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Quantifying the stormwater runoff volume reduction benefits of urban street tree canopy

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HIGHLIGHTS

- Street trees can limit stormwater runoff, but it is unclear by how much.
- A paired-basin study was used to quantify avoided runoff by street trees.
- Removal of street tree canopy increased stormwater runoff volume by 4%.
- Removal of street tree canopy did not increase peak discharge.
- Runoff avoided by street trees was within the range reported by previous studies.

GRAPHICAL ABSTRACT

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ABSTRACT

Trees in the urban right-of-way areas have increasingly been considered part of a suite of green infrastructure practices used to manage stormwater runoff. A paired-catchment experimental design (with street tree removal as the treatment) was used to assess how street trees affect major hydrologic fluxes in a typical residential stormwater collection and conveyance network. The treatment consisted of removing 29 green ash (*Fraxinus pennsylvanica*) and two Norway maple (*Acer platanoides*) street trees from a medium-density residential area. Tree removal resulted in an estimated 198 m^3 increase in surface runoff volume compared to the control catchment over the course of the study. This increase accounted for 4% of the total measured runoff after trees were removed. Despite significant changes to runoff volume ($p \leq 0.10$), peak discharge was generally not affected by tree removal. On a per-tree basis, 66 L of rainfall per m^2 of canopy was lost that would have otherwise been intercepted and stored. Runoff volume reduction benefit was estimated at 6376 L per tree. These values experimentally document per-capita retention services rendered by trees over a growing season with 42 storm events. These values are within the range reported by previous studies, which largely relied on simulation. This study provides catchment scale evidence that reducing stormwater runoff is one of many ecosystem services provided by street trees. This study quantifies these services, based on site conditions and a mix of deciduous species, and serves to improve our ability to account for this important yet otherwise poorly constrained hydrologic service. Engineers, city planners, urban foresters, and others involved with the management of urban stormwater can use this information to better understand tradeoffs involved in using green infrastructure to reduce urban runoff burden.

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1. Introduction

Residential development is a unique disturbance brought about by constructing housing and supporting infrastructure (water, wastewater, stormwater, transportation, and parking). Due to the resulting mosaic of impervious and pervious surfaces, urban geography presents a complex hydrologic setting with a wide variety of interactions among constructed and variably-permeable natural surfaces (Voter and Loheid, 2021). In order to deal with the increased direct runoff from impervious surfaces, drainage infrastructure is used to quickly collect and convey stormwater and wastewater flows. A typical residential parcel is traditionally composed of a micro-catchment that generates direct runoff from roofs, driveways, and other impervious surfaces, which is then conveyed to the storm drainage network or directed to lawn areas for infiltration. While pervious surfaces such as lawns and public right-of-way may have some level of infiltration capacity that differs from native soils, transfer of water from impervious surfaces towards these areas can create hotspots of hydrologic activity (Voter and Loheid, 2021). Although turf and typical suburban ornamental plants will protect the landscape from erosion, and may reduce runoff through infiltration and transpiration, their impacts on how water cycles through these urban systems are highly variable and understudied.

Trees are a ubiquitous part of a suburban setting and can modulate fluxes in the local hydrologic cycle in multifold ways. The canopy can intercept and store rainfall, delaying or lessening the volume available for throughfall. Interception capacity is strongly influenced by canopy structure and architecture such as foliation period and leaf surface area, which can vary by species (Xiao et al., 2000; Berland et al., 2017). Due to their extensive root systems and high leaf area, trees can also transpire substantial amounts of soil moisture, reducing antecedent moisture content during the inter-storm period, leading to higher infiltration rates during subsequent storms (Kuehler et al., 2017; Berland et al., 2017). Street trees differ from their counterparts found in rural forests in that they are usually grown in open areas and can often be limited in species diversity (Ma et al., 2020). For this reason, street trees face less competition for water and sunlight resulting in large crown and leaf surface areas (Xiao and McPherson, 2002). Trees are therefore important components of the urban water cycle and their interaction with the larger water cycle affects runoff response in these urbanized catchments.

Urban stormwater management has traditionally relied on a complex network of conveyance structures to rapidly transfer surface runoff to receiving waters. Expansion of suburban boundaries introduces new stormwater conveyances that can potentially overwhelm downstream infrastructure, creating elevated risk for localized flooding. To mitigate these concerns, cities are increasingly turning to green infrastructure to manage runoff at its source. Green infrastructure practices often rely on infiltration into underlying soils as the primary tool for volume reduction, but also reduce water by planting vegetation intended to increase evapotranspiration (ET). One form of green infrastructure, urban forests, has largely been overlooked as a means to reduce runoff volume by utilizing another hydrologic process – interception. Berland et al. (2017) suggest urban trees deserve additional consideration as a stormwater control measure. Early research into the impacts of trees on urban stormwater runoff used simple estimates based on assumptions of canopy coverage and design storm criteria. Sanders (1986) estimated tree canopy cover can potentially reduce runoff by 7% in a typical, frequent (6-h, 1-yr) design storm. In a different setting, Xiao and McPherson (2002) replicated this result when modeling the volume of canopy interception for a less-frequent 25-yr storm with greater total rainfall depth in the high-ET climate setting of Santa Monica, California.

Changes in runoff volume and percent change in runoff vary depending upon the amount of existing tree and impervious cover (Kruegler et al., 2021). More sophisticated models, such as i-Tree, have shown that increasing impervious cover by 1% can result in an average of 2.2% increase in runoff, while increasing tree cover by 1% averaged only a 0.067% decrease in runoff. Since the initial release of i-Tree in 2006, the model has been widely used to estimate the hydrologic benefits of individual trees, parcels, neighborhoods, and cities (U.S. Department of Agriculture - Forest Service, 2021). Other rainfall-runoff models do not include specific hydrologic functions of trees (e.g. canopy, species, leaf area) as calibration features, but instead implicitly lump these functions as part of a larger vegetation or pervious accounting process (Coville et al., 2020). Better information on arboricultural processes as they pertain to the urban water cycle could potentially improve model simulations. In a review of available literature on runoff reduction capabilities of urban trees, the Center for Watershed Protection (2016) found only six studies, three of which used measured data from a single plot, the other three used models. Although many of the functions that comprise i-Tree are based on empirical data from field studies, most of those studies were done at a forest site rather than neighborhood or network scale (Kuehler et al., 2017). Field studies that examine the hydrologic influence of trees at the sewershed scale are lacking. When identifying gaps in research on the role of trees in stormwater management, Kuehler et al. (2017) highlighted the need for studies that scale the local effects of urban trees to the larger sewershed catchment area, allowing a more holistic understanding of the urban tree canopy effects on hydrology.

Despite an increasing body of research asserting the hydrologic benefits of urban trees, application of a numerical stormwater "credit" is not based on an established assessment. Therefore, stormwater management utilities have resorted to the grossest of estimates to inform decisions on tradeoffs between canopy benefits, further development, and value in stormwater volume management. This is to say that there is no standard, quantitative estimate of hydrologic services rendered by trees and their canopy. The Great Lakes Restoration Initiative (GLRI) has assigned a per-tree annual stormwater volume retention of 223 L, which is counted as a credit against site runoff volume. This storage volume is recommended to be used for the purpose of planning only, with future modifications based on empirical data (Great Lakes Restoration Initiative, 2017). An alternative crediting method in the Chesapeake Bay watershed was developed by an expert panel in collaboration with the Center for Watershed Protection (Law and Hanson, 2016). This method uses land use – land cover change as a basis for determining the equivalent tree canopy cover gained or lost, such that each tree, regardless of species, planted in developed areas is eligible for a creditable area of 13.4 m^2. Reductions in runoff, as well as water-quality credits, would manifest as a result of change in land use – land cover. Other agencies have adopted a similar approach by allowing for impervious surfaces under tree canopy to be accounted for as pervious land cover (Minnesota Pollution Control Agency, 2020).

In this study, the U.S Geological Survey, in cooperation with the U.S Environmental Protection Agency, U.S. Forest Service, and the University of Wisconsin assessed the stormwater volume reduction capabilities of urban street trees through measurement of rainfall-runoff relations in a medium-density residential area. We leveraged an aggressive tree removal program mounted as a response to rapid infestation from the emerald ash borer (*Agrilus planipennis*) to develop our removal treatment in a paired-catchment experimental design. The purpose of this study was to quantify the effect of removing urban trees and their canopy on stormwater generation.

2. Materials and methods

2.1. Site description

This study characterized stormwater runoff from two medium-density residential catchments in Fond du Lac, Wisconsin, USA (Fig. 1) during the months of May through September in 2018–2020. The area was developed in the mid-to-late 1980s consisting of single-family homes on parcels that are generally 0.10 ha in area. Estimates of source area (impervious roads, sidewalks, driveways, and rooftops; pervious

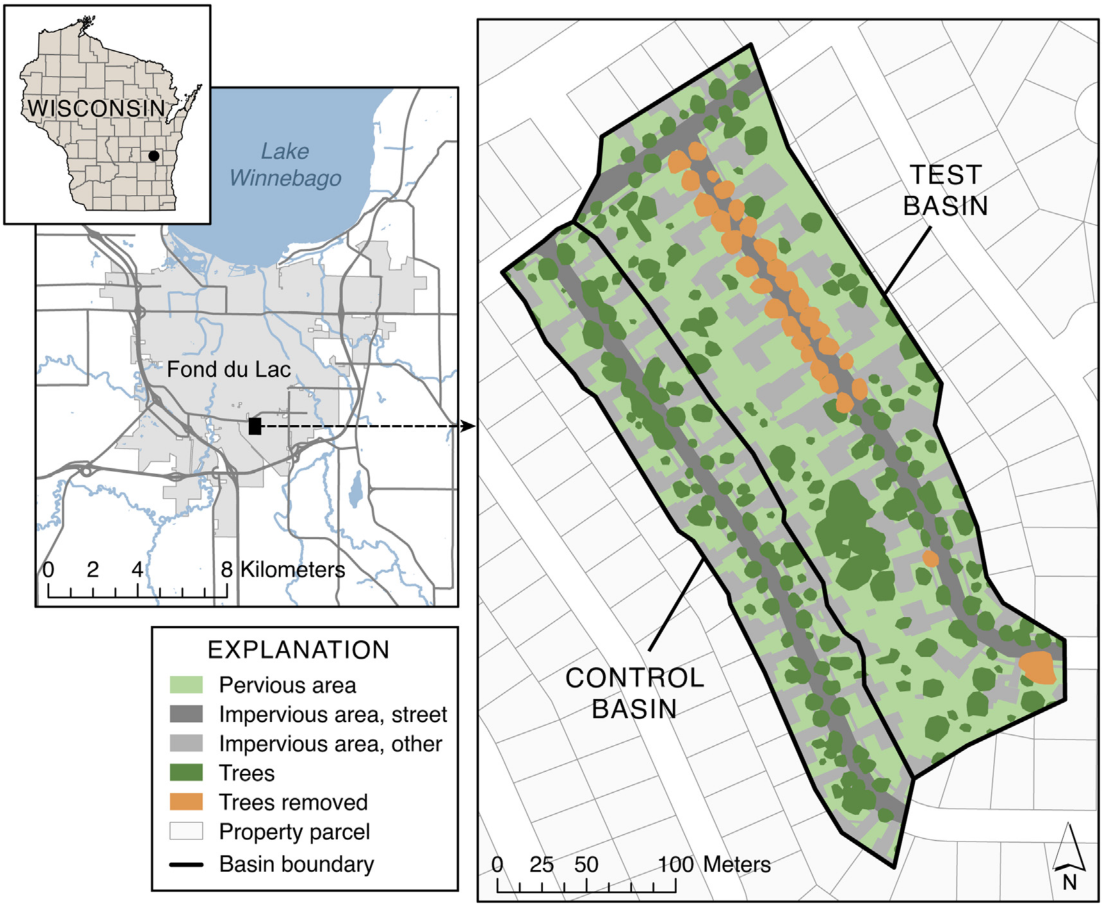

Fig. 1. This study was located in a medium-density residential neighborhood in Fond du Lac, Wisconsin which is part of the Lake Michigan drainage basin. Canopy area for individual trees were determined using GIS software coupled with aerial photographs during a period of leaf maturation.

lawns) and overhead tree canopy were made using a combination of aerial imagery, GIS software, and field surveys (Table 1). The test catchment was more than twice as large as the control; however, each had a similar distribution of source areas with lawns making up the greatest percentage. Impervious surfaces comprised 54 and 39% of the control and test catchments, respectively. Both catchments have separated septic and storm-sewer systems. Stormwater runoff is conveyed via curb and gutter to stormwater inlets as the entry point to the centralized storm-sewer collection system.

Trees in the area, both street trees and landscape trees, are similar in size and were likely planted during the time of housing construction. Tree canopy in the control catchment covered a greater percentage of impervious surface than in the test catchment (Table 1); however, less of the canopy was distributed over streets (Table 2). Street trees flanked each street and were a mix of mature, deciduous hard wood species. Trees were characterized as predominantly green ash (*Fraxinus pennsylvanica*) or Norway maple (*Acer platanoides*) (Table 2). Nearly one-half of street trees in the test catchment were green ash, a species of tree susceptible to infestation by the emerald ash borer. Like many other cities in Wisconsin, the city of Fond du Lac plans to remove all ash street trees to limit the spread of infestation. Assessment of ash trees in the control and test catchments at the beginning of the study determined they were in good health. In 2018, the city treated all ash trees in the study catchments with an insecticide to prevent infestation. The diameter at breast height for the removed street trees identified in Fig. 1 ranged from 0.40 to 0.56 m.

Table 1
Distribution of source areas and tree canopy with associated percentage in the control and test catchments. Rounding applied. [–, no data].

	Control		Test	
	Hectare	Percent	Hectare	Percent
Total drainage area	2.03		4.26	
Source area				
Streets	0.38	19	0.54	13
Driveways	0.21	10	0.20	5
Roofs	0.36	18	0.65	15
Sidewalks	0.13	7	0.14	3
Lawns/Open	0.94	46	2.60	61
Other Impervious	–		0.13	3
Tree canopy over impervious	0.21	58	0.35	30
Tree canopy over pervious	0.29	42	0.85	70

Table 2
Number of street trees identified by specie and percentage of canopy over total street area in the control and test catchment. [—, not present].

Common name	Scientific name	Control	Test
Norway Maple	*Acer platanoides*	20	30
Green Ash	*Fraxinus pennsylvanica*	15	29
Redmond Linden	*Tilia Americana*	17	–
Honey Locust	*Gleditsia triacanthos*	15	–
Freeman Maple	*Acer X freemanii*	3	–
Miyabei Maple	*Acer miyabei*	2	–
Tree Canopy Over Streets[a]		30%	38%

[a] Area of canopy over streets only.

2.2. Hydrologic and climatic measurements

2.2.1. Precipitation

Precipitation data were collected by use of a tipping-bucket rain gage calibrated to 0.25 mm per tip. The rain gage was located in an open field approximately 100 m north of the study area.

2.2.2. Surface runoff

A submersible pressure transducer and Doppler-type velocity sensor were mounted to the bottom of 38 and 53 cm diameter storm sewer pipes draining the control and test catchment, respectively (Fig. 1). A secondary bubble line with pressure transducer was also installed to verify stage and provide redundancy to the primary device. Data were continuously recorded at 1-min increments during periods of runoff and hourly during interevent periods. Instantaneous pipe discharge was computed at 1-minute intervals based on stage-discharge regressions developed by use of fluorescent dye tracer analysis (Wilson et al., 1986). Storm-event runoff volumes were then computed by integrating instantaneous discharge over the storm duration. Both storm-sewer pipes were free flowing with no presence of backwater.

Storm sewers were separated from sanitary and drinking water pipes with no cross-connections or leaks. Because of the clay-rich soils, many of the homes in the study area were equipped with sump pumps to prevent basement flooding from saturated soils. On occasion, many of the pumps would discharge, either directly or indirectly, to the storm-sewer drainage network as evidenced by repeated fluctuations in stage during non-storm periods. Any discharge from anthropogenic sources would have been part of the storm hydrograph during an event and therefore was included in the computation of event statistics. In some cases, evidence of groundwater intrusion into the storm drainage network resulted in contributions of storm volume not related to surface runoff. Occurrence of this phenomenon was determined through observation of an unusual extension of the storm hydrograph recession limb. To limit bias of groundwater contributions for these events, the end date and time of a storm was determined based on the last inflection of slope in the recession limb.

2.3. Experimental design and statistical analyses

A paired-catchment design was used to evaluate changes in rainfall-runoff relations between the control and test catchments due to tree removal and reduced street tree canopy during the treatment phase of the project. The paired-catchment approach relies on the assumption that there is a quantifiable relation between paired hydrologic data and that this relationship is valid until a major change (i.e. treatment) is made in one of the catchments (Clausen and Spooner, 1993). At that time, a new relationship can be discerned between the treatment and control catchment hydrology. The strength of this approach is that it does not require the assumption that the data distributions from control and test catchments are statistically similar. Yet, each catchment should be similarly structured, and thereby respond in a predictable manner together, such that their relation remains the same over time except for the influence of reduced street tree canopy.

We started our monitoring campaign with a calibration phase (May through September in 2018 and 2019). During this time, hydrograph metrics from paired runoff events were used to develop the relation between the control and test catchments with street trees in place. In March 2020, the treatment phase was implemented in the test catchment, which consisted of removing 29 mature *Fraxinus pennsylvanica* and two *Acer platanoides* within the right-of-way along a 400 m stretch of a residential street, while the control catchment remained the same. For consistency, evaluation of the hydrologic response to tree loss was limited to the same time span as the calibration period (May – September).

Following procedures outlined in Clausen and Spooner (1993), the significance of the relationship between log-transformed paired hydrologic data during each phase was confirmed using the analysis of variance (ANOVA, $\alpha = 0.10$). At the end of the treatment phase the significance of the effect of street tree removal was determined using analysis of covariance (ANCOVA) (Clausen and Spooner, 1993). The analysis determined the significance of difference between the slopes and intercepts of the calibration and treatment regressions. The overall increase in runoff due to street tree removal can then be estimated as a percentage change based on the average predicted and observed values during the treatment phase (Clausen and Spooner, 1993).

3. Results and discussion

3.1. Precipitation

Mean annual precipitation for this area is 765 mm of which 60% occurs between the months of May through September (National Oceanic and Atmospheric Administration, 2019). Fig. 2 illustrates departures of measured monthly precipitation from the 30-year normal. Cumulative precipitation totaled 670 mm ($n = 43$) in 2018, 590 mm ($n = 49$) in 2019, and 715 mm ($n = 42$) in 2020. Monthly precipitation exceeded the 30-year normal for all but two months (Fig. 2). The largest departure was observed in August 2018 which saw nearly three times more precipitation than normal at 269 mm compared to 93 mm (Fig. 2).

The distribution of precipitation depth was similar in all years with approximately 60% of all storms having total precipitation depths less than 13 mm (Fig. 3). Storms greater than 13 mm were observed with higher frequency in 2018 and 2020 including six events greater than 40 mm measured in both years, compared to only one event in 2019. Despite these outliers, results of the Kruskal-Wallis test (Helsel and Hirsch, 2002) show no significant differences in the population for each study year at the 95% confidence level ($p = 0.98$). Total precipitation volumes in the control and test catchment are detailed in Table 3.

3.2. Runoff volume

Analysis of paired rainfall-runoff characteristics was seasonally limited to leaf emergence through leaf senescence (May through September). Surface runoff was conveyed via conventional curb-and-gutter streets with surface drains to a network of concrete storm sewer pipes. It was assumed that existing depression storage and street tree canopy intercepted a portion of rainfall and removal of canopy would result in less abstraction of rainfall, potentially changing the precipitation depth threshold required to generate runoff and increasing the

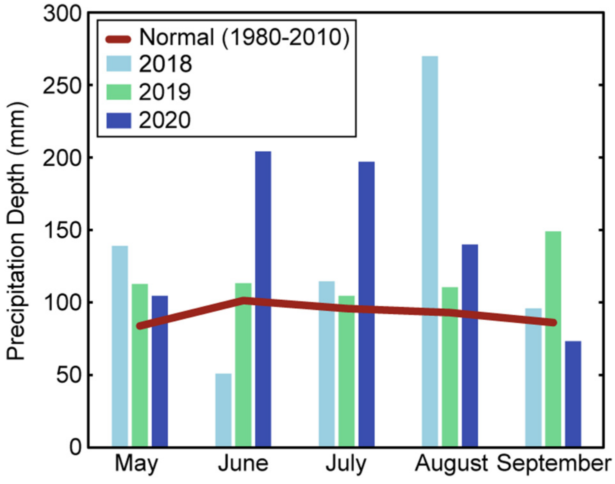

Fig. 2. Monthly precipitation depth during each study year compared to the 30-year normal (1980–2010). Data from National Oceanic and Atmospheric Administration (2019).

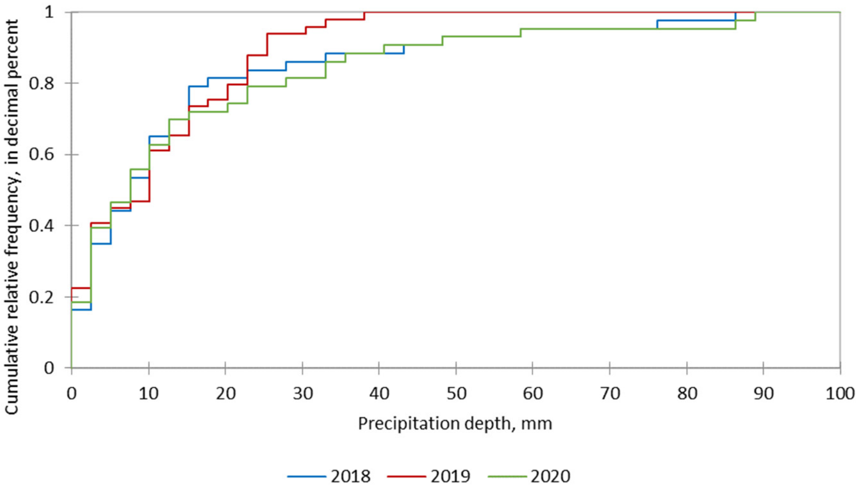

Fig. 3. Cumulative distribution of storm events over increasing precipitation depth in the study area, May through September.

volume of runoff reaching storm drains. For this reason, all storms with precipitation depth greater than or equal to 0.5 mm were included in the paired-catchment analysis regardless of whether they produced measurable runoff. A total of 135 warm-season precipitation events, each with precipitation depths greater than 0.5 mm were measured over this 15-month span. A complete list of measured hydrologic and weather parameters can be found in Carvin and Selbig (2021).

Cumulative volume, represented as a percentage of total measured volume, at the test and control catchments for the calibration and treatment phase are shown in Fig. 4. From Fig. 3, approximately 60% of storms measured during the calibration period (2018 and 2019) had depths of 10 to 12 mm or less, yet these storms produced less than 15% of all measured runoff in the control and test catchments (Fig. 4). One-half of all measured runoff during this same period came from storm events having 30 mm depth or less (Fig. 4). These values are consistent with model predictions by Pitt et al. (1999) when simulating runoff from typical residential land use across a gradient of precipitation depths. This level of precipitation depth also marks the point where departures in cumulative volume between the control and test catchments are first observed. It is at this point where the control catchment shows slightly larger gains in runoff volume than the test catchment. The separation between the control and test catchment is relatively consistent until larger storms (>75 mm) once again bring the cumulative volume curves to near parity (Fig. 4), indicating similar catchment runoff response, and validating the assumptions of the experimental design.

Similar to the calibration period, the percentage of cumulative volume in the control and test catchments follow a similar trajectory during the treatment period; however, accumulation of runoff volume in the test catchment is observed earlier than in the control, as indicated by greater separation between curves at appreciably lower rainfall depths. The departure between response curves remains consistent across all except the largest of storms (>85 mm). We attribute this difference to a potentially interactive mechanism of surface runoff production (infiltration-excess vs. saturation-excess) and degree of storage versus throughfall in the canopy. From Fig. 4 tree canopy appeared to be more retentive during the calibration period when street trees were in place. Removal of street trees reduced the interception and thus storage capacity, and this was observed across a wide range of precipitation depths.

Total measured runoff was generally proportional to catchment area. The test catchment, having approximately twice the drainage area as the control also produced nearly twice as much runoff volume (Table 3). When normalized by area, the cumulative volume of surface runoff was nearly the same in each catchment and ranged from 16 to 28% of rainfall (Table 3). Median runoff coefficients for all storms were 15 and 13% in the test and control catchment during the calibration period, respectively. Median runoff coefficients show modest decreases during the treatment period at 13 and 9% for the test and control catchment, respectively.

The larger cumulative fraction of surface runoff to total rainfall in 2018 (Table 3) is largely due to excessive runoff from low recurrence events with comparatively high storm total rainfall depth. For example, a single event having a precipitation depth of 60 mm in May 2018 was responsible for more than 15% of all runoff in both catchments measured during the calibration period. From Fig. 4, we observe the separation between accumulation curves for these two events narrows,

Table 3
Cumulative volume of precipitation and runoff in the control and test catchments observed during each study year. Rounding applied. [n, number of samples].

			Precipitation (m^3)		Runoff (m^3)		Runoff (%)	
Year	Phase	n	Control	Test	Control	Test	Control	Test
2018	Calibration	43	13,653	28,541	3302	7943	24	28
2019	Calibration	49	12,020	25,128	2471	5212	21	21
2020	Treatment	42	14,570	30,460	2262	5779	16	19

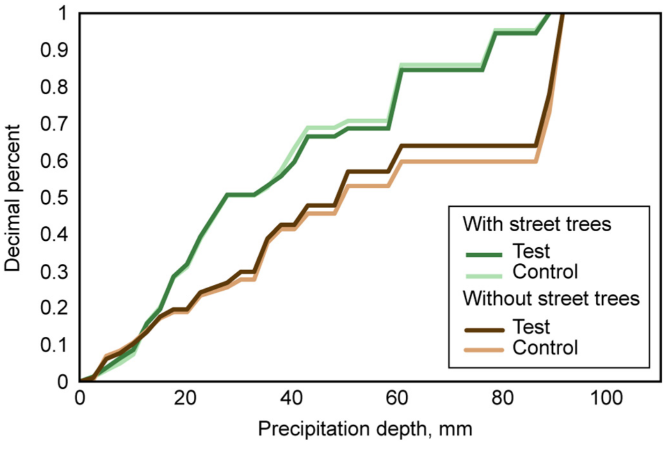

Fig. 4. Cumulative distribution of surface runoff volume as a percentage of total measured volume with increasing precipitation depth in the test and control catchments during the calibration and treatment phase.

indicating a diminished capacity for canopy interception for larger storms. Xiao and McPherson (2002) similarly concluded that little interception occurs after surface storage capacity is taken up proportionally sooner in a 25-yr storm event.

To test the stormwater volume reduction efficiency of street tree canopy, storm event volumes from the control catchment were paired with those from the test catchment to establish and test a linear regression. According to the paired-catchment approach, any change in the relation between the control and test catchments during the calibration period can be attributed directly to activities related to street tree removal. The magnitude of change reflects the cumulative effects of all changes including those related to loss of interception and storage by the canopy and branches and changing antecedent moisture conditions in the street right-of-way following removal of roots of removed street trees. Fig. 5 illustrates the relations in log-transformed event volumes between the control and test catchments during the calibration and treatment periods. Differences in these relations were quantified if results of the ANCOVA test for differences in slopes or intercepts exceeded the 90% confidence level ($p \leq 0.10$). If the treatment regression were to shift above that of the calibration phase, the form of treatment (street tree removal) could be interpreted as an increase in runoff potentially attributable to the loss of street tree canopy. No significant change in either the slope or intercept of the treatment regression indicate that removal of street trees had little to no effect on rainfall-runoff relations when compared to the calibration phase. If the results of the ANCOVA test for slope and/or intercept reveal a significant difference between the calibration and treatment regressions, the change in runoff as a result of street tree removal can be estimated by taking the difference between the observed runoff and that predicted using the regression equation from the calibration period which is representative of runoff that would have been generated if street tree removal had not occurred.

Quantification of the overall efficiency of street tree canopy reveals an increase in stormwater runoff volume after street trees were removed, as indicated by an upward vertical shift in the treatment trendline (Fig. 5). Results of the ANCOVA test met the 10% significance threshold for intercept ($p = 0.07$), but not slope ($p = 0.97$) (Table 4). A change in intercepts but not slopes between the calibration and treatment phase indicates removal of tree canopy resulted in an increase in surface runoff across the full range of observed storms. Based on paired data shown in Fig. 5, the average increase in event volume after removal of street trees compared to what would have been predicted with trees present using the pre-treatment regression equation was 30%. Although significant differences in the intercepts between the calibration and treatment phase was observed, events that produced no runoff showed potential to have leverage on the resulting trendline. For this reason, paired event volumes were discretized into smaller ranges to better understand the reductive effect tree canopy exhibits across an array of precipitation depths. Varying the precipitation thresholds for each range would affect statistical outcomes. Precipitation ranges detailed in Table 4 were selected to provide granularity across the full range of depths while maintaining a similar number of events within each range during the treatment period. Results from the ANCOVA test showed two of the five precipitation ranges had significant changes in both slope and intercept ($p \leq 0.10$) (Table 4).

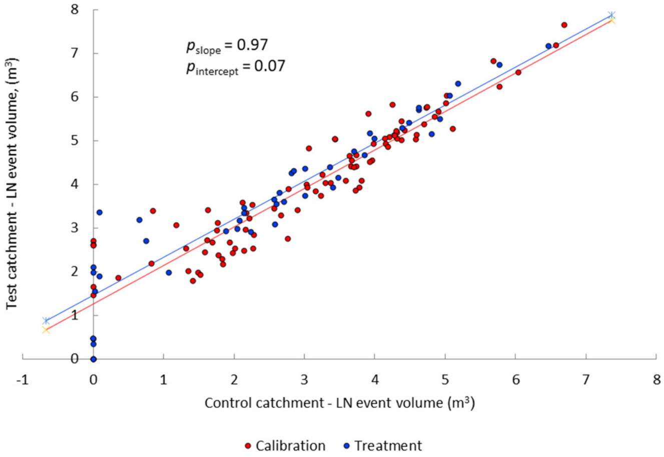

Fig. 5. Log-transformed (LN) volumes for paired storm events observed in the control and test catchments during the calibration and treatment period. Statistical significance of the difference between slopes and intercepts are indicated by the corresponding probability values (p).

Table 4
Results from the ANCOVA test for paired event volumes in the control and test catchments during the calibration and treatment periods across a gradation of precipitation ranges. Statistical significance of the difference between slopes and intercepts are indicated by the corresponding probability values (p). A positive percent change indicates an average increase in event volume after removal of street trees compared to what would have been predicted with trees present using the pre-treatment regression equation. Values in bold indicate significance at the 90% confidence level ($p \leq 0.10$). [n, number of events; –, not significant].

Precipitation depth (mm)	$n_{calibration}$	$n_{treatment}$	p_{slope}	$p_{intercept}$	Percent Change
≤2.54	19	10	0.23	0.32	–
2.55–6.10	**20**	**8**	**0.03**	**0.01**	**28**
6.11–12.45	18	8	0.40	0.40	–
12.46–25.15	**22**	**7**	**0.09**	**0.06**	**24**
≥25.16	13	9	0.74	0.21	–
All events	**92**	**42**	**0.97**	**0.07**	**30**

From Table 4, increases in runoff volume (because of street tree removal) varied with increasing precipitation. The percent increase was less pronounced at higher precipitation depths, indicating a diminishing but persistent capacity of tree canopy to intercept and retain precipitation as rainfall continued. The failure to meet statistical significance in the ≤ 2.54 mm range was likely due to depression storage in the landscape. Initial abstraction of precipitation from depression storage on impervious surfaces has been shown to be as high as 6 mm (Boyd et al., 1993). In general, the majority of trace events less than 1.3 mm total rainfall depth failed to produce measurable runoff. Variation in precipitation intensity could influence whether events ≤ 2.54 mm did or did not produce runoff, thereby limiting detectable changes during the treatment period.

For each precipitation range identified as statistically significant in Table 4, the increase in volume during the treatment phase is expressed as a percentage change between the average predicted and observed values, following the paired-catchment analysis methods of Clausen and Spooner (1993). Using the average values gives some indication of the relative change for each precipitation range but does not provide enough information to determine the cumulative increase in runoff volume for individual events. To better quantify the volumetric increase for all storms, observed and predicted runoff volumes during the treatment period were first summed for each precipitation range. The difference between these two sums represents an estimate of the increase in runoff due to the removal of street trees (Table 5).

Table 5
Estimated increase in stormwater runoff volume through removal of street tree canopy in the test catchment during the treatment period. Estimates are based on the difference between the sum of predicted and observed event volumes for each precipitation range. Only precipitation ranges that meet statistical significance (p ≤ 0.10) are presented.

	Runoff volume (m^3)		
Precipitation depth (mm)	Predicted	Observed	Increase
2.55–6.10	156	201	45
12.46–25.15	647	800	153

The volumetric increase for the 12.46–25.15 mm range during the treatment period was 153 m^3 (Table 5). An additional 45 m^3 was estimated for the 2.55–6.10 mm precipitation range, the only other precipitation range that was statistically significant. These two ranges, when combined, accounted for an increase of 198 m^3, which was equivalent to 4% of the total runoff volume measured in the test catchment during the treatment period identified in Table 3. Storm events with precipitation depths in the ≤2.45, 6.11–12.45, and ≥25.16 mm ranges were not statistically different from the control and, therefore, not considered when assessing the overall increase in runoff volume because of tree loss. It is unclear why volumetric increases associated with the 2.55–6.10 and 12.46–25.15 mm ranges satisfied statistical significance yet the 6.11–12.45 mm range did not. One reason might be the small number of paired events analyzed within each range. Closer examination of paired data in graphs similar to Fig. 5 shows one or two events had high leverage over resulting trendlines during the treatment period in the 2.55–6.10 and 12.46–25.15 mm ranges, thereby influencing both slope and intercept, whereas the 6.11–12.45 mm range did not (Carvin and Selbig, 2021). While these few events seemingly influenced resulting statistical tests, there is no evidence to support censorship. A larger data set would reduce variability and uncertainty commonly associated with environmental data such as rainfall-runoff characteristics in urban environments reducing the effect of outliers (Burton and Pitt, 2002).

A total of 31 street trees were removed at the onset of the treatment period, resulting in a loss of 2990 m^2 of canopy over streets, driveways, sidewalks, and grassed areas. Each of these surfaces provide variable contributions of runoff to nearby storm drains during a rain event with impervious surfaces transferring surface runoff more quickly that pervious surfaces. An increase in runoff volume of 198 m^3 indicates the normalized, aggregated volume reduction capacity of the removed canopy to be approximately 66 L/m^2 (6.6 cm equivalent water depth) over the 42 storms that occurred during the five months of May through September 2020. Together these values represent the cumulative impact on stormwater generation from changes (interception, transpiration, and infiltration) that are associated with removing mature *Fraxinus pennsylvanica* street trees from the test catchment.

Empirically determining how urban trees reduce the overall proportion of rainfall that becomes runoff would provide a means to better calibrate hydrologic models that incorporate arboricultural, canopy hydrologic processes. When properly used, these models can better inform urban foresters as they work towards minimizing harmful impacts of urban stormwater runoff. Simple estimates of an annual reduction in runoff volume per individual tree do not account for the complexity of influencing factors, such as species diversity, leaf area, age, and soils (Berland et al., 2017). For example, using the GLRI guideline of 223 L per tree would result in an estimated annual runoff volume reduction of 6913 L in the test catchment (31 street trees removed multiplied by 223 L). This value is appreciably less than this study's field-based estimate of 198,000 L, or 6376 L per tree (198 m^3 divided evenly by the assumed equal contribution of 31 trees). The mature *Fraxinus pennsylvanica* trees in this study do not accurately reflect the average tree intended by the GLRI estimate and illustrates the problem of assigning a single value per tree without consideration for variation in leaf area or canopy structure. For comparison, Xiao and McPherson (2002) estimated, on average, individual street trees in Santa Monica, California intercepted 6600 L of annual rainfall per tree but note this value varied by species and other tree characteristics, ranging from 610 up to 26,000 L per tree. Other studies report similar values ranging from 3200 to 7570 L per tree per year (Center for Watershed Protection, 2016). The range of interception reported by Xiao and McPherson (2002) is similar to the per tree volume reduction calculated in this study. Unfortunately, these estimates consider only interception and do not consider runoff reduction that might occur if root water uptake by street trees during inter-storm periods create lower antecedent moisture conditions and increased infiltration rates on the street terrace during storms. However, our estimate of 6376 L per tree reflects the influence of street tree removal as part of the complete urban water budget including factors beyond just interception such as transpiration and soil moisture. It also represents avoided runoff volume over a period with total precipitation equaling 715 mm, 43% higher than the 30-year normal. Values reported by Xiao and McPherson (2002) were simulated using a total precipitation of only 570 mm recorded in 1996, of which only 22% fell while deciduous trees were in full leaf.

The abstraction of gross precipitation is strongly influenced by tree species composition, canopy cover and dimensions as well as rainfall spatial distribution and intensity (Berland et al., 2017; Kermavnar and Vilhar, 2017). An alternative method to express runoff avoided is through an expression of volume per unit area of canopy; however, few studies use this metric when reporting results, opting for water retention capacity of individual leaves and branches instead. Klimenko et al. (2020) showed the amount of water that is retained on the leaf of the deciduous Siberian larch (*Larix sibirica*) can be as high as 0.4 L/m^2. While this information provides insight into the variation of water retention capacity for different species, it does not readily translate into reduced surface runoff for stormwater managers. A more common metric of reporting retention is based on the percentage of total rainfall. In a review of urban tree studies, Kuehler et al. (2017) and Center for Watershed Protection (2016) reported rainfall retention in the canopy of various trees to range from less than 10 to more than 60%. The increase in runoff volume of 198 m^3, when normalized by the 2990 m^2 of canopy removed, equates to an equivalent water depth of 6.6 cm (9% of the 71.5 cm of rainfall that fell during the treatment period), that would have been retained had the canopy remained intact. While this falls within the range of values reported by Kuehler et al. (2017) and Center for Watershed Protection (2016) for interception alone, our estimate represents interception and retention by the canopy as well as the transpiration driven feedback between antecedent moisture conditions and infiltration beneath the canopy. Thus, the rainfall retention capacity of canopy alone is only a portion of the 9% of water falling on the urban canopy that is retained.

Because the maximum capacity of water retained on the leaf surface area varies considerably, extrapolating the unit area metric to larger stands of urban forests with a diversity of tree species would require normalization based on the average annual rainfall. In practice, this would most likely be estimated through an average leaf area index because of its strong correlation to canopy cover (Sadeghi et al., 2016). Once refined for individual species, a unit-area calculation can be applied to larger areas of canopy for rapid assessment of potential volume reduction from existing or future trees. This method may be preferred by cities because most already maintain spatial information on urban forest composition.

3.3. Peak discharge

Like runoff volume, changes to peak discharge were evaluated through use of the ANCOVA test. No significant differences were detected when evaluating peak discharge for all storms inclusively ($p = 0.36$ for slope and 0.71 for intercept). When evaluating differences between the control and test catchments using the same discretized precipitation ranges identified in Table 4, peak discharge showed significant decreases in the ≤2.54 and 2.55–6.10 ranges, and a slight, but still significant, increase in the 6.11–12.45 mm precipitation range after trees were removed (Table 6). Results of a two-sided Mann-Whitney test (Helsel and Hirsch, 2002) confirmed the ANCOVA results. This was unexpected based on Asadian (2010) who found that tree canopy can delay throughfall by less than 0.75 to as much as 6.5 h after rainfall; however, Asadian (2010) also concludes the delay does not affect the peak in net precipitation. Xiao and McPherson (2002) suggest this delay in throughfall would translate into similar delays for peak runoff but not affect peak magnitude.

Table 6
Results from the ANCOVA test for paired event peak discharge in the control and test catchments during the calibration and treatment periods across a gradation of precipitation ranges. Statistical significance of the difference between slopes and intercepts are indicated by the corresponding probability values (p). A positive percent change indicates an average increase in peak discharge after removal of street trees compared to what would have been predicted with trees present using the pre-treatment regression equation. Values in bold indicate significance at the 90% confidence level ($p \leq 0.10$). [n, number of events; –, not significant].

Precipitation depth (mm)	$n_{calibration}$	$n_{treatment}$	p_{slope}	$p_{intercept}$	Percent Change
≤2.54	**19**	**10**	**0.03**	**0.21**	**−13**
2.55–6.10	**20**	**9**	**0.09**	**0.39**	**−19**
6.11–12.45	**18**	**8**	**0.08**	**0.28**	**1**
12.46–25.15	24	22	0.38	0.22	–
≥25.16	17	13	0.66	0.58	–
All events	92	42	0.36	0.71	–

Potentially, peak discharge did not exhibit similar increases to those observed for runoff volume because changes to both interception and infiltration are greatest early in the storm, while the storm hydrograph is just beginning to rise. The effects of these processes would be greatly reduced as soils and leaves become wetter, reducing infiltration capacity and reaching maximum canopy storage (Xiao and McPherson, 2002; Stovin et al., 2008). Thus, if peak precipitation intensity occurs after this threshold is reached, appreciable changes in resulting peak runoff may be less apparent.

Miller et al. (2021) has shown assessment of urban rainfall-runoff response to stormwater management can be difficult. The ability to detect changes to hydrograph metrics, such as peak discharge, through small-scale alterations in the urban landscape was inconclusive across a gradient of impervious area in urban catchments. They conclude that stormwater management is less effective at attenuating urban hydrographs than is commonly assumed.

4. Implications for stormwater management

Understanding the value of urban tree canopy as a tool for stormwater management can help cities assess how removal or planting of street trees may influence the volume of stormwater runoff reaching receiving water bodies. Previous research has primarily focused on individual hydrologic components of trees with few studies examining trees holistically within the context of the urban water cycle. An extensive literature review by the Center for Watershed Protection (2016) identified 33 studies characterizing rainfall interception or transpiration of urban trees, most of which occurred in semi-arid climates. Similar studies covering a broad range of tree species commonly found in humid climates would be helpful to improve understanding of regional variability. Quantifying the combined effects of a tree's ability to intercept, transpire, and infiltrate water into soils at the sewershed or watershed scale would be beneficial to limit variability and uncertainty inherent in studies of a single tree or at the plot scale.

The diversity of street trees in the test catchment was limited to only the *Acer* and *Fraxinus* genus, which are the two most common street trees found in the Midwest USA (Ma et al., 2020). Since its discovery in 2002, the emerald ash borer (*Agrilus planipennis*) has revealed that while all species of North American ash (*Fraxinus*) are susceptible to attack, green and black ash trees are preferred by the emerald ash borer, dying within a few years of initial infestation and colonization (U.S. Department of Agriculture, 2015). Major economic damage from infestations occurs in cities and populated places where high-value ash species trees grow along streets or in parks (Poland and McCullough, 2006). An estimated 17 million trees are at risk of replacement in the central and eastern United States due to infestation (Kovacs et al., 2010). Although the runoff reduction volumetric benefits reported in this study reflect only green ash, a review of leaf area index shows the *Fraxinus* genus to be a good average representation of the diverse species of urban street trees commonly used in the Midwest (Ma et al., 2020).

5. Summary and conclusions

As urban areas continue to expand, limiting the amount of stormwater runoff has become increasingly important when developing strategies to protect water resources and prevent urban flooding. More attention has been directed towards a variety of green infrastructure practices to capture, retain, and infiltrate surface runoff. Although the hydrologic effects of trees have been studied for decades, renewed interest in the use of trees as a green infrastructure tool has led to a need for more sophisticated models that aim to simulate ecosystem services of urban forests, including stormwater runoff reduction.

Based on a paired-catchment study design, the removal of green ash (*Fraxinus pennsylvanica*) street trees resulted in a 198 m^3 increase in surface runoff entering storm drains over 42 storm events between May and September 2020. This translated into 4% of the total measured runoff after trees were removed. The runoff volume reduction-benefit rendered by the green ash trees was similar to what had been reported for other tree species by similar studies. Much of the savings were reported for larger rainfall events indicating that while interception depth may increase only marginally with increasing precipitation, retention by other mechanisms such as increased infiltration may be more persistent with increasing rainfall.

As cities engage in a campaign to replace municipally owned street trees, a comprehensive understanding of the full range of ecosystem services offered by a diversity of tree species would support development of an institutional framework for replacement of diseased trees. Reducing stormwater runoff is one of many aspects of street trees environmental managers and urban foresters consider as they work towards a more sustainable future. Novel methods to crediting expansion of urban trees will continue to improve provisioning of ecosystem services as additional research provides the information that can be used to adjust for the broad range of hydrologic impacts inherent in an increasing diversity of street tree species and weather regimes.

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Declaration of competing interest

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