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Assessing the effects of catchment-scale urban green infrastructure retrofits on hydrograph characteristics

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Abstract:

Run-off from impervious surfaces has pervasive and serious consequences for urban streams, but the detrimental effects of urban stormwater can be lessened by disconnecting impervious surfaces and redirecting run-off to decentralized green infrastructure. This study used a before–after-control-impact design, in which streets served as subcatchments, to quantify hydrologic effectiveness of street-scale investments in green infrastructure, such as street-connected bioretention cells, rain gardens and rain barrels. On the two residential treatment streets, voluntary participation resulted in 32.2% and 13.5% of parcels having green infrastructure installed over a 2-year period. Storm sewer discharge was measured before and after green infrastructure implementation, and peak discharge, total run-off volume and hydrograph lags were analysed. On the street with smaller lots and lower participation, green infrastructure installation succeeded in reducing peak discharge by up to 33% and total storm run-off by up to 40%. On the street with larger lots and higher participation, there was no significant reduction in peak or total stormflows, but on this street, contemporaneous street repairs may have offset improvements. On the street with smaller lots, lag times increased following the first phase of green infrastructure construction, in which streetside bioretention cells were built with underdrains. In the second phase, lag times did not change further, because bioretention cells were built without underdrains and water was removed from the system, rather than just delayed. We conclude that voluntary green infrastructure retrofits that include treatment of street run-off can be effective for substantially reducing stormwater but that small differences in design and construction can be important for determining the level of the benefit. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS green infrastructure; stormwater management; low-impact development; urban watersheds; hydrograph analysis; Ohio, USA

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HIGHLIGHTS

- Before–after-control-impact study of two streets retrofit with green infrastructure.
- One street showed substantial reductions in peak and total stormflow.
- Street-connected bioretention cells are effective relative to household participation.
- Bioretention cells with underdrains affected hydrograph lag times.

INTRODUCTION

In urban areas, headwater streams are being replaced by headwater streets. The combination of increasing run-off by preventing infiltration, increasing drainage efficiency through headwater streets and storm drains and replacing headwater streams with pipes results in the rapid delivery of high volumes of stormwater to urban streams and sewer networks (Leopold, 1968; Shuster *et al.*, 2005; Elmore and Kaushal, 2002; Meierdiercks *et al.*, 2010). At the end of the pipes, stormwater run-off causes flooding, erosion, pollution and degradation of aquatic ecosystems, and the discharge of raw sewage into the environment when combined sewers overflow (Booth and Jackson, 1997; Lee and Bang, 2000; Walsh *et al.*, 2005b; O'Driscoll *et al.*, 2010). When impervious surfaces, such as rooftops and roadways, exceed ~10% of the catchment area, or when directly connected impervious surfaces exceed only 2–3% of the catchment area, substantial geomorphic and ecological changes arise from stormwater influences on hydrograph characteristics and water quality (Booth and Jackson, 1997; Walsh *et al.*, 2005a; Chin, 2006; Vietz *et al.*, 2014). These problems, especially in the context of increasing global urbanization and climate change, have provoked

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intense interest in mitigating stormwater run-off (e.g. Roy *et al*., 2008; Barbosa *et al*., 2012; Burns *et al*., 2012; Fletcher *et al*., 2013).

Run-off from rooftops and roadways is routed via downspouts and curb and gutter systems into storm drains and ditches, which have been referred to as engineered headwaters (Kaushal and Belt, 2012). Traditional stormwater control measures (SCMs) manage stormwater between the engineered headwaters and the stream through end-of-pipe solutions. Typified by wet retention ponds, dry detention ponds and constructed wetlands, SCMs store run-off and slowly release it to streams, with the goal of improving water quality by settling particles and reducing peak flows in the receiving streams (e.g. Lawrence *et al*., 1996; Roesner *et al*., 2001; Burns *et al*., 2012). While mitigating peak flows, most traditional SCMs are not designed for significant infiltration or volume reduction (Burns *et al*., 2012; Walsh *et al*., 2012). Further, many of these SCMs require large amounts of land, taking it away from valuable building space or making stormwater management difficult to retrofit into already developed areas.

As opposed to traditional SCMs, low-impact development (LID) manages stormwater before it reaches engineered headwaters, through decentralized practices and source control. The goal of LID is to mimic predevelopment hydrology, reduce peak stormflows and total storm volume and improve water quality (Dietz, 2007). LID is implemented through site design, impervious surface reduction and practices such as green roofs, porous pavements, rain gardens, rain barrels and bioretention cells (Hood *et al*., 2007; Mayer *et al*., 2012). Here, we use LID to refer to the general principles of decentralized stormwater management with predevelopment hydrology as a goal, and we use green infrastructure to describe the individual decentralized stormwater management practices (Fletcher *et al*., 2014). Green infrastructure practices generally promote infiltration and/or evapotranspiration as a means of reducing stormwater run-off and improving water quality. At the site scale, their effectiveness is well documented (e.g. Rushton, 2001; Davis, 2008; Li *et al*., 2009; Czemiel Berndtsson, 2010; Hunt *et al*., 2010).

Modelling studies of the potential for large-scale implementation of green infrastructure practices are increasingly common (e.g. James and Dymond, 2011; Lee *et al*., 2012; Walsh *et al*., 2014; Versini *et al*., 2015), but only a handful of studies have assessed real-world catchment-scale green infrastructure projects. When urban development occurs with LID principles and extensive green infrastructure practices, paired catchment studies (2–110 ha) have shown that peak discharges and total run-off volumes are lower than in nearby catchments with traditional SCMs (Selbig and Bannerman, 2008; Bedan and Clausen, 2009; Loperfido *et al*., 2014). Stormflow lag times are longer in LID catchments (Hood *et al*., 2007), and baseflow is higher (Loperfido *et al*., 2014). Water quality benefits have also been reported (Selbig and Bannerman, 2008; Bedan and Clausen, 2009).

To date, only one study has reported on the hydrological effects of green infrastructure retrofits at the catchment scale. In the Shepherd Creek watershed (Ohio, USA), a reverse-auction approach for voluntary homeowner participation resulted in 83 rain gardens and 170 rain barrels on 30% of 350 eligible properties across three 28- to 69-ha subcatchments (Mayer *et al*., 2012; Shuster and Rhea, 2013). The green infrastructure retrofits in this study led to a small reduction in stormwater run-off, minor changes in water quality and no changes in stream biota (Shuster and Rhea, 2013; Roy *et al*., 2014). The reductions in directly connected impervious surface were insufficient to yield clear improvements, relative to the size of the watershed and other confounding factors (Roy *et al*., 2014). Notably, the green infrastructure practices in the Cincinnati study were focused on rooftop run-off and did not treat run-off from roadways in the catchments (Shuster and Rhea, 2013).

The lack of demonstrated catchment-scale benefits associated with green infrastructure retrofits contrasts with the demonstrated efficacy of green infrastructure at reducing stormwater impacts at the scale of a single practice or when applied extensively in a newly urbanized area. This contradiction highlights the need to advance knowledge of green infrastructure effectiveness where it is retrofitted into existing urban landscapes. In particular, the Shepherd Creek results identify the need to assess the effectiveness of street-connected green infrastructure retrofits and to undertake studies at a scale with a high potential to detect the effects of retrofit activities. *We hypothesize that green infrastructure retrofits that include streets will produce substantial reductions in stormwater run-off in a residential landscape.*

Studies of headwater streets as subcatchments provide an opportunity to focus on street-connected green infrastructure and embrace some of the complexities of scaling up green infrastructure implementation and effectiveness, while remaining a practical scale for minimizing confounding factors. *The goal of this research is to determine the effectiveness of catchment-scale green infrastructure retrofits, including rain gardens, street-connected bioretention cells and rain barrels, on reducing overall stormwater run-off, reducing peak flows and increasing stormwater lag times from headwater streets.*

METHODS

Study design

The study makes use of a double paired watershed approach with a before–after-control-impact design (Green, 1979; Clausen and Spooner, 1993). The before–after-control-impact design has produced key insights into the effects of land cover change in experimental forest (e.g. Hornbeck *et al.*, 1970; Harr *et al.*, 1975; Likens *et al.*, 1977). In urban areas, comparisons across variable catchments (e.g. Rose and Peters, 2001; Loperfido *et al.*, 2014; Valtanen *et al.*, 2014) are much more common than before–after-control-impact designs (DeFries and Eshleman, 2004), although Bedan and Clausen (2009) and Shuster and Rhea (2012) are notable exceptions. Cross-site comparisons lack the ability to test causality for observed hydrologic differences and may suffer from both modern and legacy confounding factors (King *et al.*, 2005; Bain *et al.*, 2012).

Site description and green infrastructure installation

Two streets with 0.05- to 0.075-ha lots (Klusner Ave and Hetzel Dr.) and two streets with 0.1- to 0.2-ha lots (Parkhaven Dr. and Mazepa Trail) are served by storm sewers that drain into West Creek, within the city of Parma, Ohio (Figure 1). Each street then forms a subcatchment of West Creek. The streets exemplify a land use pattern typical of residential areas developed in the 1960s. The storm sewer outfalls at the end of the treatment streets are approximately 0.7 km apart, across the valley containing West Creek, a tributary of the Cuyahoga River. The downslope end of Klusner Ave is located at 41.377°N, 81.698°W. Mean annual precipitation is 994 mm/year at Cleveland Hopkins International Airport, located 13.5 km to the west–northwest. Soils in the study are somewhat poorly drained silty clay loams, overlying their glacial till parent material (Soil Survey Staff, n.d.). The combination of poorly drained soils and high amounts of imperviousness contributes to problems with stormwater run-off throughout the region (e.g. Schleis, 2015).

Each of the study streets utilizes standard curb and gutter stormwater collection practices. Additionally, roof run-off from downspouts is directed into the storm drain at each residence. Street and driveway run-off is carried along streetside curbs, which lead directly into storm drains at centralized catch basins. In both neighbourhoods, transportation surfaces (streets, sidewalks and driveways) comprise more than 50% of the total imperviousness. On Klusner Ave, house roofs cover an average of 104 m^2 per parcel, while detached garages have an average roof area of 46 m^2. On Parkhaven Dr., roofs cover an average of 242 m^2 per parcel, inclusive of the attached garages. On Parkhaven Dr., 61% of houses have patios or decks at the rear of the house. Where they exist, they average 50 m^2. On Klusner Ave, houses and garages are largely rectangular with two or four facets of the roofs. On Parkhaven Dr., homes have more complicated roof geometries and more downspouts.

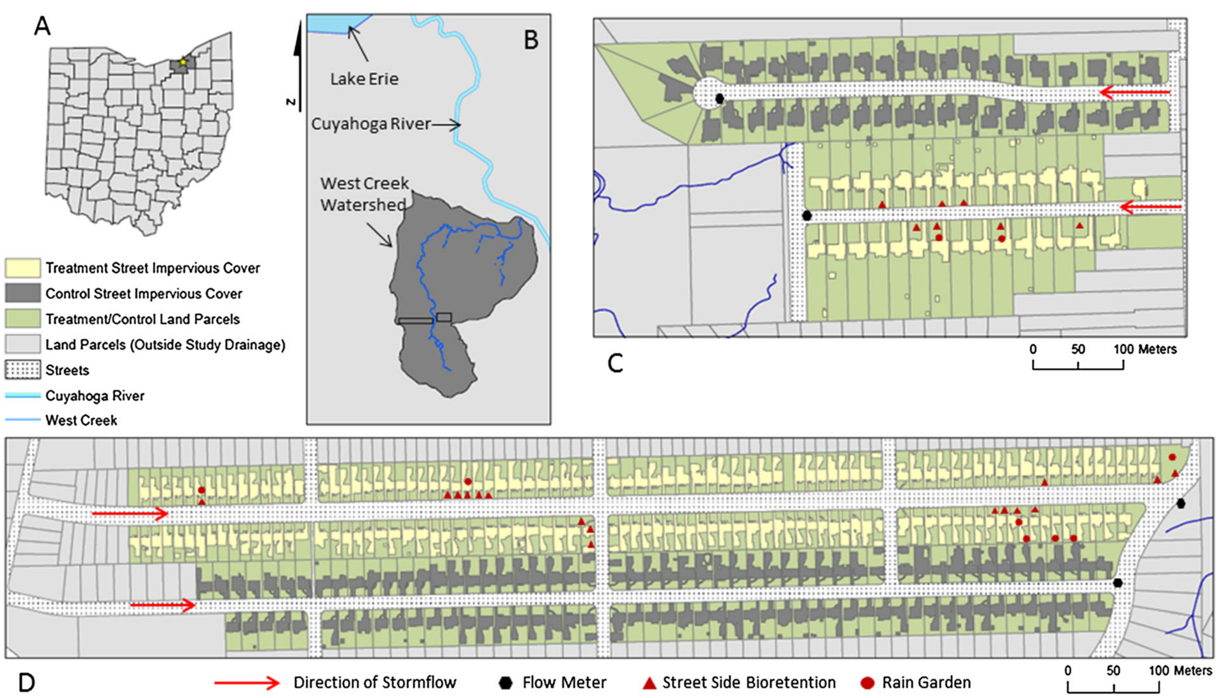

Figure 1. Map of study area, showing (A) general location in Ohio, (B) location of the study streets within the West Creek watershed and in relation to the Cuyahoga River and Lake Erie and (C, D) the two sets of study streets, with associated impervious surfaces, green infrastructure, stormwater run-off direction and treatment status. Parkhaven (t) and Mazepa (c) are shown in C. Klusner (t) and Hetzel (c) are shown in D (t for treatment, c for control)

During the summer of 2013, before construction of green infrastructure treatments on Parkhaven, a new street surface, storm drains, curbs and gutters were installed. Also, at this time, houses on Parkhaven were disconnected from septic and incorporated into municipal sewers. Previously, the street surface, curbs and gutters on Parkhaven were in very poor repair, with numerous cracked and broken sections. There was no construction that took place on Mazepa, the control street, during the study period.

A total of 91 rain gardens, street-connected bioretention cells and rain barrels have been installed on the two treatment streets (Table I). Rain gardens ($<25\,m^2$) were installed in front yards and backyards and were connected to nearby roof downspouts where available. Bioretention cells (~26–44 m^2) were installed between the sidewalk and street and contain curb cuts that allow for run-off from the street to be directed into the bioretention cell. One or more 227-l rain barrels connected to downspouts were installed at homes with rain gardens and bioretention cells.

Green infrastructure installation occurred in two phases (Table I). The first green infrastructure treatments were installed and planted on Klusner in May 2013 (phase 1). Additional green infrastructure treatments were installed on Parkhaven and Klusner in November 2013 and were planted in March 2014 (phase 2). During phase 1 construction on Klusner, underdrains were installed in 10 of 12 bioretention cells and connected to storm drain catch basins closest to each site. Underdrains are designed to allow water to percolate through the bioretention cells prior to arriving in the storm drain. Two bioretention cells were distal from any catch basins, so no underdrains were installed. One of these cells had gravel pits installed to add some additional capacity for water storage. Initial performance of the bioretention cells without underdrains appeared successful based on the visual observations of infiltration. As a result, underdrains were eliminated from the design of the bioretention cells in phase 2 of construction on both Klusner and Parkhaven. While the bioretention cells in this project do not fully meet the Ohio Rainwater and Land Development standards (Ohio Department of Natural Resources, 2006) because they lack an explicitly designed internal water storage zone, they fit within the range of practices commonly described as bioretention (Davis *et al*., 2009).

Specific sites for green infrastructure installation were determined by soliciting landowners through public meetings, mailings and direct contact (Turner *et al*., 2015). Green infrastructure treatments were installed at no cost to homeowners, and general maintenance of the treatments, including weeding and plant upkeep, was provided for the duration of the study by Cleveland Metroparks staff and volunteers, with limited involvement of some landowners. Within the rain gardens and bioretention cells, a sediment mixture, with ≥72% sand, 5–28% organic material and ≤10% clay, was topped with mulch. Plantings included perennial sedges and ferns, grasses, shrubs and trees designed to withstand the local deer population.

Table I. Study area characteristics and treatment timeline

	Klusner Ave (treatment)	Hetzel Dr. (control)	Parkhaven Dr. (treatment)	Mazeppa Tr. (control)
Drainage area (ha)	11.7	10.5	6.0	6.7
Lot size (ha)	0.05	0.075	0.1	0.2
Number of houses	163	114	31	42
Pretreatment imperviousness	55.5%		26.4%	
Roof imperviousness (% of total)	42%		43%	
Street, driveway and sidewalk imperviousness (% of total)	58%		51%	
Other imperviousness (% of total)	<1%		5%	
Parcels with green infrastructure	22 (12.5%)	0	10 (32.2%)	0
Pretreatment monitoring	8/27/2012–11/12/2012, 4/8/2013–4/29/2013		8/27/2012–11/12/2012	
Phase 1 treatment	May 2013: 12 street side bioretentions, 22 rain barrels, 2 rain gardens		May–August 2013: road repair and sanitary sewer connection	
Phase 1 monitoring	6/1/2013–11/1/2013		N/A	
Phase 2 treatment	Nov. 2013–Mar. 2014: 4 street side bioretentions, 15 rain barrels, 5 rain gardens		Nov. 2013–Mar. 2014: 7 street side bioretentions, 21 rain barrels, 3 rain gardens	
Phase 2 monitoring	4/3/2014–10/4/2014		4/14/2014–10/22/2014	

Data collection

Stormflow monitoring began in August 2012 for Klusner and Hetzel and in October 2012 for Parkhaven and Mazepa. Isco 2150 area velocity flow modules (Teledyne Isco, Lincoln, NE) were installed in storm drains near the outfall for each street. The pressure transducer level sensor has an accuracy of ±3 mm, while the Doppler ultrasonic velocity sensor has an accuracy of ±0.03 m/s when velocity is <1.5 m/s and ±2% when velocity is >1.5 m/s. Data were collected in 15-min intervals, using storm drain dimensions to convert from velocity and level to discharge. Data from 2013 were used to establish regression relationships between velocity and discharge that were then applied to the 2012 and 2014 data for Klusner Ave, which had issues with level sensor drift and offsets. The combined uncertainty from velocity data and regression relationships is ±5% for individual discharge time points from 2012 and 2014 on Klusner Ave.

Precipitation data were collected in 15-min intervals at two WXT520 meteorological stations (Vaisala, Boulder, CO) operated by Cleveland Metroparks. Peak precipitation was defined as the most intense 15-min precipitation interval for a storm event. The Ridgewood rain gauge is located 1.6 km north of the study streets and was the primary meteorological station used for the study. From 2 April 2013 at 08:00:00 to 13 September 2013 at 13:30:00, the Abram Creek rain gauge was used because the Ridgewood Road gauge was not functioning. The Abram Creek rain gauge is located approximately 10 km west of the study streets.

Individual storm events were defined as periods when recorded velocity and calculated discharge from flow meters in the storm outfall rose above zero and then returned to zero (Jarden, 2015). To be included in the analyses, at least three data points (45 min) with greater than zero discharge were required on both the treatment and control streets, and a nearby meteorological station must have recorded precipitation. At least three data points of zero flow were used to separate storm events. This separation was used because scattered thunderstorms often occur in this area and times of intermittent heavy precipitation could produce distinct responses. Only storm events occurring between 1 April and 15 November were analysed, because the likelihood of snow was higher in winter months, confounding interpretation.

Data Analysis

The effect of street-scale best-management-practices retrofits on storm hydrograph characteristics was analysed by quantifying the effects on peak discharge, total run-off volume and lag time for storm events. All statistical analyses were completed in JMP version 11 (SAS Institute, Cary, NC). Analyses focused on stormflow, because the storm sewer monitoring locations were not appropriate for assessing effects on baseflow.

For each storm, peak discharge (Q_p) was identified as the highest recorded flow during each storm, while the total run-off volume (Q_t) was calculated as

$$Q_t = \sum_{i=1}^{n} Q_i \times t_i \tag{1}$$

where Q_i is the discharge recorded in each increment and t_i is the time interval between measurements (15 min).

For each phase of the project, the relationship between Q_p and Q_t on the treatment and control streets was calculated via linear regression. Regressions were forced through the origin because the definition of storm events for analysis required non-zero flow on both streets. When regressions are forced through the origin, r-squared values can be spuriously high, so they are not reported (Gordon, 1981). Instead, the standard error of the estimate is reported. To test for statistically significant differences between the slopes of the regression lines, Student's t-test least squares method was employed (Zar, 1998). While not all residuals were completely normally distributed and homoscedastic based on visual assessment, non-transformed parametric statistics were used for all regressions to maintain consistency of approach and allow direct comparisons.

Four measures of lag time were calculated for each set of treatment streets: centroid lag to peak (time from the centroid of precipitation to the peak discharge), centroid lag (time from the centroid of precipitation to the centroid of discharge), lag to peak (time from the beginning of precipitation to the peak discharge) and peak lag to peak (time from the peak rainfall intensity to the peak discharge), following (Dingman 2002). The centroid of precipitation (t_{wc}) was calculated as

$$t_{wc} = \frac{\sum_{i=1}^{n} W_i \times t_i}{\sum_{i=1}^{n} W_i} \tag{2}$$

where W_i is the precipitation for period i. The centroid of run-off (t_{qc}) was calculated as

$$t_{qc} = \frac{\sum_{i=1}^{n} Q_i \times t_i}{\sum_{i=1}^{n} Q_i} \tag{3}$$

In order to highlight the effects of green infrastructure treatments on lag times, it was necessary to normalize for variations across storms by reporting the difference in lags between control and treatment streets. In other words, if the peak lag to peak was 30 min for Hetzel (control) and 45 min for Klusner (treatment), the peak lag-to-peak time difference was 15 min. If the treatment street had a shorter lag time than the control street, the lag time difference was negative. This differencing also negates any potential effect on lags associated with the use of different weather stations. Non-parametric Wilcoxon pair comparisons were used to test the statistical significance of lag time differences for each pair of treatment and control streets during each phase of treatment, following Hood *et al*. (2007).

RESULTS

Overview of precipitation and discharge

Over the 3-year study, 162 storm events were monitored on Klusner and Hetzel, and 106 storm events were monitored on Parkhaven and Mazeppa (Table II). The smaller number of storms on Parkhaven and Mazeppa reflects the later onset of monitoring. Parkhaven and Mazeppa data from 2013 were not used because of ongoing street repair and sanitary sewer installation on the street. Precipitation amounts ranged from 0.5 to 89 mm, and flow durations ranged from 45 min to 23.25 h. A wide range of antecedent moisture conditions were also experienced, with up to 162 mm in the 7 days prior to some events (Jarden, 2015). Median 7-day antecedent precipitation amounts were 36 mm (2012), 23 mm (2013) and 22 mm (2014). Maximum peak flows reached 0.503 m^3/s (15.5 mm/h) on Klusner, 0.926 m^3/s (31.7 mm/h) on Hetzel, 0.170 m^3/s (10.2 mm/h) on Parkhaven and 0.653 m^3/s (35.1 mm/h) on Mazeppa.

Peak discharge

Strong relationships were observed between peak discharges on control and treatment streets during all phases of the project (Figure 2). During the pretreatment phase, the largest peak discharges measured on Hetzel were substantially smaller than during the post-construction years (Table II). Similarly, peak discharges measured during the pretreatment phase on Mazeppa were smaller than those following green infrastructure installation. This may be a by-product of the lower number of events included in the pretreatment monitoring period. Unfortunately, the paucity of large pretreatment peak discharges limited the power of the dataset in terms of calculating the effects of green infrastructure additions relative to unmodified streets.

For the Klusner–Hetzel paired street, we separated the peak discharge dataset into two sections based on (1) the range of discharges measured in the pretreatment period and (2) a visual break in the behaviour of the phase 1 and phase 2 peak discharges. Events that produced peak discharges on Hetzel $<0.3\,m^3/s$ (10.3 mm/h) were analysed separately from larger events. For the smaller group of events, linear regression lines were forced through the origin, but no such requirement was placed on the larger events.

In the smallest events, data from all three phases overlapped substantially, but when peak discharges up to 0.3 m^3/s (10.3 mm/h) were included, distinct regression equations were produced. The relationship between peak flows on the control and treatment street did not change significantly following the first phase of green infrastructure installation ($p=0.825$), relative to the pretreatment condition. However, following the second phase of green infrastructure installation, peak discharges decreased significantly relative to both pretreatment ($p=0.0009$) and phase 1 ($p=0.0002$). Overall, for small storms, the green infrastructure installation decreased peak flows by 42% relative to pretreatment conditions.

The larger peak discharges ($>0.3\,m^3/s$, >10.3 mm/h) from phases 1 and 2, which fall outside the range of pretreatment discharge, indicated a reduction in peak

Table II. Summary of monitored storm events

Monitoring phase	Street	Storm events (n)	Event precipitation (mm)	Maximum peak discharge (m^3/s)	Maximum peak discharge (mm/h)	Maximum total run-off volume (m^3)	Maximum total run-off volume (mm)	Maximum storm duration (h)
Pretreatment	Klusner (t)	40	0.5–42.9	0.413	12.7	3981	34.0	9.75
	Hetzel (c)			0.247	8.5	1846	17.6	
Phase 1	Klusner (t)	56	0.5–89.2	0.503	15.5	3153	26.9	18.75
	Hetzel (c)			0.769	23.7	1626	15.5	
Phase 2	Klusner (t)	66	0.3–81.3	0.386	11.9	3793	32.4	23.25
	Hetzel (c)			0.926	31.7	3631	34.6	
Pretreatment	Parkhaven (t)	27	1.0–42.9	0.081	4.9	1154	19.2	15.25
	Mazepa (c)			0.189	10.2	1361	20.3	
Phase 2	Parkhaven (t)	55	0.5–81.3	0.170	10.2	1306	21.8	17.25
	Mazepa (c)			0.653	35.1	2703	40.3	

(t) indicates the treatment streets and (c) indicates the control streets.

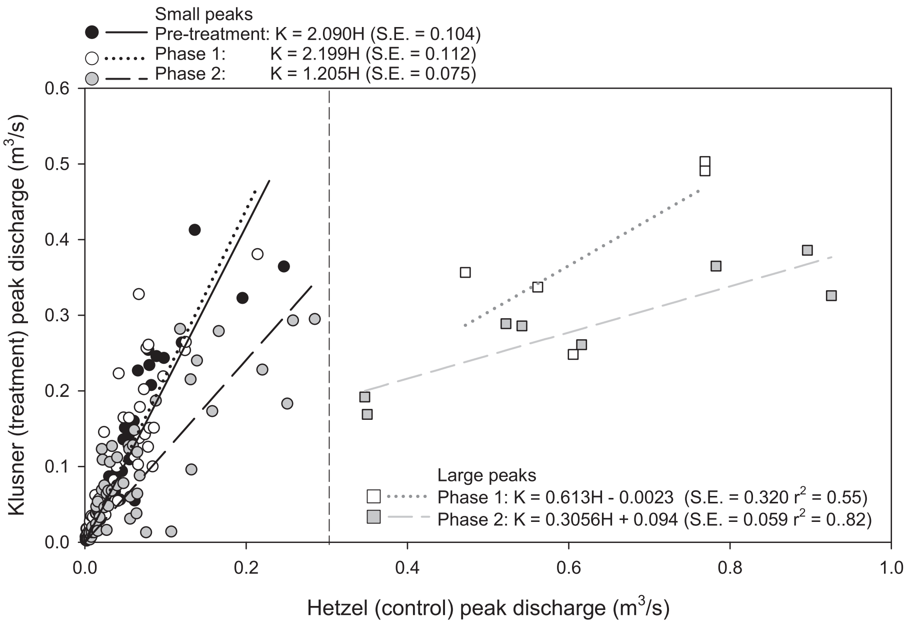

Figure 2. Peak stormflow for all storm events from pretreatment, phase 1 and phase 2 on Klusner and Hetzel (n = 40, 56, 66). Values on the left side of the plot show storms for all three phases, only in the range of pretreatment values (n = 40, 51, 58). Larger peak discharge values for phases 1 and 2 are analysed separately because of lack of pretreatment comparison (n = 5, 8). S.E. corresponds to the standard error of the parameter estimate for each regression. p-values are reported for Student's t-test result of the difference between pairs of regressions. For small peaks, p = 0.83 for pretreatment *versus* phase 1, p = 0.0009 for pretreatment *versus* phase 2 and p = 0.0002 for phase 1 *versus* phase 2. For large peaks, p = 0.014 for phase 1 *versus* phase 2. Residuals are normal for phase 2 (small and large peak flows) and phase 1 (large peak flows)

discharge with the installation of additional green infrastructure. Using Student's t-test, there was a statistically significant difference (p = 0.014) between the larger events on Klusner and Hetzel in phases 1 and 2. Based on the trend lines, the additional green infrastructure of phase 2 reduced peak discharges on Klusner by 5–33% for peak discharges of 0.35–0.9 m^3/s (12.0–30.9 mm/h) on Hetzel, with larger reductions occurring in the larger storms.

Logarithmic curves were also fit to the entire peak discharge dataset for phase 1, and phase 2 produced similar goodness of fit to the linear regression (r^2 = 0.75 phase 1; r^2 = 0.72 phase 2). Based on the logarithmic curves, peak discharges were reduced by 25–27% for peak discharges of 0.1–0.9 m^3/s (3.4–30.9 mm/h) on Hetzel, with the slightly larger reductions occurring in the smaller storms.

On Parkhaven (treatment) and Mazepa (control), there was no statistically significant difference between peak flows in the pretreatment period and phase 2 (p = 0.18) (Figure 3). Phase 2 had peak stormflows outside the range of flows for the pretreatment period (Table II). Similar to the behaviour observed on Klusner and Hetzel, the slope of the relationship between the control and treatment streets appeared to flatten when peak flows exceed 0.3 m^3/s (10.3 mm/h), but a logarithmic curve did not improve the goodness of fit (r^2 = 0.72) relative to the linear fit (r^2 = 0.81).

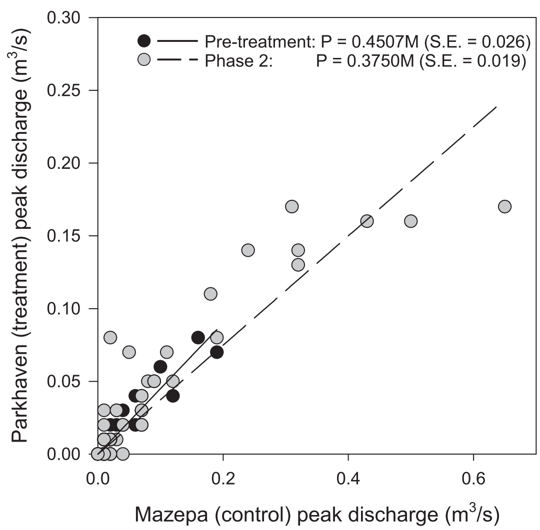

Figure 3. Peak stormflow for all storm events from pretreatment and phase 2 on Parkhaven and Mazepa (n = 27, 55). S.E. corresponds to the standard error of the parameter estimate for each regression. Student's t-test result of the difference between the regressions is p = 0.18. Residuals are normal for pretreatment data

Total run-off volume

As with peak flows, strong relationships were seen between total run-off volume on the control and treatment streets for each event (Figures 4 and 5). The range of total run-off volumes was similar across pretreatment, phase 1

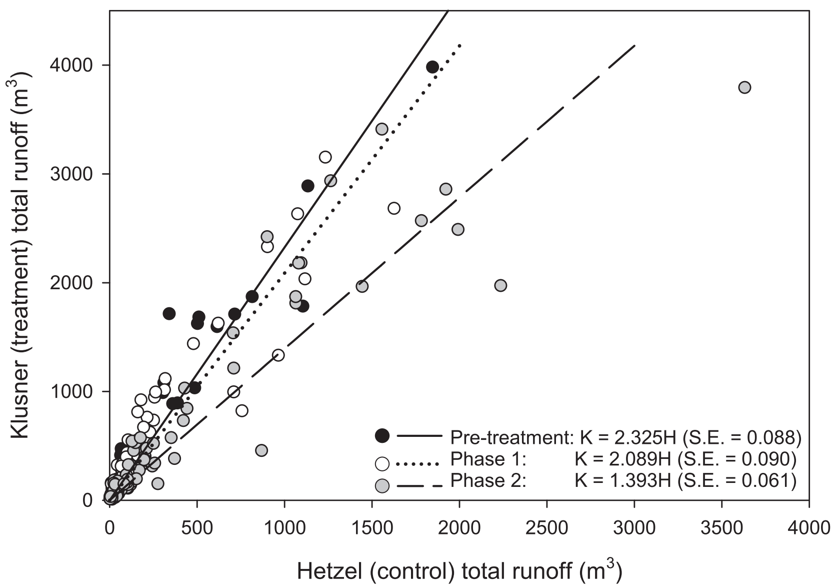

Figure 4. Total stormflow for all storm events from pretreatment, phase 1 and phase 2 on Klusner and Hetzel ($n = 40, 56, 66$). S.E. corresponds to the standard error of the parameter estimate for each regression. p-values are reported for Student's t-test result of the difference between pairs of regressions. For pretreatment *versus* phase 1, $p = 0.97$, for pretreatment *versus* phase 2, $p = 0.0078$, and for phase 1 *versus* phase 2, $p = 0.0033$. For pretreatment and phase 2, residuals are slightly non-normal, because the models tend to underpredict events for which control street total stormflow is $<700\,m^3$.

and phase 2, with the exception of one very large storm in phase 2 (12 May 2014). The exclusion of this large event makes little difference in the slopes or fits of the regression equations. For both pairs of streets, exclusion of the large event results in a slightly higher slope of the phase 2 regression equation but does not affect whether slope differences are statistically significant.

Results for total run-off volume were similar to the peak flows. On Klusner, no significant difference was observed in total run-off volumes from pretreatment to phase 1, while a decrease in total run-off volume was observed between phases 1 and 2 (Figure 4). Using Student's t-test for least square means, linear trend lines are not significantly different between phase 1 and pretreatment ($p = 0.97$), but phase 2 was significantly different from pretreatment ($p = 0.078$) and phase 1 ($p = 0.0033$). Based on the linear trend lines, there was a 10% reduction in total run-off volume between pretreatment and phase 1, and following completion of phase 2, there was a 40% decrease in run-off volume relative to the pretreatment period. On Parkhaven and Mazeppa, a decrease in total run-off volume is observed between pretreatment and phase 2, but the difference in slopes was not statistically significant ($p = 0.090$) (Figure 5). Based on the slopes of the linear trend lines, there was a 35.5% reduction in total run-off volume.

Lag time differences

Throughout the study, many storms produced hydrograph peaks at the same time on the treatment and control streets, based on the 15-min time step data, resulting in the frequent occurrence of a lag time difference of 0 min (Figure 6). Because of the data time step, lag time differences for individual storms occur in 15-min intervals. This relatively long time step, given the flashy nature of stormwater run-off, limits the ability of this project to fully resolve subtle differences in hydrograph lag times.

All measures of lag time difference (centroid lag to peak, centroid lag, lag to peak and peak lag to peak) showed significant increases between pretreatment and the phases following green infrastructure installation on Klusner (Figure 6). However, when comparing phase 1 with phase 2, significant differences were only observed in the centroid lag variable. In other words, the installation of green infrastructure on the treatment street increased lag time differences, but the green infrastructure added in phase 2 did not add significantly to the lag times on the treatment street. The geometric means of the peak lag time differences were close to zero during the pretreatment phase (Table III). During phases 1 and 2, the geometric mean of lag time differences increased, such that water was arriving at the end of the street later on Klusner than on Hetzel. Overall, the addition of green infrastructure enhanced the difference in arrival times of hydrograph peaks and centroids between the control and treatment streets (as indicated by the absolute value of the lag time differences).

There were no statistically significant differences in the lag time variables on Parkhaven between the pretreatment and Phase 2 periods (Figure 6). However, the geometric means indicate that lag time differences decreased, with run-off reaching the end of the street more quickly after

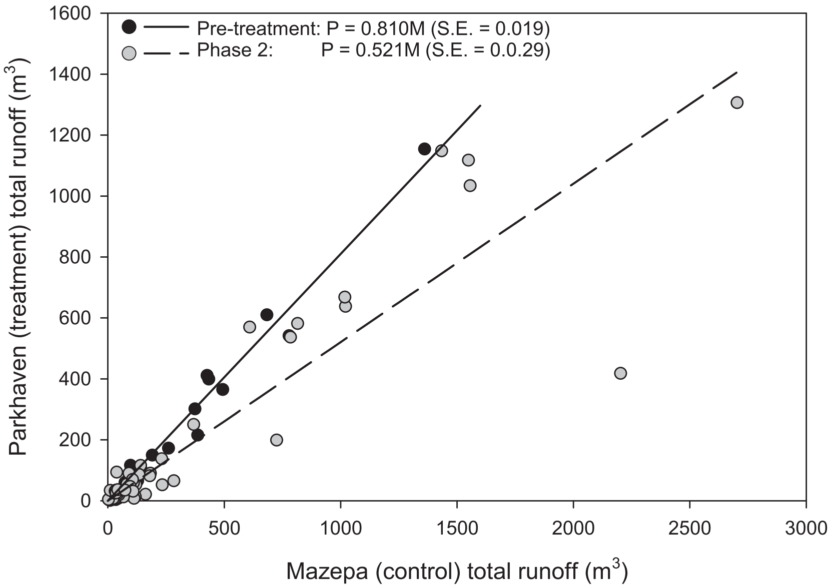

Figure 5. Total stormflow for all storm events from pretreatment and phase 2 on Parkhaven and Mazepa (n = 27, 55). S.E. corresponds to the standard error of the parameter estimate for each regression. Student's t-test result of the difference between the regressions is p = 0.090.

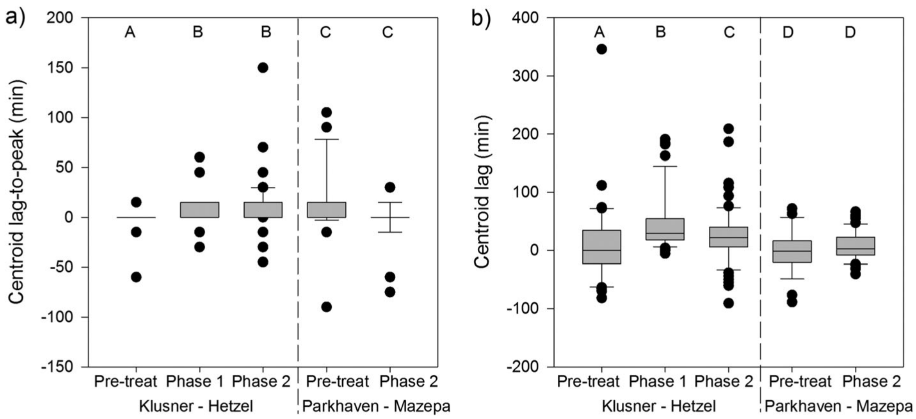

Figure 6. Box plots of (a) centroid lag to peak and (b) centroid lag for treatment as compared with control streets for all storm events. Positive values indicate longer lag time on the treatment street. For each pair of streets, groups that do not share a letter are significantly different ($p < 0.05$) based on non-parametric Wilcoxon each pair tests. Peak lag to peak and lag to peak are not displayed because after differencing between treatment and control, results were identical to centroid lag to peak. Treatment streets are Klusner and Parkhaven. Control streets are Hetzel and Mazepa

Table III. Geometric means of lag time variables for treatment as compared with control streets

	Centroid lag to peak (min)	Centroid lag (min)	Lag to peak (min)	Peak lag to peak (min)
	Klusner Ave (t) *versus* Hetzel Dr. (c)			
Pretreatment	−1.1	8.8	−1.1	−0.9
Phase 1	5.4	48.6	4.3	4.1
Phase 2	9.4	28.1	10.0	9.4
	Parkhaven Dr. (t) *versus* Mazeppa Tr. (c)			
Pretreatment	15.2	−29.5	15.4	15.5
Phase 2	−0.1	6.0	−0.1	−0.04

Positive values indicate longer lag time on the treatment street. (t) indicates the treatment streets and (c) indicates the control streets.

the addition of green infrastructure, as measured by centroid lag-to-peak, lag-to-peak and peak lag-to-peak differences (Table III). Conversely, the centroid lag difference increased. Unlike on Klusner and Hetzel, the overall result of green infrastructure addition to Parkhaven was to bring the timing of hydrograph peaks and centroids into sync on Parkhaven and Mazeppa.

DISCUSSION

Overall project success

The before–after-control-impact design of this study showed that the addition of green infrastructure to the treatment streets had a substantial positive effect on reducing stormwater flow. After one phase of green infrastructure construction, reductions in peak and total stormflow were not statistically significant, but when further green infrastructure was added to Klusner Ave, reductions of up to 33% of peak discharge and 40% of total run-off volume were measured. Installation of green infrastructure on the treatment streets appears to have reduced peak flows by slowing flow to the storm sewers via street-connected bioretention cells with underdrains and removing water from the storm sewers through rain barrels, rain gardens and street-connected bioretention cells without underdrains.

Including street run-off in the design of the green infrastructure retrofits seems to be an important factor in the overall performance of subcatchment green infrastructure implementations. Small but significant treatment effects are possible with parcel-level implementation, even with no direct connection to street run-off (Shuster and Rhea, 2013), but treating imperviousness associated with streets can exert greater hydrological impact, because streets generally cover a larger and more directly connected impervious surface (Lee and Heaney, 2003; Mayer *et al.*, 2012). In this study, transportation surfaces (streets, driveways and sidewalks) comprised more than 50% of the total imperviousness.

In the present study, connection to streets allowed the green infrastructure to capture stormwater from beyond the boundaries of the participating parcels and effect a much larger reduction in peak and total stormflows than the voluntary participation scheme would have achieved through rooftop disconnection alone. The installed rain gardens disconnected only 0.8% of the impervious surface on Klusner Ave and 4.2% on Parkhaven Dr., assuming full disconnection of the roof. Based on the number of participating properties and downspouts per property, the rain barrels installed in this project captured run-off from 2.9% and 5.6% of the impervious surfaces on Klusner Ave and Parkhaven Dr., respectively. The actual disconnection achieved is almost certainly lower. Based on the average roof size *versus* rain barrel capacity, rain events greater than 4–5 mm exceeded rain barrel capacity. The effectiveness of rain barrels also depends strongly on whether they are emptied between storms (Jones and Hunt, 2010). Finally, some rain barrels were installed on downspouts of houses that had rain gardens, so they are being double counted. Even in the earlier best-case scenarios, the project disconnected only 3.7% of impervious surfaces on Klusner Ave, with stormwater controls focused on rooftops. If house and garage rooftops had been completely disconnected at all participating parcels on Klusner Ave, 5.6% of the impervious surface in the watershed would have been disconnected.

On both streets, we expect that the street-connected bioretention cells were responsible for the majority of the peak flow reduction. However, calculating the disconnection of impervious area by the cells is difficult, because street run-off can flow past the bioretention cell inlets and into downslope catch basins. How much water is captured depends on the effectiveness of the curb cut in routing water into the cell (as discussed later) and the ponding depth in the bioretention cells *versus* flow depth in the gutter, which is a function of infiltration rate and precipitation intensity. Thus, the disconnection achieved will depend on event dynamics, antecedent conditions, position of the cell relative to upslope bioretention cells and catch basins and the effects of construction practices. Given these dynamics, we do not attempt to quantify impervious surface disconnected by the street-connected bioretention cells. Instead, we observe that the reductions in peak and total stormflow on Klusner were much larger than would be estimated based on the percentage of properties participating in the project (13.5%) and that such large reductions could not be achieved through rooftop disconnection alone.

Retrofitting green infrastructure at the catchment scale requires cooperation of multiple property owners and working within the constraints of existing infrastructure and land uses. The more green infrastructure required to achieve desired hydrological, water quality or ecological benefits, the more difficult those constraints may be to overcome. Thus, quantifying benefits relative to the percentage of participating properties provides a proxy metric for the human outreach and logistical work required for such a retrofit project. Street-connected bioretention cells, when well designed and constructed, appear to produce substantial hydrological benefits from a small number of practices and should be considered an important tool for green infrastructure retrofits in residential neighbourhoods.

Effects of green infrastructure design and construction on run-off reduction

Differences in Klusner Ave bioretention cell design between phases 1 and 2 may explain why substantial reductions in peak and total stormflows were observed after phase 2 installation, but not after phase 1. In terms of total stormflow, underdrains in the green infrastructure in phase 1 meant the water was mostly being slowed by infiltration in the bioretention cells and was still connected to the storm sewers. In phase 2, the additional front yard and backyard rain gardens and absence of underdrains in the street-connected bioretention cells allowed for the water captured in the green infrastructure to be completely removed from the stormwater system, resulting in major changes to both peak flows and total run-off volumes. The presence or absence of underdrains, however, does not explain why peak stormflow did not decrease following phase 1 installation, as peak flows should have been attenuated by slow flow through the bioretention media (Davis *et al.*, 2009). Instead, we attribute the lack of peak flow attenuation to the presence of a gravel/cobble channel leading from the curb cut down the centreline of the bioretention cell, which we observed routing peak flows quickly into overflow outlets that led to the underdrain system.

During small storm events with low run-off volumes, stormwater would flow down the street, along the curbs and sometimes bypass the street-connected bioretention cells. However, during larger storm events, where run-off was much higher, it was observed that run-off would typically be diverted into the street-connected bioretention cells. Based on visual observations, imperfections in the curb cuts or accumulation of rocks or debris at the entrance to the bioretention cells served as a barrier to entry for shallow gutter flow that occurred during small storms. During larger or more intense storms, gutter flow was deeper, and run-off was more effectively routed into the bioretention cells. The lack of large storms in the pretreatment period limits our ability to quantify the project's overall effects on peak flows from large storms, but it is possible that the bioretention cells have an even more substantial effect during large peak flows than during small ones. The logarithmic relationship between control and treatment streets observed in post-treatment peak flows may be a function of this increased effectiveness of street-connected bioretention cells for larger storms.

The design of the bioretention cells on Parkhaven may have been less effective at trapping street run-off than the bioretention cells on Klusner. The Parkhaven bioretention cells featured curb cuts at the downslope end of each bioretention cell and required water to flow into the bioretention cell and then backward into the bowl of the bioretention cell. Parkhaven's slope (3.6%) is steeper than that of Klusner (1.7%), so grading of the bioretention cell to achieve a flat profile required a fairly deep excavation at the upslope end. In some cases, this flat profile was not achieved because of contractor error or underlying pipes limiting excavation depth. Also, the available width for the bioretention cell between the street and sidewalk was <2.5 m, whereas on Klusner ~5 m was available, limiting the available detention volume for a given excavation depth. The combination of a deep and narrow geometry and the curb cut at the downslope end may have promoted ponding near the entrance to the bioretention cell with the result that less street run-off entered the bioretention cell. Ponding and run-off bypass of the bioretention cells were observed during storms on Parkhaven.

Taken together, these observations suggest that design, construction and maintenance practices around the inlets of street-connected bioretention cells may be important determinants of their hydrological effectiveness. Smooth, even curb cuts and regular removal of rocks and debris should promote bioretention cell efficacy during small or low-intensity storms, while locating curb cuts upslope, paying careful attention to grading and avoiding creation of preferential flowpaths to overflow outlets should promote bioretention cell efficacy during larger or more intense storms.

Despite the relatively high (34%) participation rate of residents on Parkhaven, there were no significant reductions in peak and total stormflows. On Parkhaven, results may have been confounded by the street repair and sanitary sewer connection that occurred between the pretreatment and post-treatment periods. Prior to fixing the street, Parkhaven had areas of crumbling asphalt and broken and cracked curbs, which may have allowed stormwater to infiltrate or escape onto lawns. Pavement fractures have high hydraulic conductivity and can have significant potential to infiltrate water (Wiles and Sharp, 2008). After the street was repaved, flowpaths to the storm sewer were improved, and potentially more run-off reached the storm drains. Once green infrastructure was installed, avenues for run-off to escape routing to the storm drains were once again added to the street. It is therefore possible that the installed green infrastructure offset what otherwise would have been an increase in stormwater run-off from Parkhaven.

The presence of underdrains appears to play an important role in determining the effects of green infrastructure on hydrograph lags at the street scale. Increased lag times from pretreatment to phase 1 on Klusner can be attributed to the underdrains in the street-connected bioretention cells slowing down the flow of water to the storm drain. However, with underdrains absent from the design of the street-connected bioretention cells in phase 2, the diverted stormflow is completely removed from the storm sewer system, and no further increases in lag time were detected. Similarly, on Parkhaven, where no underdrains were installed in the green infrastructure, lag times did not significantly change. Ultimately, infiltrated water may emerge in the stream as baseflow, days, weeks or months after the storm (Hamel *et al*., 2013; Soulsby *et al*., 2014). As a result of the green infrastructure, Klusner and Hetzel became more dissimilar in the timing of run-off delivery to the receiving stream. At the catchment scale, desynchronizing peak flows delivered by storm sewers can help to mitigate the stream's peak flow and consequent adverse effects of stream erosion and flooding (McCuen, 1979). Based on the results of this study, green infrastructure with underdrains can be effective at slowing peak flows and desynchronizing them from other streets, providing catchment-scale benefits, even if the green infrastructure is not sufficient to mitigate peak flow or total run-off volumes.

Future research needs

While the phase 2 green infrastructure installation on Klusner succeeded in reducing peak and total stormflows, phase 1 on that street and the green infrastructure on Parkhaven did not produce significant reductions on stormwater run-off. Thus, we can conclude that green infrastructure retrofits have the demonstrated potential to improve catchment-scale stormwater run-off, but they do not always perform up to that potential. As green infrastructure becomes ever more widely adopted, it is imperative that we develop a robust understanding of how to maximize the effectiveness of green infrastructure retrofit projects. The results of this study suggest several important areas requiring further research.

The ultimate goal of LID and green infrastructure techniques is to mimic predevelopment hydrology, reduce peak stormflows and total storm volume and improve water quality (Hood *et al*., 2007). In retrofit projects, such as this one, it is difficult to quantify how well green infrastructure does at meeting this goal because predevelopment hydrology is not fully known (part of the larger problem of prediction in ungauged basins; Blöschl *et al*., 2013). In the present study, even the goal of fully understanding hydrological improvements relative to developed pretreatment conditions was limited by the lack of larger storms in the pretreatment observation period. Pre-construction and post-construction, continued monitoring over multiple years would help to better quantify long-term effectiveness of the green infrastructure retrofits, particularly with respect to larger storms and maintenance efforts or lack thereof (Emerson and Traver, 2008; Davis *et al*., 2009). This study focused on stormflows, which were appropriate for monitoring in storm sewers, but future research should pursue more holistic approaches to understanding the effects of green infrastructure on the flow regime, including baseflow (e.g. Price, 2011; Hamel *et al*., 2013).

This project highlights a number of design and construction decisions that appear to have significant impacts on the hydrologic effectiveness of the project. In particular, underdrains and street repairs appear to be potentially important mediators of green infrastructure performance. The phase 1 and phase 2 periods on Klusner indicate that the addition or removal of underdrains from the design of the street-connected bioretention cells has cross-cutting effects on peak flows, total run-off volume and hydrograph timing. Further research is needed to fully understand the effects of underdrains and their applicability to the overall goals of a green infrastructure project. If future studies suggest that street repairs are associated with increased stormwater production, as indicated by the data from Parkhaven Ave, green infrastructure retrofits should be encouraged at the time of street repairs in order to offset the stormwater impacts. Effects of the distribution of street-connected green infrastructure should also be further explored. Having multiple street-connected bioretention cells in adjacent parcels could show diminished efficiency, because most of the street run-off might be captured in the upslope bioretention cells, leaving little volume to divert to subsequent cells.

In an ideal world, the number, type and spatial distribution of green infrastructure practices would maximize the hydrologic benefits while minimizing cost and would be resilient to changing hydroclimatic conditions (Gilroy and McCuen, 2009; Pyke *et al*., 2011; Walsh *et al*., 2012). Monitoring projects such as this one can provide real-world data on the hydrologic effectiveness of particular configurations for current climate, but modeling efforts at the catchment scale are also necessary to generalize and provide guidance for future green infrastructure efforts. Particular issues raised in this project that are ripe for exploration in a model include whether clusters of street-connected bioretention cells are as effective as distributed cells and how much performance was lost by opportunistically co-locating rain gardens, rain barrels and bioretention cells on some parcels.

Finally, in green infrastructure retrofit projects, such as this one, the human dimension cannot be ignored. This project required massive effort to recruit homeowners to allow the green infrastructure to be installed on their properties and only succeeded with ~15% of residents. Understanding how to increase social acceptance of green infrastructure and encourage participation in voluntary retrofit projects is a critical need if future green infrastructure retrofits are to have a chance at success in residential areas (Nemes *et al*., 2014; Bos and Brown, 2015; Turner *et al*., 2015). Further, in order to ensure long-term hydrologic benefits from the retrofit project, residents must continue to support and maintain the green infrastructure, so understanding post-installation perceptions and problems is also important (Turner *et al*., 2015).

CONCLUSIONS

Green infrastructure retrofits, which included street-connected bioretention cells, reduced peak and total stormflow and increased lag times from a suburban residential headwater street. On Klusner Ave, a voluntary participation scheme in which 13.5% of households had rain barrels and rain gardens or street-connected bioretention cells added to their parcels resulted in up to 33% reductions in peak flows, 40% reductions in total storm volumes and desynchronization of peak flow timing compared with an adjacent street where no green infrastructure was installed. Connecting green infrastructure to transportation surfaces may have helped produce the substantial reductions of stormflow by affecting a greater surface area of directly connected imperviousness than could be affected by disconnection of rooftops alone (<3.7% of impervious area on Klusner Ave).

The presence or absence of underdrains in bioretention cells appears to affect peak discharge, total flow volume and lag time by either retaining and slowing the flow of stormwater or completely removing stormwater from the storm sewer system. On Parkhaven Dr., where no significant changes in peak and total stormflows occurred following green infrastructure installation, we tentatively attribute the lack of apparent change to street repairs that occurred contemporaneously. Fixing degraded street surfaces can enhance flowpaths for stormwater, but adding green infrastructure may help to reduce the impacts of those improved flowpaths. Subtle differences in the design and construction of street-connected bioretention cells resulted in observable differences in run-off capture, particularly during small storms.

The results of this study demonstrate promising effectiveness of catchment-scale green infrastructure retrofits in mitigating stormwater run-off from headwater streets. In particular, connection to streets appears to leverage high value out of a limited number of installations. The site of this study is very typical of mid-20th-century American residential development, suggesting that the results achieved here may be possible to replicate in other areas. However, the observed differences in green infrastructure effectiveness between the two phases on Klusner and between Klusner and Parkhaven suggest that careful attention must be paid to the design and construction of the green infrastructure and to other activities ongoing in the subcatchment in order to achieve significant reductions in stormwater run-off.

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