVA generalized linear models comparing the log transformed runoff depth response between the treatment and control sewersheds. Shallower slopes signify statistically different and decreased runoff from treatment sewersheds such as in Indian Springs and Blenheim-Glencoe.

hydrologic variables are included for each sewershed and period in the Supplementary Material (Table A1). Results of percent change in least square means (LSM) for runoff depth, peak flow rate and lag-to-peak derived from ANCOVA models are summarized in Table 4 and are indicative of results from all monitored storm events (Table 3). Completion of GI in BG and all infrastructure improvements in IS resulted in significant decreases in runoff depth. Post-GI construction in IS and CG resulted in significant decreases in peak flow rate (see section 3.4). Similarly, GI and infrastructure improvements retrofitted into CG and IS resulted in increases in lag-to-peak for the post-GI and post-AI^2 periods (see section 3.5).

Significant decreases (48–96%) in slope of the runoff response indicate that runoff was being generated differently in the BG and IS compared to the control during the post-GI and post-AI^2 periods, respectively (Table A1). Because of the robust nature of the paired watershed design, these effects can be attributed to the addition of GI and other infrastructure improvements. Runoff reductions of 37% and 62% were observed in the IS and BG sewersheds during the post-AI^2 and post-GI periods, respectively (Table 4). Other sewershed scale studies observed runoff volume decreases of 40–80% following the installation of GI (e.g., Barr Engineering 2006; Bedan and Clausen, 2009; Page et al., 2015a,b, UNH Stormwater Center, & City of Dover, 2017). Conclusions from BG and IS-post-AI^2 should however be kept in context as only 15 storm events post-GI were compared against 118 and 63 pre-GI storm events, respectively. These 15 storm events were also significantly less intense (median peak 5-minute intensity: 8.4 mm/hr compared to 19.8 mm/hr; Table 3), which likely contributed to the enhanced runoff reduction observed during this period.

No significant differences in runoff depth were observed in the post-GI periods in CG and IS compared to the control (Table 4). A smaller number of storm events were monitored at the CG sewershed during the pre-GI period which may have impacted these results. The lack of significance at IS between the pre- and post-GI periods could be attributed to the ongoing construction of other infrastructure improvements (Table 2, Fig. 3) and the temporary blocking of BRC inlets to prevent sediment accumulation which occurred during the post-GI period. The high IFR of the media determined from field tests (which ranged from 23.5 to 51.6 cm/hr) paired with high rainfall intensity events which were common in the post-GI periods (Table 3) likely caused the BRCs in CG and IS to function as filters and may have limited opportunities for runoff reduction.

In addition to high infiltration rates within the media, lack of IWS zones or use of flow limiting devices (e.g., ball valves) resulted in much of the runoff volumes to pass through the GI into the existing storm sewer system. Proper usage and placement of flow limiters can create an internal water storage layer (IWS) which has be shown to increase the runoff volume reduction of BRCs over a variety of soil types (Brown and Hunt, 2011a; Hunt et al 2012; Winston et al 2016a). In addition, post-construction surveys revealed that the height of overflow structures (and thus potential ponding depths) were reduced by approximately one-third compared to design specifications (i.e., actual mean height of 10 cm compared to desired 30.5 cm storage depth) in over half of the BRCs. Increased instances of overflow have been linked to undersized BRCs (i.e., those with lower as-built surface storage compared to designed volumes), decreasing the potential hydrological benefits of these systems (Brown and Hunt, 2011b). The lack of IWS coupled with lower overflow structures in the Blueprint BRC designs likely impacted the runoff reductions, or lack-thereof, observed in the treatment sewersheds.

3.3. Runoff thresholds and coefficients

Runoff thresholds were found to increase in the post-GI period, indicating that greater amounts of rainfall were necessary to initiate runoff within treatment sewersheds following GI implementation (Table 5). Between the pre- and post-GI period, RO_T increased between 0.8 and 1.25 mm in the treatment sewersheds. Runoff thresholds ranged from 1.5 to 4.6 mm and 1.5–4.8 mm in the pre-GI and post-GI periods, respectively. Page et al. (2015a) and Hood et al. (2007) found similar RO_T for residential neighborhoods in Wilmington, NC (3.3 mm) and Waterford, CT (2.8 mm), respectively.

Conversely, the RO_T in the control sewershed, BW, decreased during the pre- and post-GI phases of the BG and IS sewersheds (by 3 and 2 mm, respectively). These increases in RO_T for the treatment sewershed would be expected to be due in part to reduction in effective impervious area brought on by the GI retrofits in the sewersheds. However, the lack of significant differences in runoff depth (Table 4) suggests the marginal increases or decreases (<1mm difference) observed in RO_T are likely due to other factors beyond GI (e.g., rainfall characteristics). Peak 5-minute and average rainfall intensity as well as antecedent soil moisture conditions also influence runoff generation from pervious surfaces (Horton, 1933) which are not considered in the determination of RO_T.

Runoff coefficients from the four sewersheds varied from 0.2 to 0.33 in the pre-GI period (Table 6), similar to two residential neighborhoods in Waterford, CT (0.19–0.24; Hood et al. 2007). Line and White (2007) reported a C_R of 0.55 for a residential development on moderate slopes and in clayey soils in North Carolina, whereas Page et al. (2015b) found a C_R of 0.38 for a coastal North Carolina residential development. Both Line and White (2007) and Page et al. (2015b) studied watersheds with higher imperviousness than those studied herein.

The changes to C_R between the pre- and post-GI phases in the treatment sewersheds were similar to those observed in the control sewershed (Table 7). This was particularly true for the longer operational GI sewersheds (i.e., CG and IS) where the differences between the pre- to post-GI changes in C_R were 0 and 0.02, respectively, when compared to the control sewershed. Conversely, Page et al. (2015a) reported far higher reductions in C_R following the installation of GI in Wilmington, NC (from 0.38 to 0.18).

While impervious disconnection was achieved by the installation of GI retrofits in the treatment sewersheds, there are many aspects of the local soil profiles and hydrological cycle that could impact the runoff generation in the sewersheds which are not accounted for in C_R calculations. The underlying soils in the treatment sewersheds have low infiltration rates (<5 mm/hr), limiting exfiltration and potential runoff volume reduction. Furthermore, IWS or restrictions to flow on the underdrains were not employed in the current study. In contrast, the GI in North Carolina was constructed over sandy subsoils (>50 mm/hr) which influenced runoff reduction and likely led to the observed reduction in C_R (Page et al., 2015a). Similar to calculations of RO_T, rainfall characteristics have been recognized as important drivers in stormwater generation as they dictate the volume and rate at which water can be infiltrated into pervious surfaces without being accounted for in runoff coefficient analyses (Horton, 1933; Ran et al. 2012).

Table 5
Runoff thresholds (mm) for each of the Blueprint project periods. Runoff thresholds were calculated for the control sewershed (BW) correspond to the respective time periods in each treatment sewershed. A positive increase in the threshold indicates more rainfall is needed before runoff occurs.

Sewershed	Pre-GI	Post-GI		Post-AI^2	
	Runoff Threshold	Runoff Threshold	ΔRunoff Threshold (Pre-GI to Post-GI)	Runoff Threshold	ΔRunoff Threshold (Pre-GI to Post-AI^2)
IS	1.78	3.05	+1.27	1.52	−0.26
BW	3.81	1.78	−2.03	2.29	−1.52
CG	1.53	2.29	+0.76	——	——
BW	2.29	3.56	+1.27	——	——
BG	3.81	4.83	+1.02	——	——
BW	4.57	1.52	−3.05	——	——

3.4. Normalized peak flow rate response

Significant differences in normalized peak flow rate were observed for all treatment sewersheds except BG (Table 4, Fig. 8), attributable to the addition of GI in the sewersheds. The post-AI^2 phase for IS also had slightly significant reductions ($p < 0.10$) in peak flow rate vis-à-vis the control sewershed. This result could be attributed to the additional infrastructure improvements that added stormwater into the sewer network. Peak flow mitigations for other sewershed-scale GI studies ranged from 20 to 44% (Bedan and Clausen, 2009; Page et al. 2015a; Jarden et al 2016) with larger reductions occurring for smaller storm events. Peak flow mitigations between 40 and 58% were observed in the treatment sewersheds (Table 5, Table A2), with potential differences compared to previous literature potentially due to differences in GI design or density of SCMs. Further, the elevated hydraulic conductivity of the media resulted in substantial available storage during the peak of the runoff hydrograph, aiding in peak −1270091440000flow mitigation.

A linear relationship with peak rainfall intensity explained approximately 67 ± 8% of the variance in the peak flow rates across the four sewersheds for the pre-GI period (Table A2). After GI was implemented, the variability of the normalized peak flow rates increased. The post-GI and post-AI^2 periods were explained by lower R^2 linear relationships with a greater standard deviation between the sewersheds (50 ± 33%). Variability of peak flow rate responses likely depended on available GI storage at the occurrence of peak rainfall intensity. If the BRC was partially or completely full at the time of peak rainfall intensity, overflow directly into the storm sewer may result which would decrease peak flow mitigation. This trend was observed by Winston et al. (2016a) in three BRCs in northern Ohio where a greater degree of peak flow rate mitigation (>53%) corresponded to peak rainfall intensities which occurred prior to the hyetograph centroid. The increased variability of peak flow rate reductions has also been supported by Hunt et al. (2012) who concluded that restrictions on depressional storage depths limit BRCs peak flow mitigation capabilities.

Table 4
Summary of changes in Least Square Means for runoff depth, peak 5-minute flow rate, and lag-to-peak. Statistically significant changes which occurred in the treatment sewersheds are noted in bold with the respective ANCOVA p-value ($p < 0.05$).

Sewershed	Runoff Depth		Peak Flow Rate		Lag-to-Peak	
	% Change in LSM (Pre- to Post-GI)	% Change in LSM (Pre- to Post- AI^2)	% Change in LSM (Pre- to Post-GI)	% Change in LSM (Pre- to Post- AI^2)	% Change in LSM (Pre- to Post-GI)	% Change in LSM (Pre- to Post- AI^2)
IS	5.5	**−37.3**	**−40.9**	−51.2	**6.4**	**43.8**
CG	58.0	——	**−57.6**	——	**64.2**	——
BG	**−61.7**	——	−51.9	——	26.2	——

Table 6
Runoff coefficients (C_R) in the pre-GI period for the Clintonville sewersheds and reported C_R values from previous studies.

Sewershed or Reference	Runoff Coefficient	Percent Impervious	Primary Land Use	Soil Texture	Drainage Area (ha)	Location
Beechwold	0.2	38.2	Residential	Silt Loam	111.4	Columbus, OH
Blenheim	0.23	44.5	Residential	Silt Loam	62.2	Columbus, OH
Cooke-Glenmont	0.24	30.9	Residential	Silt Loam	13.0	Columbus, OH
Indian Springs	0.33	40.3	Residential	Silt Loam	46.6	Columbus, OH
Page et al (2015b)	0.38	60	Residential	Sandy	0.52	Wilmington NC
Line and White (2007)	0.55	53	Mixed Use	Clayey	3.88	Raleigh, NC
Hood et al. (2007)	0.19	29	Residential	Sandy Loam	5.44	Waterford, CT
Hood et al. (2007)	0.24	32	Residential	Sandy Loam	2.07	Waterford, CT

Table 7
Comparison of runoff coefficient (C_R) for the three treatment sewersheds compared to the control during all project phases. Negative changes in C_R between the phases indicate that less runoff was generated from the sewershed per unit rainfall depth.

Sewershed	Pre-GI	Post-GI		Post- AI^2	
	C_R	C_R	Δ C_R	C_R	Δ C_R
BG	0.28	0.21	−0.07	——	——
BW	0.23	0.17	−0.06	——	——
CG	0.20	0.27	0.07	——	——
BW	0.21	0.28	0.07	——	——
IS	0.33	0.40	0.07	0.35	0.02
BW	0.20	0.29	0.09	0.17	−0.03

3.5. Lag-to-Peak response

Lag-to-peak increased by 6–64% during the post-GI compared to the pre-GI period, indicating that additions of GI delayed runoff conveyance to the monitored outfalls (Table 4, Table A3). Significant increases were observed in the slope of the lag-to-peak response between the pre-GI to post-GI periods in IS ($p < 0.045$) and CG ($p < 0.003$) (Table A3, Fig. 9). Changes in lag-to-peak ranged from 0.3 h (ISpost-GI) to 3.1 h (CG post-GI). A significant decrease in IS slope post-AI^2 was observed, corresponding to the increased stormwater volumes generated for each storm event once the additional infrastructure improvements were installed which could impact the timing of peak flow at the monitored outfall. Previous studies of individual BRCs have observed lag-to-peak times ranging from 40 to 530 min depending on the drainage area to BRC area ratio, media depth, composition, and underdrain configuration (Schlea et al. 2014; Liu and Fassman-Beck 2017). Hood et al. (2007) found GI

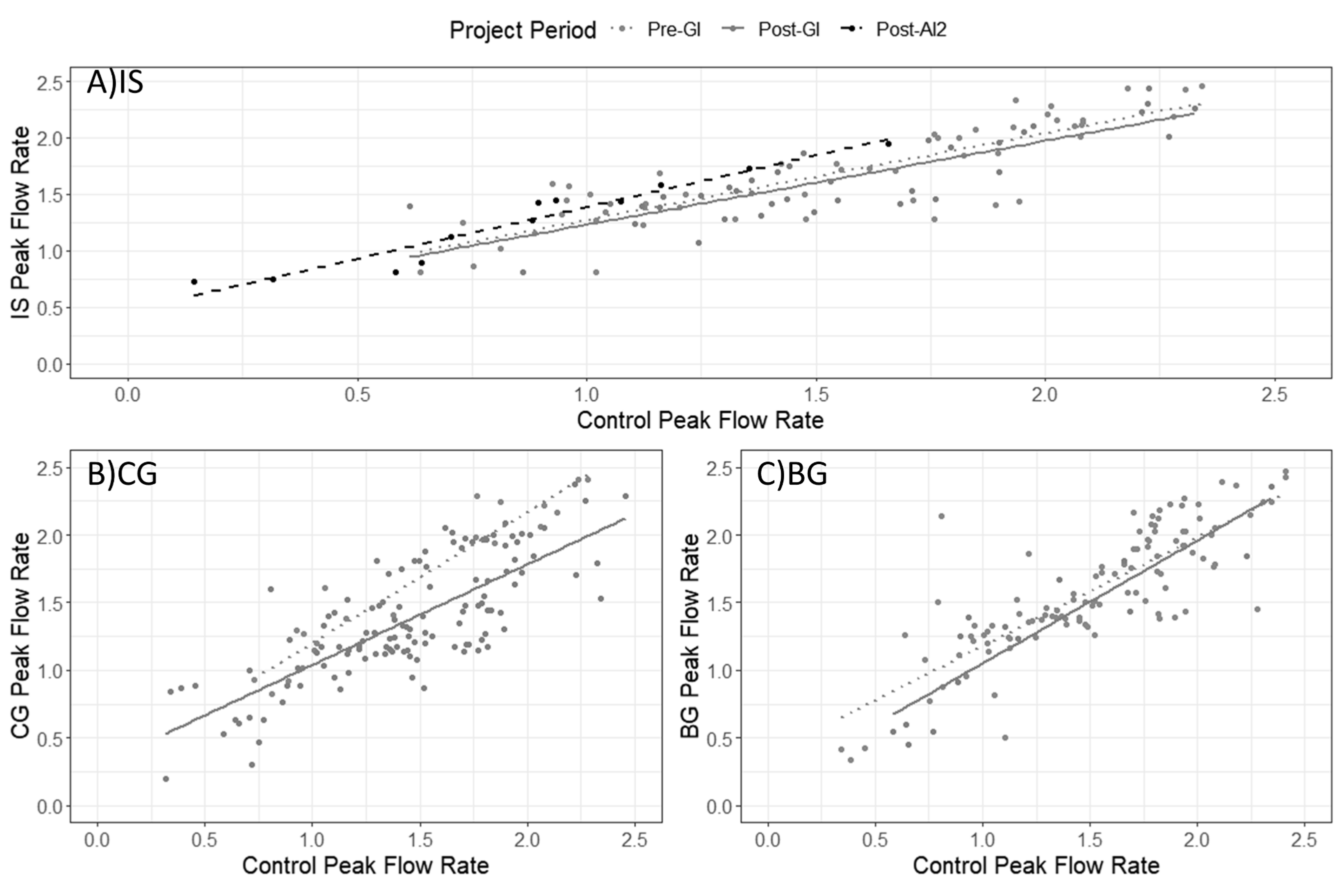

Fig. 8. ANCOVA generalized linear models comparing the normalized peak runoff flow rate (mm/hr) response for each treatment sewershed to the control. Peak flow rates were significantly reduced for smaller storm events more often than larger storm events across all three sewersheds post-GI.

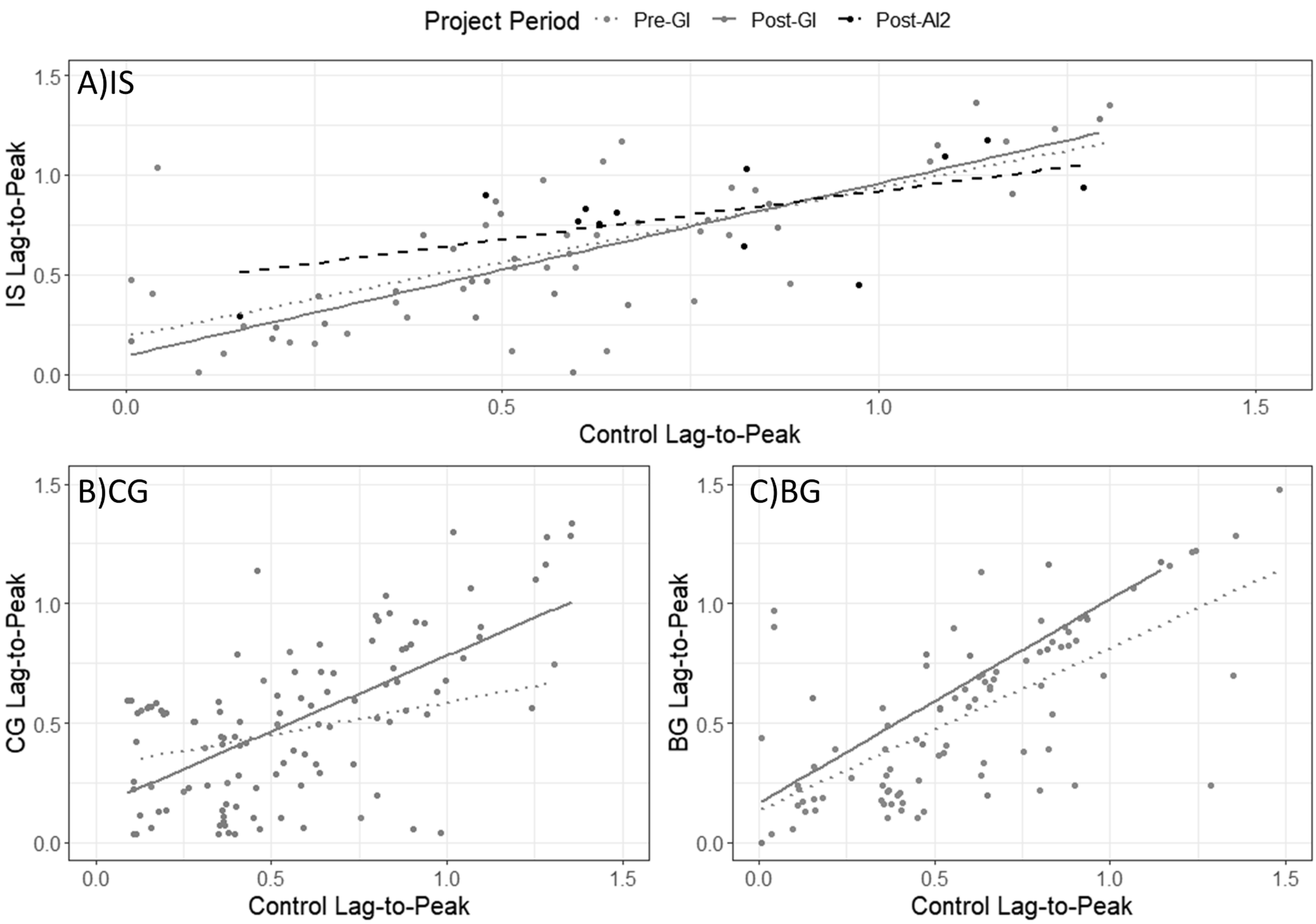

Fig. 9. ANCOVA generalized linear model for comparing lag-to-peak (hrs) across treatment sewersheds and the control. A steeper slope corresponds to longer lag-to-peak for the treatment sewershed compared to the control.

increased lag-to-peak times were between 8 and 10 times greater (i.e., 4 min to 40 min) than traditionally managed sewersheds. The smaller changes in lag-to-peak observed in the treatment sewersheds herein could be a function of the percentage of sewershed treated by GI as well as the GI design parameters mentioned above.

The lack of significant differences in lag-to-peak observed at BG could be attributed to the small number of storm events captured during the post-GI period. In addition, the smaller surface areas of the BRCs (80% of the BRCs were < 9 m^2) when compared to the GI in the other two treatment sewersheds (28% in IS and 0% in CG) could have influenced this result. The density and placement of GI in relation to the sewershed outlet and the amount of storage capacity created by the GI are design elements which could also impact the lag-to-peak. ANCOVA results (Fig. 9C) produced a model similar to the retrofitted catchment studied by Page et al. (2015a) who also observed an intersection of regression lines. The North Carolina study observed BRC abstraction farther from the sewer outfall; this led to the remaining (i.e., untreated) stormwater to reach the monitoring point more rapidly (Page et al., 2015a).

3.6. Conclusions

This paired watershed study was performed to verify the sewershed-scale impacts of>200 individual GI practices installed in the Clintonville neighborhood of Columbus, Ohio, USA. Results showed significant decreases in peak flow rate (40–58%) as well as increases in lag-to-peak (6–60%) resulting from GI retrofits installed in three treatment sewersheds compared to a control. Runoff volume and depth reductions varied across treatment sewersheds with significant reductions observed (37% and 65%) for project periods with smaller numbers of monitored storm events (<20) that were significantly less intense than those in other project periods. The high infiltration rates of the bioretention media (derived from simulated storm testing) and lack of IWS zones implemented in the BRCs led to lower than anticipated runoff reductions, particularly during high intensity, large rainfall events where the cells functioned more as filters instead of retaining runoff. Results presented herein may have been improved if GI practices were specifically designed for targeted hydrological mitigation.

In the post-AI^2 period for the Indian Springs sewershed, which included the completion of other infrastructure improvements associated with the retrofit effort (e.g., implementation of sump pumps, sanitary sewer lateral lining, and downspout redirections), hydrologic responses more closely resembled the pre-GI period due to the additional stormwater volumes conveyed to the GI. Regression slopes of peak flow rate and lag-to-peak significantly increased post-AI^2, often reverting to values near the pre-GI period. This indicated that the Blueprint projects effectively directed more stormwater to the GI and, ultimately, the storm sewer system. However, the GI provided effective mitigation of the additional stormwater introduced to the sewershed with the completion of these infrastructure improvements, returning the hydrologic response to pre-retrofit conditions.

This study demonstrates the benefits of large-scale implementation of GI in a developed urban area. Further exploration into the importance of GI design, placement, and functionality of the practices within the greater sewershed hydrology, with a particular focus on runoff volume reductions, is recommended. This study found that while significant peak flow reductions and increased lag-to-peak times were observed in all treatment sewersheds, the ability to retain and reduce the overall volumes leaving each practice was limited. These results contribute key knowledge about sewershed scale impacts of GI to aid engineers and city planners to improve the design of GI retrofits to optimize stormwater management.

CRediT authorship contribution statement

Kathryn M. Boening-Ulman: Methodology, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Ryan J. Winston:** Conceptualization, Methodology, Supervision, Writing – review & editing, Resources. **David M. Wituszynski:** Investigation, Writing – review & editing. **Joseph S. Smith:** Investigation, Writing – review & editing. **R. Andrew Tirpak:** Writing – review & editing, Validation. **Jay F. Martin:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2022.128014.

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