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Research article

The seasonality of nutrients and sediment in residential stormwater runoff: Implications for nutrient-sensitive waters

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ABSTRACT

The discharge of excess nutrients to surface waters causes eutrophication, resulting in algal blooms, hypoxia, degraded water quality, reduced and contaminated fisheries, threats to potable water supplies, and decreases in tourism, cultural activities, and coastal economies. An understanding of the contribution of urban runoff to eutrophication is needed to inform management strategies. More broadly, the seasonality in nutrient concentrations and loads in urban runoff needs further analysis since algal blooms and hypoxia are seasonal in nature. This study quantifies the variation of nutrients and sediment in stormwater runoff across seasons from four urban residential sewersheds located in Columbus, Ohio, USA. An average of 62 runoff events at each sewershed were sampled using automated samplers during stormflow and analyzed for nutrients and total suspended solids (TSS). Spring total nitrogen concentrations had a significantly ($p < 0.05$) higher median concentration (2.19 mg/L) than fall (1.55 mg/L) and summer (1.50 mg/L). Total phosphorus concentrations were significantly higher in spring (0.22 mg/L) and fall (0.23 mg/L) than summer (0.15 mg/L). TSS concentrations were significantly higher in the spring (74.5 mg/L) and summer (56.5 mg/L) than the fall (34.0 mg/L). In contrast, seasonal loading differences for nutrients or sediment were rare because runoff volume varied in such a way as to offset significant concentration differences and significant seasonality in rainfall intensity. Annual pollutant loadings were similar in magnitude to other residential and even some agricultural runoff studies. Although nutrient loads are the key indicator for determining algal biomass, nutrient concentrations are important for real-time algal growth. Future research efforts should be focused not only on understanding how seasonal urban concentrations and loads impact coastal eutrophication, but also developing improved watershed management focused on critical periods. Improved designs for stormwater control measures need to account for seasonality in pollutant discharge.

1. Introduction

Throughout the world, water quality crises exist because anthropogenic nutrients have threatened reservoirs used as drinking water sources (Conley et al., 2009; Michalak et al., 2013), and reduced and contaminated fisheries (Bukaveckas et al., 2017; Wituszynski et al., 2017). Further, poor water quality has decreased tourism, cultural activities, and coastal economies (Watson et al., 2016; Wolf et al., 2017). Excess nutrients can cause eutrophication, in which abundant nitrogen and phosphorus fuel rapid algal growth (Xu et al., 2010); this can lead to fish kills and toxic algal blooms, which pose a threat to public health (Grattan et al., 2016; Line et al., 2002). These nutrients may come from anthropogenic sources, such as fertilizer application (Long et al., 2014) and industrial and wastewater treatment plant effluents (Li et al., 2014), as well as natural processes such as atmospheric deposition (Pease et al., 2018) and the breakdown of organic material (Bedan and Clausen, 2009).

Stormwater runoff is a major source of anthropogenic nutrients to water bodies (Müller et al., 2019), and managing nutrients in runoff is therefore an important factor in the mitigation of eutrophication. The volume and rate of stormwater runoff increase as impervious surfaces are constructed during urban development (Walsh et al., 2005), and this increased runoff delivers elevated nutrient loads as land is converted to urban uses (Line and White, 2016). Fertilizer, sewage, atmospheric

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deposition, and combustion processes are key nutrient sources in urban areas (Jordan et al., 2012; Kim et al., 2010; Long et al., 2014), and nutrients from these sources are conveyed to lakes and rivers by stormwater.

Recent work has shown that the severity of algal blooms, and other negative impacts of eutrophication, depend as much on the seasonality of nutrients as on the total load of nutrients delivered. For example, spring nutrient inputs are used to predict the yearly algal bloom in Lake Erie (Bertani et al., 2016; Ho and Michalak, 2017; Stumpf et al., 2012) and the extent of hypoxic zones in the Chesapeake Bay (Test a et al., 2017) and the Gulf of Mexico (Lau rent & Fennel, 2019; Scavia et al., 2013). Further, it has been shown that nutrient loading from agricultural runoff can be disproportionally driven by short periods or events, also known as “hot moments” (Williams et al., 2018). There is good reason to suspect that nutrient loads from urban stormwater also exhibit seasonal variation. Previous studies have observed seasonality of pollutants due to anthropogenic sources, such as nitrogen concentrations and loads increasing in the spring coinciding with fertilizer application (Long et al., 2014; Schilling and Streeter, 2018). Other studies have focused on natural seasonal trends, such as the rainy season generating more runoff and therefore an elevated phosphorus load (Fan et al., 2012; Toor et al., 2017). Seasonality has also been observed in the water quality of treated stormwater discharging from stormwater control measures (SCMs), particularly for biologically-mediated processes which fluctuate with air temperature or due to effects of deicing salts on SCM performance (Blecken et al., 2011; Winston et al., 2016). The temperature dependency of the viscosity of water (Emerson and Traver, 2008) and atmospheric deposition of windblown fertilizer (Collins et al., 2010) have been cited as reasons for seasonal variation observed in SCM performance.

Despite evidence for the importance of the timing of nutrient delivery for eutrophication, and the variety of seasonal mechanisms contributing to nutrient loads from urban stormwater, little work has investigated the seasonality of nutrient loadings from urban stormwater runoff at the catchment scale. This is an important gap in knowledge, as many affected bodies of water are adjacent to large cities and are impacted by stormwater runoff from urban areas. If urban areas are contributing nutrients at times critical for the development of algal blooms, it is imperative to consider how these nutrient loads might be reduced. In particular, current restrictions on nutrient export in stormwater generally rely on average or median event mean concentrations collected across an entire year, which may misrepresent the actual threat posed by seasonal nutrient loads (Hathaway et al., 2012). By contrast, if most nutrient loading from urban areas happens during times less important to bloom formation, resources might be better spent elsewhere.

The present study addresses this gap in knowledge by reviewing an average of 62 water quality events sampled over two years from four urban, primarily residential sewersheds in Columbus, Ohio, USA. By analyzing the seasonal norms of nitrogen, phosphorus, and sediment in runoff from urban watersheds, researchers can discover which seasons release the most nutrients and subsequently optimize both nutrient source control and SCM countermeasures. Furthermore, policymakers can utilize these trends to devise more effective approaches in preventing eutrophication.

The first research objective of this study was to describe the seasonal variation of nutrient and sediment concentrations and loads in stormwater runoff in four residential sewersheds, including potential causes of seasonality. Further, urban runoff was compared to agricultural runoff, which has the broad impact of informing stakeholders on how to best allocate resources and focus efforts between these sources of nutrients and sediments. Lastly, maintenance and design measures are proposed to enhance SCM nutrient removal performance in areas experiencing seasonal differences in water quality.

2. Site description

Four sewersheds in the Clintonville neighborhood of Columbus, Ohio, USA were monitored for storm event runoff quality during 2016–2018: Beechwold, Blenheim, Cooke-Glenmont, and Indian Springs (Fig. 1, Table 1). Stormwater runoff from Clintonville was routed through a system of separated storm sewers that drain into the Olentangy River. The soils in the sewersheds were primarily silt loams in the Cardington and Bennington soil series (Soil Survey Staff, 2019). Six glacial ravines run east to west through Clintonville, and one of these ravines was located within the study area (Fig. 1).

Columbus experiences four distinct seasons. Summers are moderately warm with an approximate average high temperature of 29 °C, and winters are moderately cold with an approximate average low of -7 °C. Typical average yearly rainfall is 1016 mm and average yearly snowfall is 559 mm.

Clintonville is primarily comprised of residential neighborhoods with small-lot, single-family homes (Fig. 1, Table 1). Of the four sewershed monitored, Beechwold was the largest (111.5 ha) and Cooke-Glenmont was by far the smallest (11.5 ha) and least impervious (30.9%; Table 1). Beechwold, Blenheim, Indian Springs, and Cooke-Glenmont drained to 137-cm diameter, 91 by 91-cm square, 107-cm diameter, and 46-cm diameter concrete outfalls, respectively. The Cooke-Glenmont sewershed was made up entirely of residential land use, while the other sewersheds were ≥75% residential land use. Roofs (range of 12.5%–16.7% of the total sewershed areas), roads (8.6%–11.0%), and driveways (6.4%–9.9%) represented the vast majority of the imperviousness in all four sewersheds. Pervious areas were primarily residential yards and recreational fields. Cooke-Glenmont contained 21.6% undisturbed natural or forested area; the other sewersheds were completely urbanized. Bioretention cells were installed in the Cooke-Glenmont sewershed in April of 2017; other sewersheds had no SCMs implemented.

3. Materials and methods

3.1. Data collection

A rain gage cluster, consisting of a tipping bucket and a manual rain gage attached to a 2-m tall wooden post, was installed in locations free from overhead obstructions in each of the four experimental sewersheds. Rainfall data were collected using 0.254-mm resolution Davis Rain Collector tipping bucket rain gages (Davis Instruments, Hayward, California) and stored on Hobo Pendant data loggers (Onset Computer Corporation, Bourne, Massachusetts). Rainfall data were stored on a 1-min interval and downloaded every three weeks. Manual rain gauges (Productive Alternatives, Fergus Falls, Minnesota) were checked after each rainfall event to re-calibrate sampler pacing.

An integrated instrumentation network was used to measure runoff hydrographs and to collect stormwater samples. Similar to previous stormwater sampling arrangements (e.g., Page et al., 2015; Bedan and Clausen, 2009), instrumentation was installed at sewer outfalls so that the total sewershed contribution was quantified. Stormwater discharge from Beechwold and Cooke-Glenmont was monitored using ISCO 750 area velocity meters (AVM; Teledyne Isco, Lincoln, NE) mounted to the bottom of outfalls. AVMs measure the depth of flow using a pressure transducer and velocity of stormwater using ultrasonic doppler technology. These measurements along with the known outfall cross-section were used by ISCO 6712 samplers to determine flow rate on a 1-min interval. At Blenheim and Indian Springs, AVMs transmitted measurements to ISCO 2150 flow modules. These data were stored in ISCO 2100 sample interface modules and used to trigger sample aliquots obtained by ISCO 3700 series samplers. Measured water depth was recalibrated after each event to prevent sensor drift. Hydrologic data were downloaded every three weeks.

Runoff volume proportional, composite stormflow samples were

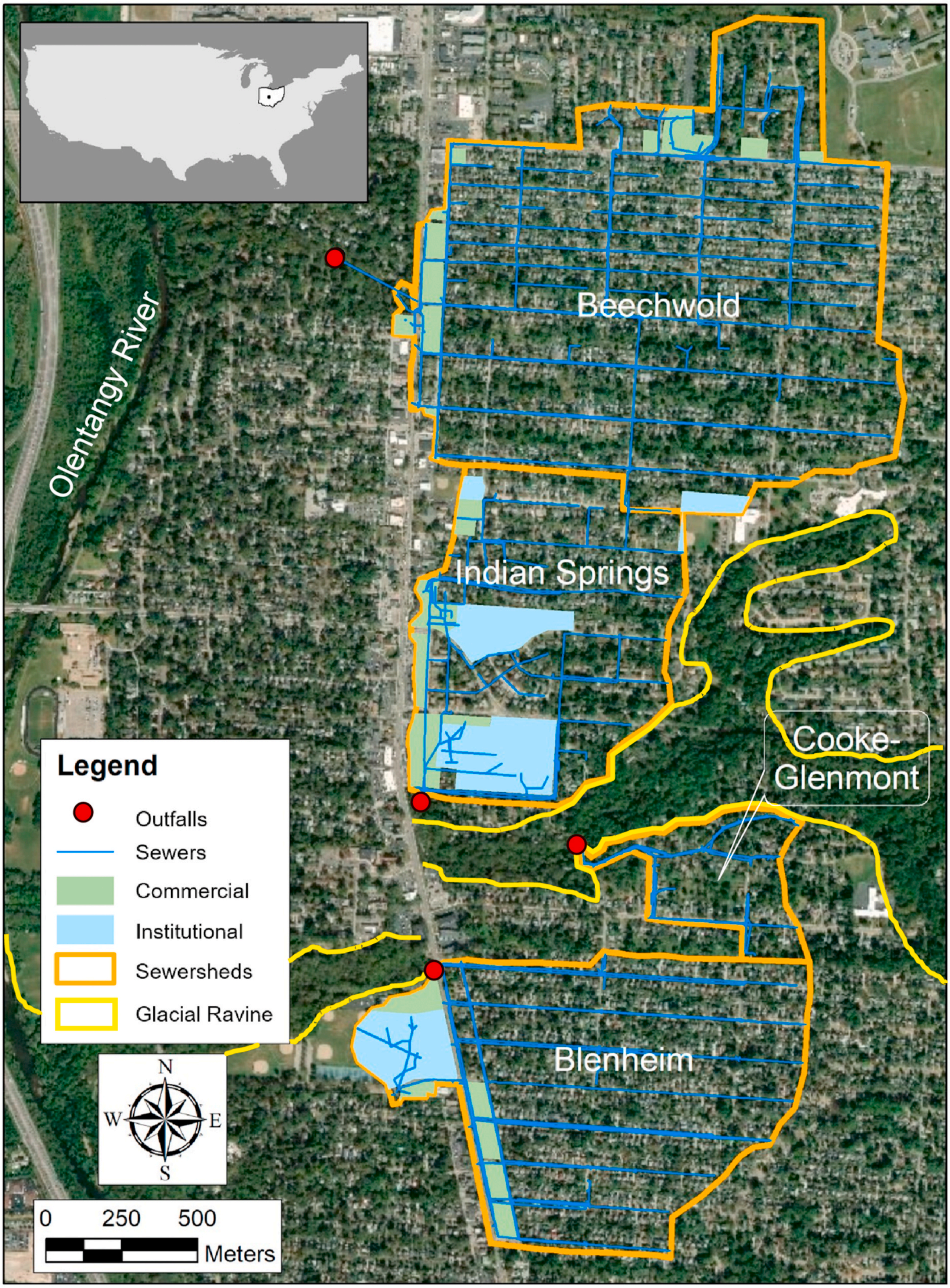

Fig. 1. A map of the Clintonville neighborhood of Columbus, Ohio, showing the four monitored sewersheds, the sewer network, outfalls, and sewershed land use. Areas that are not shaded were residential land use. The glacial ravine, outlined in yellow, runs east to west through the study area, eventually conveying water into the Olentangy River. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Sewershed characteristics.

Sewershed	Area (ha)	Land Use (ha)			Land Use (%)			Imperviousness (% of total area)
		Residential	Commercial	Institutional	Residential	Commercial	Institutional	
Beechwold	111.5	106.7	4.0	0.8	95.7	3.6	0.7	38.2
Blenheim	61.3	54.3	3.0	4.0	88.6	4.9	6.5	44.5
Cooke-Glenmont	11.5	11.5	0	0	100	0	0	30.9
Indian Springs	47.8	36.1	3.6	8.3	75	7.6	17.4	40.3

collected by either ISCO 6712 or 3700 series samplers. Flow rates were integrated with time to determine stormwater volume and trigger sample aliquots. Aliquots were paced such that up to a 50 mm rainfall event could be effectively sampled; the runoff volume needed to trigger each aliquot was calibrated based upon measured runoff volume and associated rainfall depth at a monitoring site. While flow from the Cooke-Glenmont outfall was ephemeral, the Beechwold, Blenheim, and Indian Springs outfalls had baseflow during inter-event periods. For outfalls with baseflow, an enable trigger based on flow depth was set to ensure the sampler did not count baseflow volume in the volumetric trigger for aliquot collection. Within each sampler, aliquots were composited in a single 19-L bottle; thus, resulting laboratory analyses characterized pollutant event mean concentrations (EMC). Sample strainers were used to remove gross solids from the samples and were attached to the bottom of the outfall where flow was well-mixed.

All composite samples were composed of a minimum of five and a maximum of 50, 350-mL aliquots describing greater than 80% of the pollutograph (US EPA, 2002). All samples were collected within 24 h of the cessation of rainfall. Data were collected during the 30-month period from June 2016 to December 2018. Rainfall, hydrologic, and water quality data were not collected from December 20, 2016 through March 15, 2017 and from December 14, 2017 to March 19, 2018 in order to prevent damage to monitoring equipment during freezing temperatures.

3.2. Laboratory methods

Water quality samples were composited in the ISCO sampler during rain events. After thorough resuspension of particles in the compositing bottle, samples were divided among various bottles: a 500 mL plastic bottle pre-acidified with sulfuric acid for total ammoniacal nitrogen (TAN), total Kjeldahl nitrogen (TKN), TP, and nitrite (NO_2) analysis, a 500 mL unpreserved bottle for nitrate (NO_3) and total suspended solids (TSS) analysis, and a 50 mL bottle (following field filtration through a Whatman Puradisc 0.45 μm filter) for orthophosphate (OP) analysis. All water quality samples were placed immediately on ice and chilled to less than 4 °C for transit to the laboratory located approximately 16-km from the sampling sites. Field and lab duplicates, along with blanks and spikes, were analyzed for approximately 10% of samples to ensure no errors were imparted in reported pollutant concentrations by sample handling and laboratory analysis techniques.

Total nitrogen (TN) was calculated as the sum of TKN, NO_2, and NO_3; organic nitrogen (ON) was calculated as the difference between TKN and TAN; and inorganic nitrogen (IN) was calculated as the sum of TAN, NO_2, and NO_3. Nitrate-nitrate ($NO_{2\text{-}3}$) concentrations were determined by summing NO_3 and NO_2 concentrations for each sampled event. Samples were analyzed using either U.S. EPA (1983) or American Public Health Association (APHA et al., 2012) methods.

3.3. Data analysis

Seasons were based on solstices and equinoxes, considering mid-March through mid-June to be spring, mid-June through mid-September to be summer, and mid-September through December to be fall. Due to operational challenges, sampling equipment was not deployed during the cold winter months; thus, this study focused on the quality of stormwater runoff in spring, summer, and fall.

Qualifying storm events were defined using the following criteria: a minimum antecedent dry period (ADP) of 6 h and a minimum rainfall depth of 2.5 mm. Summary statistics for each precipitation event were developed, including rainfall depth (mm), rainfall duration (hrs), average rainfall intensity (mm/hr), peak 5-min rainfall intensity (mm/hr), and ADP (days). Depending on the sewershed, anywhere from 41% to 58% of rainfall events over the monitoring period were sampled for water quality.

Pollutant loads at each monitoring location were determined as the product of pollutant EMC and runoff volume on a storm-by-storm basis.

Table 2
Summary of statistically significant differences for seasonality of rainfall ($p < 0.05$).

Site	Parameter	Dunn's Test p value	Differences
Beechwold	Peak Rainfall Intensity	0	Summer> Fall
		0.002	Summer > Spring
	Average Rainfall Intensity	0.0031	Summer > Fall
		0.0079	Summer > Spring
	Rainfall Duration	0.0023	Fall > Summer
Blenheim	Peak Rainfall Intensity	0.0001	Summer > Fall
		0.0409	Summer > Spring
	Average Rainfall Intensity	0.0007	Summer > Fall
		0.0307	Summer > Spring
	Rainfall Duration	0.0114	Summer > Fall
Cooke-Glenmont	Peak Rainfall Intensity	0	Summer > Fall
		0.0069	Summer > Spring
	Average Rainfall Intensity	0.0006	Summer > Fall
		0.0448	Summer > Spring
	Rainfall Duration	0.0976	Fall > Spring
Indian Springs	Peak Rainfall Intensity	0.0159	Fall > Summer
		0	Summer > Fall
	Average Rainfall Intensity	0.003	Summer > Spring
		0.0011	Summer > Fall
	Rainfall Duration	0.0055	Summer > Spring

Table 3
Summary of concentration (mg/L) statistics for each pollutant and season, and comparison to similar studies. Superscript lettering used when seasonal differences in median concentrations were observed ($p < 0.05$).

Pollutant	Columbus, Ohio			Ohio region NSQD [a] (version 4.02)			Other Residential Studies for Comparison (annual)			
	Spring	Summer	Fall	Spring	Summer	Fall	Page et al. (2015)	Line et al. (2002)	Bedan and Clausen (2009)	U.S. EPA (1983) [b]
TN										
n	77	79	79	–	–	–	25	–	–	–
Median	2.19^{A}	1.50^{B}	1.55^{B}	–	–	–	1.36	–	–	–
Mean	2.54	1.82	1.67	–	–	–	–	–	–	–
Standard Deviation	1.56	1.63	0.96	–	–	–	–	–	–	–
Maximum	11.24	11.00	6.83	–	–	–	–	–	–	–
TKN										
n	79	77	74	57	37	34	25	70	56	899
Median	1.30^{A}	0.98^{A}	0.90^{B}	3.00	2.02	1.98	1.14	1.48	1.1	1.90
Mean	1.72	1.33	1.09	3.95	2.70	2.91	–	5.92	–	–
Standard Deviation	1.14	1.57	0.77	3.24	2.31	2.48	–	–	–	–
Maximum	5.70	11.00	6.10	13.00	13.06	13.00	–	61.8	–	–
TAN										
n	59	62	61	8	3	16	25	70	56	–
Median	0.18^{A}	0.06^{B}	0.06^{B}	0.36	0.30	0.40	0.06	0.34	0.16	–
Mean	0.22	0.30	0.18	0.36	0.34	0.48	–	0.55	–	–
Standard Deviation	0.18	1.06	0.25	0.25	0.35	0.31	–	–	–	–
Maximum	0.71	7.70	0.93	0.76	0.70	1.30	–	5.91	–	–
$NO_{2\text{-}3}$										
n	49	49	61	6	4	21	25	70	56	593
Median	1.00^{A}	0.73^{B}	0.74^{B}	1.33	0.80	0.66	0.14	0.49	1.1	0.74
Mean	1.22	0.85	0.84	1.14	0.96	1.71	–	0.79	–	–
Standard Deviation	1.14	0.37	0.67	0.42	0.71	3.77	–	–	–	–
Maximum	8.24	2.01	5.03	1.54	1.90	18.00	–	3.25	–	–
TP										
n	81	84	83	67	42	38	25	70	56	1029
Median	0.22^{A}	0.15^{B}	0.23^{A}	0.54	0.50	0.35	0.22	0.4	0.16	0.38
Mean	0.32	0.22	0.27	0.68	0.69	0.52	–	0.59	–	–
Standard Deviation	0.31	0.27	0.15	0.46	1.05	0.37	–	–	–	–
Maximum	2.20	2.10	0.78	1.70	6.90	1.50	–	3.06	–	–
OP										
n	49	47	55	–	–	–	25	–	–	344
Median	0.12	0.11	0.12	–	–	–	0.11	–	–	0.14
Mean	0.12	0.11	0.14	–	–	–	–	–	–	–
Standard Deviation	0.03	0.07	0.08	–	–	–	–	–	–	–
Maximum	0.20	0.38	0.33	–	–	–	–	–	–	–
TSS										
n	76	80	79	96	73	43	25	70	56	1102
Median	74.5^{A}	56.5^{A}	34^{B}	189.2^{A}	162.9^{A}	44.0^{B}	42	42	22	101
Mean	158	88.8	79.5	275.4	195.3	78.5	–	73	–	–
Standard Deviation	221	91.5	226	302	192	95.7	–	–	–	–
Maximum	1400	510	2000	2139.13	1284.7	500.8	–	880	–	–

[a] These National Stormwater Quality Database (NSQD, Version 4.02) sites were selected because they had greater than or equal to 75% residential land use in Illinois, Indiana, Kentucky, and Michigan, and Pennsylvania. These states were selected because they are geographically close to Ohio and exhibit similar rainfall patterns. Data were not available for West Virginia.
[b] 39 different residential sites as measured by U.S. EPA (1983).

Pollutant loads were reported on a sewershed area-normalized basis:

$$L = 1 \times 10^{-6} \times \frac{EMC \times V}{A_{WS}}$$

where L is pollutant load (kg/ha), EMC is the event mean concentration (mg/L), V is the runoff volume (L) measured after discounting baseflow, A_{WS} is the sewershed area (ha), and the constant (10^{-6}) converts milligrams to kilograms. Nutrient and sediment loading analyses were calculated on a seasonal (kg/ha) and annual basis (kg/ha/yr).

Two substantial outliers were removed from the nitrate (and subsequently TN and IN) data sets. On November 1, 2017 at Beechwold and May 21, 2017 at Cooke-Glenmont, nitrate concentrations of 850 and 780 mg/L, respectively, were reported by the laboratory; these were 2 orders of magnitude higher than the next highest nitrate concentration (8.2 mg/L). These concentrations were attributed to potential cross-contamination during sample collection or laboratory analysis and thus were excluded from the assessment. All other concentrations, across all pollutants and sewersheds, were included in the analysis that follows as reported by the laboratory.

For pollutant concentrations below the detection limit, a value of one-half the detection limit was substituted for EMCs (Antweiler and Taylor, 2008). Pollutant concentrations and loads were compared across seasons within each sewershed and across seasons for the four sewersheds combined using the Kruskal-Wallis k-sample omnibus test (Kruskal and Wallis, 1952). When this test was significant, Dunn's test with a Bonferroni correction (Higgins, 2004) was used for multiple comparisons. A criterion of 95% confidence ($p < 0.05$) was utilized.

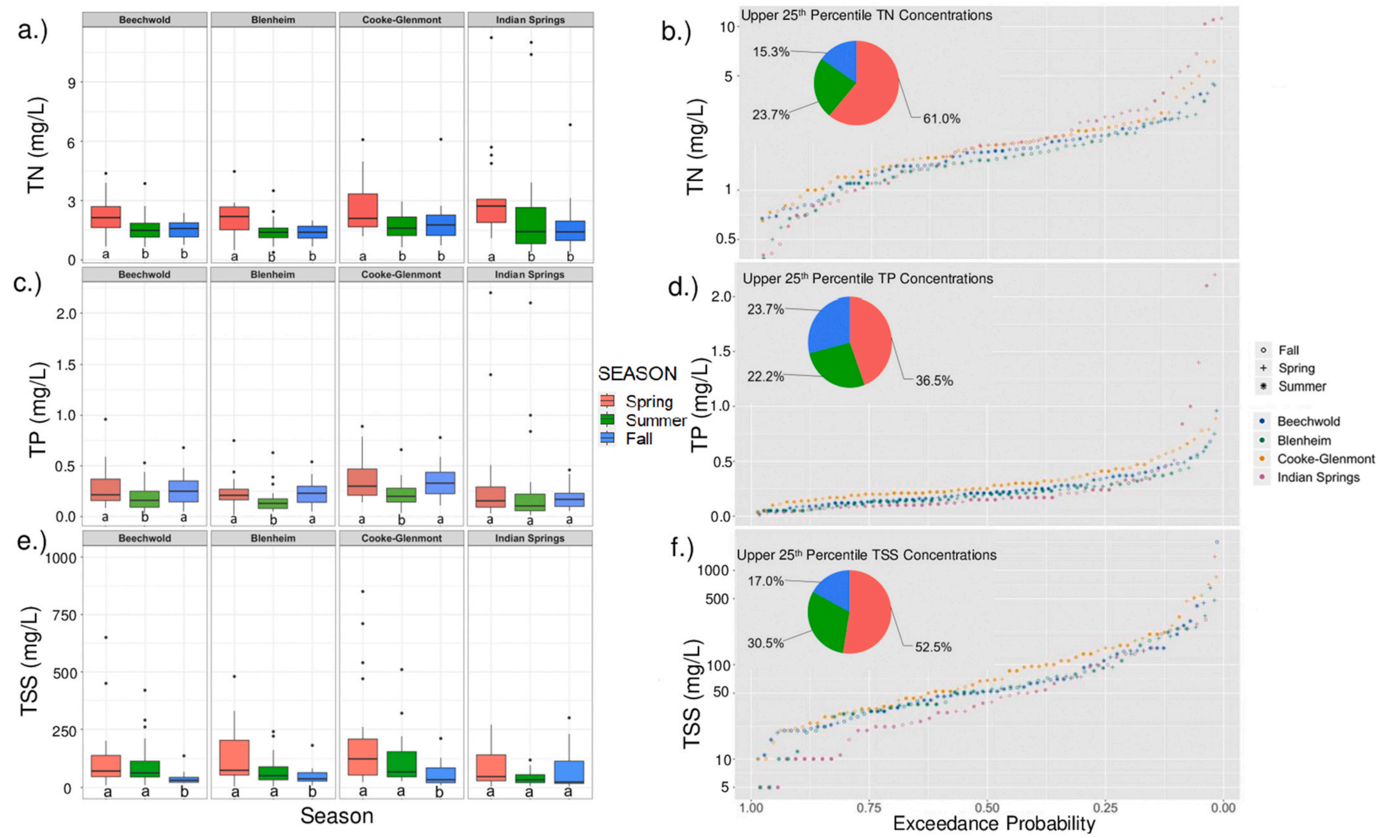

Fig. 2. (a,c,e) Boxplots of pollutant concentration for each sewershed and season. Letters show the statistical relationship among seasons. (b,d,f) Pollutant exceedance probabilities indicating season by shape and sewershed by color. Pie charts indicate seasonal distribution of pollutant concentrations in the upper 25th percentile. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

SCMs were installed in the Cooke-Glenmont sewershed during this study, as such, the Wilcoxon signed-rank test was used to determine if there were significant differences pre- and post-SCM installation.

Exceedance probability plots and boxplots were constructed for each pollutant. Within analyses of pollutant concentrations, the top ten storms and the top 25th percentile of storms were grouped by their respective season to show which seasons deliver the most nutrient and sediment in runoff. Concentration and pollutant load data from other urban and agricultural studies were included for comparison purposes. Data analysis and figure preparation were completed using R statistical software version 3.5.1 (R Core Team, 2020).

4. Results and discussion

4.1. Description of data sets

Between 151 and 162 rainfall events were observed during the 30-month period from June 2016 to December 2018, with 126–139 events meeting qualifying event requirements. Of these, 72, 54, 65, and 57 were sampled for water quality at the Beechwold, Blenheim, Cooke-Glenmont, and Indian Springs sewershed outfalls, respectively.

Average rainfall depths for the overall population of events were 15.7–16.4 mm. Storm events sampled for water quality represented between 1186.2 and 1600.2 mm, or approximately 46–65%, of the 2446.0–2550.2 mm of precipitation that occurred at the four monitoring sites during the study period. Sampled storms had significantly larger rainfall depths than the central tendency of observed events, but there were no significant differences in sampled versus observed rainfall intensity or antecedent dry period (ADP). Mean sampled storm event depth was 21.6–23.9 mm, which was significantly greater ($p < 0.0012$ in all cases) than the overall population; this is because events smaller than 5.1 mm were only sampled 2–5 times out of 32–43 such storms, depending on the sewershed, due to insufficient sample volume for laboratory analysis.

While the depth of some of the largest events varied across Clintonville, overall the rainfall characteristics that drive stormwater runoff generation and pollutant transport were similar across the sewersheds. The Kruskal-Wallis k-sample test showed that rainfall characteristics (i.e., rainfall depth, average intensity, peak 5-min intensity, ADP, and rainfall duration) did not significantly differ between the four sewersheds ($p > 0.67$ in all cases). This is logical since the maximum distance between any two rain gages was 1.85 km. Rainfall depth and ADP did not significantly differ across seasons within any sewershed. Consistent rainfall depth across seasons is uncharacteristic for central Ohio; a rainfall dataset from 1948 to 2013 from the Columbus airport showed summer rainfall depths were significantly greater than fall (NOAA, 2019). Rainfall depth is highly related to runoff volume, which is key for pollutant load determination. Significant seasonality in peak and average rainfall intensity as well as rainfall duration was observed (Table 2); summer average and peak rainfall intensities were greater than fall and spring. Rainfall duration was longer in the fall than in the summer. This is most likely related to convective thunderstorms during the summer season (Fritsch et al., 1986).

The Wilcoxon signed rank test was used to compare nutrient and sediment data before and after SCM installation in the Cooke-Glenmont sewershed. Only TAN was significantly different pre- and post-retrofit. Therefore, TAN data are not included in the analysis that follows for the Cooke-Glenmont sewershed. Otherwise, pre- and post-retrofit data were combined in the analysis that follows.

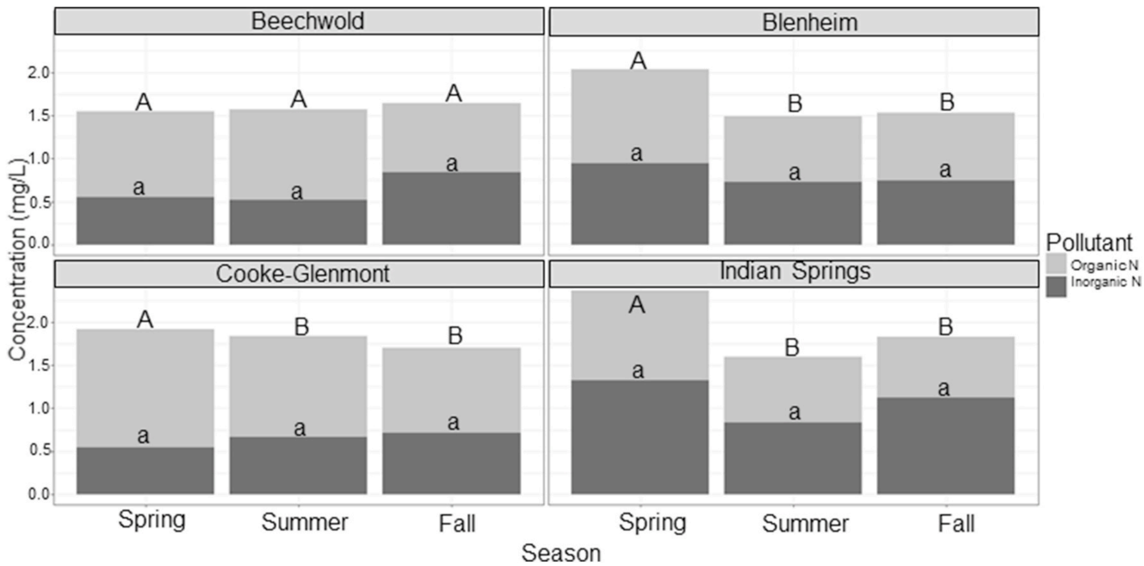

Fig. 3. Median organic and inorganic nitrogen concentration for each sewershed and season. Capital letters show the statistical relationship among seasons for organic nitrogen, while lower case letters represent inorganic nitrogen. Median organic nitrogen concentrations varied by season, but median inorganic nitrogen concentrations did not.

4.2. Pollutant concentrations

4.2.1. Nitrogen concentrations

When analyzing averages across the four sewersheds, significant seasonality was found for all nitrogen species. In all cases except TAN, spring median concentrations were significantly greater than those obtained during the summer and fall (Table 3). Individual sewersheds often followed this same pattern. Nitrogen concentrations were comparable to those reported by other studies. In particular, the Ohio region in the National Stormwater Quality Database (NSQD, Version 4.02) presents similar nitrogen concentrations.

Significant seasonal differences in TN concentrations were observed in all four sewersheds (Fig. 2a), where spring median TN concentrations were significantly greater than those in summer and fall. For example, the median spring (2.14 mg/L) concentration was significantly higher than summer (1.50 mg/L) and fall (1.59 mg/L) concentrations at Beechwold. Across the four Columbus sewersheds, spring TN concentrations had a significantly higher median concentration (2.19 mg/L), than those of fall (1.55 mg/L) and summer (1.50 mg/L). Among the ten highest TN concentrations observed from September 2016 to December 2018, six occurred in the spring, two during the summer, and two in the fall. Examining the top quartile of TN concentrations, 61.0% occurred in spring, 23.7% in summer, and 15.3% in fall (Fig. 2b). This is important, as TN loads in May drive the current forecasts of the hypoxic zone in the Gulf of Mexico (Scavia et al., 2013), which is the ultimate destination of stormwater from these Columbus sewersheds. While TN loads did not exhibit seasonality (see below), high TN concentration in the spring may present opportunities for targeted remediation that directly benefits downstream water quality.

Seasonal trends of median TN concentrations suggest they may be related to lawn fertilizer use since fertilizers are often applied in the spring (Bannerman et al., 1993). Yang and Toor (2017) found fertilizer to be the second most common source of total nitrogen in a residential sewershed behind atmospheric deposition. Atmospheric deposition, which is a major source of inorganic nitrogen in urban stormwater, is seasonal in nature as well. Atmospheric deposition of nitrogen accelerates during warmer, wetter months than colder, dryer months (Sickles and Shadwick, 2007). Yang and Toor (2016) found that during the wet season, more than 50% of the nitrate in urban stormwater runoff originated from atmospheric deposition. The median concentration of TKN was significantly higher in the spring than the fall and summer at Blenheim and Indian Springs, but only significantly higher in the spring than the fall at Beechwold. For all sewersheds combined, median spring TKN concentrations (1.30 mg/L) were significantly higher than summer (0.98 mg/L) and fall (0.90 mg/L) concentrations. Among the ten highest TKN concentrations, seven occurred in the spring, two during the summer, and one in the fall. Within the top quartile of TKN concentrations, 55.2% occurred in spring, 24.1% in summer, and 20.7% in fall. NSQD data from the Ohio region showed a similar trend, but no significant seasonality for median TKN concentrations, with greatest concentrations in the spring followed by summer and fall.

The median TAN concentration was significantly higher in spring (0.19 mg/L) than those of summer and fall (both 0.05 mg/L) at Blenheim. Similarly, for the four sewersheds combined, median spring TAN concentrations (0.18 mg/L) were significantly higher than summer and fall (both 0.06 mg/L) concentrations. Among the ten highest TAN concentrations, zero occurred in the spring ($\mu = 0.22 \pm 0.18$ mg/L), four during the summer ($\mu = 0.30 \pm 1.06$ mg/L), and six in the fall ($\mu = 0.18 \pm 0.25$ mg/L). Within the top quartile of TAN concentrations, 44.4% occurred in spring, 22.2% in summer, and 33.3% in fall. The Ohio region NSQD (NSQD, version 4.02) reported higher median TAN (0.30–0.40 mg/L) values than observed from these sewersheds. The median TAN values in the Columbus sewersheds were comparable to those reported by other studies (Line et al., 2016; Bedan and Clausen, 2009; Page et al., 2015).

TAN concentrations in the range of 0.005–5 mg/L can cause acute or chronic toxicity to aquatic life (Russo, 1985; Miltner and Rankin, 1998; Dodds and Welch, 2000). All median TAN values from the Columbus sewersheds and the residential sewersheds used for comparison fall within this range. Late winter to early spring (February to April) is a critical time to control TAN concentration because it fuels the growth of *Prorocentrum minimum*, a bloom-forming dinoflagellate that can be toxic, and the summer and fall abundance of *Heterosigma akashiwo*, a raphidophyte that can also be toxic (Hathaway et al., 2012). These algal forms are a concern primarily in temperate waters, similar to surface waters in Columbus, Ohio, and coastal regions to which Columbus watersheds eventually drain (Heil et al., 2004;Band-Schmidt et al., 2004).

Median $NO_{2\text{-}3}$ concentrations were significantly higher in the spring than the fall at Beechwold, Blenheim, and Indian Springs, and significantly higher in the spring than the summer at Beechwold and Indian Springs. For the four sewersheds combined, the median spring $NO_{2\text{-}3}$ concentration (1.00 mg/L) was significantly higher than those of

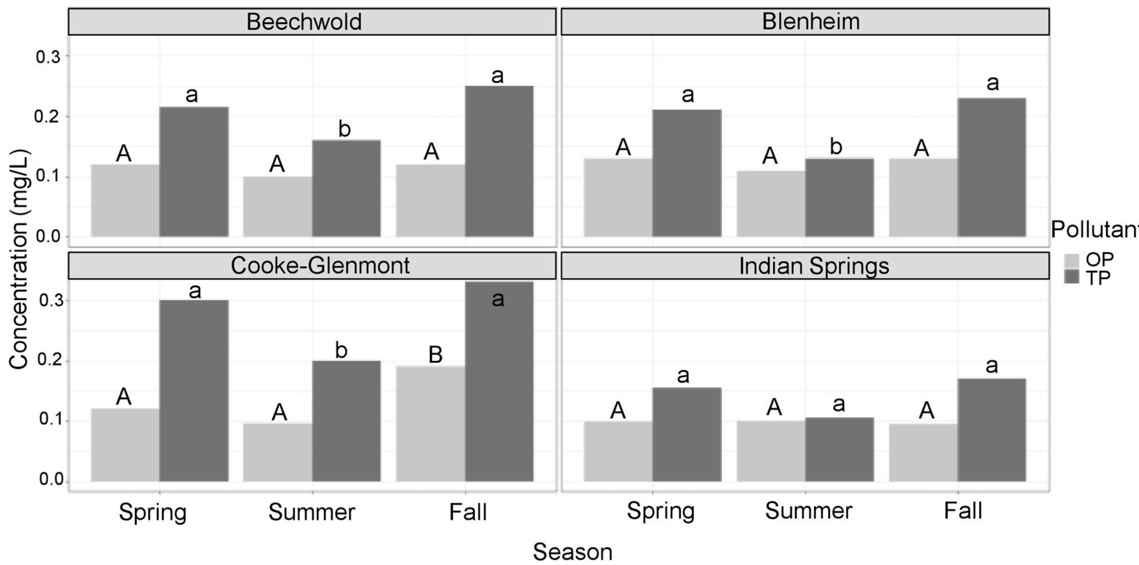

Fig. 4. Median orthophosphate (OP) and total phosphorus (TP) concentration for each sewershed and season. Capital letters show significant differences among seasons for OP. OP contributed an average of 60.9% of the TP for all sewersheds and seasons in Columbus.

summer (0.73 mg/L) and fall (0.74 mg/L). Among the ten highest $NO_{2\text{-}3}$ concentrations, seven occurred in the spring, one during the summer, and two in the fall. Within the top quartile of $NO_{2\text{-}3}$ concentrations, 45% occurred in spring, 30% in summer, and 25% in fall. The NSQD for the Ohio region showed no significant seasonality, but the trend of greatest median $NO_{2\text{-}3}$ concentrations in spring (1.33 mg/L), followed by summer (0.80 mg/L) and fall (0.66 mg/L) was observed (NSQD, version 4.02). Bedan and Clausen (2009) reported a median $NO_{2\text{-}3}$ of 1.1 mg/L, which is greater than the spring median values for the Columbus sewersheds. The National Urban Runoff Program (U.S. EPA, 1983) reported a median $NO_{2\text{-}3}$ value of 0.74 mg/L, which is identical to the fall value across Columbus sewersheds. Late fall to early spring (November to March) is a critical time for $NO_{2\text{-}3}$ to mitigate diatom blooms (Hathaway et al., 2012). Diatoms are needed to support food chains, but their springtime death and sharp population decline has been shown to drive summer hypoxia in Lake Erie, since degrading diatom biomass consumes dissolved oxygen (Reavie et al., 2016).

Significant ON seasonality was observed at Blenheim, Cooke-Glenmont, and Indian Springs, where the spring median concentration was greater than those of summer and fall. For example, at Blenheim the median spring ON concentration (1.09 mg/L) was greater than summer (0.76 mg/L) and fall (0.78 mg/L) concentrations. Similarly, the four Columbus sewersheds had significantly higher median ON concentrations in the spring (1.13 mg/L) than in the summer (0.85 mg/L) and fall (0.81 mg/L). Among the ten highest ON concentrations, six occurred in the spring, three during the summer, and one in the fall. Within the top quartile of ON concentrations, 53.6% occurred in spring, 28.6% in summer, and 17.9% in fall. While significant ON seasonality was seen at three of the four sewersheds, no significant seasonality was seen at any of the sewersheds in Columbus for inorganic nitrogen (Fig. 3). In Columbus, ON contributed a minimum of 38.1% of TN in residential stormwater runoff at Indian Springs in the spring and a maximum of 73.0% for Cooke-Glenmont in the summer. Across all sewersheds and seasons, ON contributed an average of 55.1% of the TN concentration in these residential sewersheds. ON is often preferentially bound to particulate matter. Particulate matter was significantly higher in the spring and summer, as TSS concentrations were significantly higher in the spring and summer than the fall for three of the four sewersheds in Columbus (see section 4.2.3). Since ON is often preferentially bound to particles, it is more readily treated than dissolved pollutants using sedimentation-based SCMs.

4.2.2. Phosphorus concentrations

Median TP concentrations were significantly higher in the spring and fall than in the summer at Beechwold, Blenheim, and Cooke-Glenmont (Fig. 2c). For example, at Beechwold spring (0.22 mg/L) and fall (0.25 mg/L) mean TP concentrations were significantly higher than that of summer (0.16 mg/L). Similarly, for the four Columbus sewersheds combined, spring (0.22 mg/L) and fall (0.23 mg/L) median TP concentrations were significantly higher than the summer (0.15 mg/L) concentration. Among the ten highest TP concentrations, six occurred in the spring, three during the summer, and one in the fall. Within the top quartile of TP concentrations, 36.5% occurred in spring, 22.2% in summer, and 41.3% in fall (Fig. 2d).

While there were minor differences with trends from stormwater databases, overall the concentrations from these sewersheds were similar to those from previous studies. No significant seasonality was observed in the NSQD for the Ohio region; the non-significant trends differ from those observed in this study, with the greatest concentrations reported by the NSQD in spring, followed by summer, followed by fall. Page et al. (2015) reported the same median TP concentration as the spring in Columbus (0.22 mg/L). Bedan and Clausen (2009) reported a similar median TP concentration (0.16 mg/L) as the summer value for Columbus. The median TP concentration values for all seasons in Columbus were similar to values reported by Line et al. (0.4 mg/L, 2015), the U.S. EPA (0.38 mg/L, 1983), and all seasons in the NSQD for the Ohio region (spring = 0.54 mg/L, summer = 0.50 mg/L, fall = 0.35 mg/L)

Sources of phosphorus in residential watersheds include erosion, which mobilizes phosphorus-rich sediments; atmospheric deposition; human and animal wastes; relic phosphorus in soil from fertilizers; and starter fertilizer (P was eliminated from commercially available lawn fertilizer in Ohio in 2013; Makepeace et al., 1995;OLEPTF, 2013; Yang and Toor, 2018). Spring TP loads have been shown to drive algal blooms in some freshwater systems, such as Lake Erie (Stumpf et al., 2016). Early summer to fall (June to September) is a sensitive period for elevated TP concentrations in saltwater systems because they fuel harmful "pfiesteria-like" algal species (Hathaway et al., 2012).

At Cooke-Glenmont, median OP concentrations were significantly higher in the fall (0.19 mg/L) than the summer (0.10 mg/L), while that of spring (0.12 mg/L) was not significantly different from fall or summer. The four Columbus sewersheds combined showed no significant seasonality for OP concentrations, and concentrations were similar to other studies (Page et al., 2015; U.S. EPA, 1983). Among the ten highest

Table 4
Summary of load statistics for each pollutant and season in Columbus, OH.

Pollutant	Units	Load		
		Spring	Summer	Fall
TN				
N		79	70	76
Median	kg/ha	0.08	0.05	0.06
Mean		0.163	0.126	0.095
Standard Deviation		0.219	0.177	0.144
Maximum		1.017	0.9	0.536
Total Seasonal Load	g/ha/mm	7.511	4.186	4.119
TKN				
N		79	68	71
Median	kg/ha	0.05	0.04	0.03
Mean		0.11	0.08	0.06
Standard Deviation		0.15	0.1	0.07
Maximum		0.73	0.75	0.31
Total Seasonal Load	g/ha/mm	5.066	2.738	2.268
TAN				
N		58	56	58
Median	kg/ha	0.007	0.002	0.004
Mean		0.011	0.008	0.008
Standard Deviation		0.014	0.014	0.012
Maximum		0.0836	0.0855	0.0573
Total Seasonal Load	g/ha/mm	0.359	0.202	0.266
$NO_{2\text{-}3}$				
n		49	44	60
Median	kg/ha	0.05	0.03	0.02
Mean		0.086	0.069	0.054
Standard Deviation		0.104	0.122	0.07
Maximum		0.469	0.614	0.302
Total Seasonal Load	g/ha/mm	2.446	1.448	1.852
TP				
n		81	73	78
Median	kg/ha	0.009	0.005	0.01
Mean		0.018	0.016	0.015
Standard Deviation		0.027	0.029	0.015
Maximum		0.178	0.147	0.0657
Total Seasonal Load	g/ha/mm	0.853	0.568	0.648
OP				
n		49	42	54
Median	kg/ha	0.004	0.003	0.004
Mean		0.01	0.009	0.006
Standard Deviation		0.013	0.014	0.008
Maximum		0.054	0.061	0.039
Total Seasonal Load	g/ha/mm	0.285	0.188	0.199
TSS				
n		75	70	74
Median	kg/ha	3.1	2	1.6
Mean		11.2	6.7	4.0
Standard Deviation		24.8	13.8	6.8
Maximum		177.6	85.1	35.5
Total Seasonal Load	g/ha/mm	488.9	221.5	168.8

OP concentrations, zero occurred in the spring, two during the summer, and eight in the fall. Within the top quartile of OP concentrations, 21.1% occurred in spring, 21.1% in summer, and 57.8% in fall. High fall OP concentrations can fuel "pfiesteria-like" algae species. In Minnesota, phosphorus contributions from leaf matter in residential areas during fall represented up to 60% (excluding winter) of the annual phosphorus yield (Selbig, 2016). This source is also likely a major contributor to the seasonality of OP in Cooke-Glenmont given that it has the greatest amount of woody vegetation of the four sewersheds (Table 1).

OP is a key contributor to algal blooms (Correll et al., 1998). Erickson et al. (2012) found OP represents an average 45% of TP in stormwater and in some cases more than 95%. In Columbus, OP contributed a minimum of 40% of TP in residential stormwater runoff at Cooke-Glenmont in the spring and a maximum of 95.2% for Indian Springs in the summer (Fig. 4). Averaging all sewersheds and seasons, OP contributed an average of 60.9% of the TP concentration in these residential sewersheds.

4.2.3. Total suspended solids concentrations

Significant seasonality of TSS concentrations was observed at Beechwold, Blenheim, and Cooke-Glenmont, where concentrations in spring and summer were significantly greater than the fall concentration (Fig. 2e). For example, median spring (72.0 mg/L) and summer (63.5 mg/L) concentrations were significantly higher than that of fall (32 mg/L) at Beechwold. Across the four sewersheds, median TSS concentrations were significantly higher in the spring (74.5 mg/L) and summer (56.5 mg/L) than the fall (34.0 mg/L). Of the highest 10 observed TSS concentrations across the four sewersheds, seven occurred during the spring, two during the summer, and one in the fall (Fig. 2f). Of the upper 25th percentile of total suspended solids concentrations, 52.5% occurred in spring, 30.5% in summer, and 16.9% in the fall (Fig. 2f).

Two substantial TSS outliers were observed: (1) 1400 mg/L at Indian Springs on March 26, 2017, and (2) 2000 mg/L at Beechwold on October 7, 2017. The March 26th event was 33.3 mm and had the second highest peak 5-min rainfall intensity on record during this study of 89.9 mm/h, driving the suspension of particulate matter (Garafalo et al., 2014).

The NSQD for the Ohio region showed the same seasonality trend for median TSS concentrations as the combined Columbus sewersheds, with spring (189.2 mg/L) and summer (162.9 mg/L) concentrations significantly higher than that of fall (44.0 mg/L). Page et al. (2015) and Line et al. (2002) both reported median TSS concentrations of 42 mg/L, which is between the summer and fall median values across the four sewersheds. Bedan and Clausen (2009) reported a median TSS concentration (22 mg/L), less than all seasons in the Columbus sewersheds, but U.S. EPA (1983)reported 101 mg/L, which is higher than all seasons in the four sewersheds.

Sources of sediment in residential watersheds include soil erosion, construction site runoff, wearing of pavement materials, and atmospheric deposition (Morgan et al., 2017). Summer had significantly higher peak rainfall intensities than spring (Table 2), so other factors are the cause for spring TSS mobilization. This seasonal trend may be due to dormant grass and bare patches in lawns in early spring, causing more solids to be carried by stormwater runoff, or due to the spring flushing of solids that accumulate during winter snow plowing (Brezonik and Stadelmann, 2002). Another possible explanation for high TSS concentrations in the springtime is related to soil chemistry. When snow greater than 50 mm occurred, combinations of salt and liquid calcium or salt and sand were spread on arterial, collector, and some residential roads in the study region. In total, Columbus experienced 767.1 mm of snow during the study period. Salty runoff/meltwater interacts with roadside soils, causing elevation of the sodium adsorption ratio and exchangeable sodium percentage of the soil. This results in deflocculation, mobilization of sediment, and subsequent transport of nutrients and metals bound to the sediment (Hallberg et al., 2007). This effect has been observed in the underlying soils beneath a permeable pavement in northeast Ohio (Winston et al., 2016). Vaishali and Punita (2013), Helmreich et al. (2010), and Westerlund and Viklander (2006) all reported that pollutant loads and concentrations were considerably higher during and immediately following winter than during summer and fall seasons in cold climates, which is consistent with this theory. Stormwater runoff with increased chloride concentrations from deicing salts has been shown to degrade habitat for aquatic organisms and threaten drinking water supplies (Kaushal et al., 2005). Perhaps an alternate deicer is needed in these regions. Also, temporary TSS removal, perhaps through street sweeping, is needed in spring, and/or higher maintenance of SCM pretreatment devices after the spring season.

4.3. Pollutant loading

4.3.1. Pollutant load seasonality

Average rainfall depths did not differ significantly across seasons in this study, but historical data show significantly higher precipitation in summer than in fall ($p = 0.0297$) in Columbus (NOAA, 2019). While significant seasonality was frequently present in pollutant

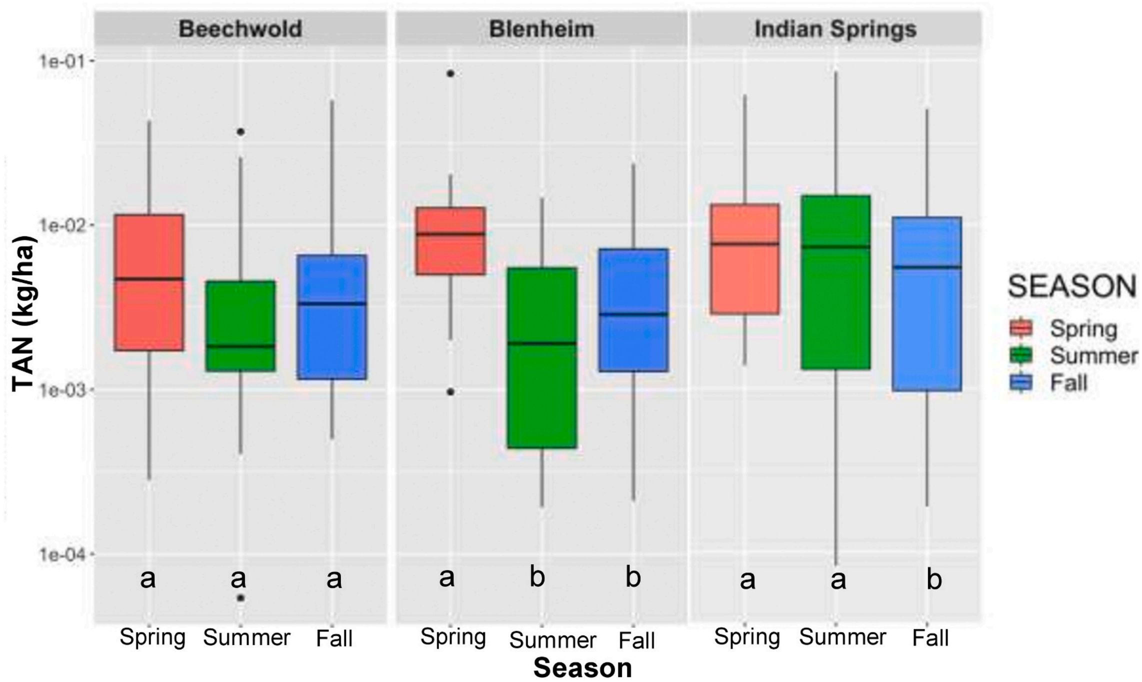

Fig. 5. TAN load boxplot for each sewershed and season. Cooke-Glenmont is omitted because of significant TAN differences between pre- and post- SCM installation. Lettering within boxplot represents significant differences.

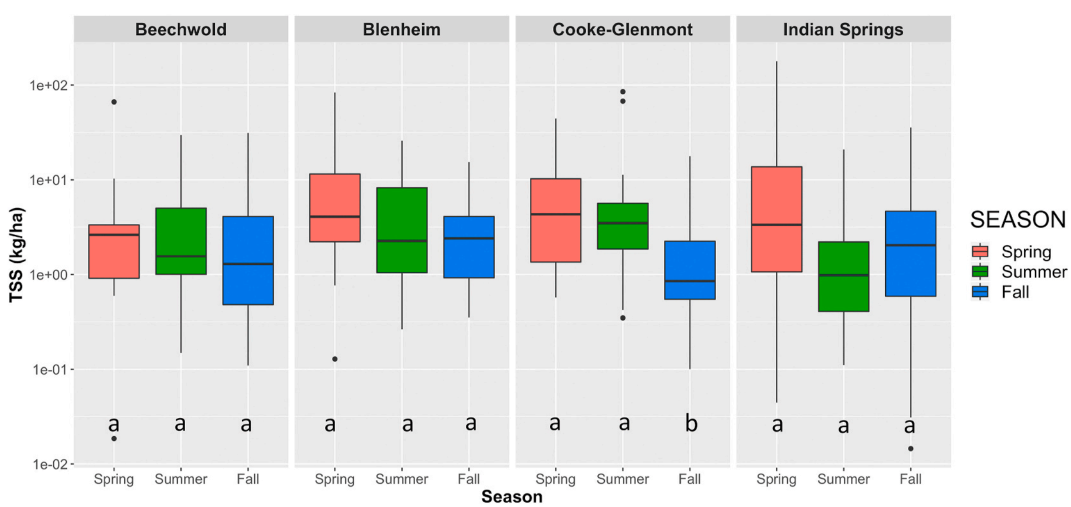

Fig. 6. TSS load boxplot for each sewershed and season. Lettering within boxplot represents significant differences.

Table 5
Summary of annual pollutant loading (kg/ha/yr) for Columbus sewersheds. Other studies provided for comparison.

Pollutant	Columbus, Ohio by Sewershed				Other Residential Runoff Studies			
	Beechwold	Blenheim	Cooke-Glenmont	Indian Springs	Page et al. (2015)	Line et al. (2002)	Line et al. (2007)	Bedan and Clausen (2009)
TN	7.6	9.4	9.7	12.5	3.8	23.9	18.0	–
TKN	4.6	6.0	7.0	8.4	3.4	20.7	16.2	3.6
TAN	0.5	0.6	–	0.9	0.4	2.4	1.7	0.48
$NO_{2\text{-}3}$	4.9	5.2	3.7	6.6	0.4	3.2	1.8	3.29
TP	0.8	1.3	1.5	1.5	0.9	2.3	1.7	0.462
OP	0.7	0.7	0.7	0.5	0.3	–	–	–
TSS	344	535	679	653	116	387	1958	64

concentrations, no significant differences in seasonal pollutant loading were observed across all four Columbus sewersheds (Table 4). Runoff volume and rainfall intensity varied in such a way as to offset concentration differences. Total seasonal load (g/ha/mm) was highest in spring, summer, and then fall for all nitrogen species and TSS; however, total seasonal load for fall was greater than that for summer for

Table 6
Comparison of Columbus seasonal mean P concentration (mg/L) and load (kg/ha) to agricultural surface runoff. Superscript lettering used when seasonal mean differences were observed ($p < 0.05$).

Pollutant	Combined Columbus, Ohio Sewersheds			Agricultural Study (Pease et al., 2018)		
	Spring	Summer	Fall	Spring	Summer	Fall
TP						
Mean Concentration	0.32 ± 0.31	0.22 ± 0.27	0.27 ± 0.15	0.77 ± 0.84	0.63 ± 0.67	0.88 ± 1.02
Mean Load	0.018 ± 0.027	0.016 ± 0.029	0.015 ± 0.015	0.25 ± 0.54^{A}	0.06 ± 0.13^{B}	0.08 ± 0.18^{B}
OP						
Mean Concentration	0.12 ± 0.03	0.11 ± 0.07	0.14 ± 0.08	0.37 ± 0.45	0.37 ± 0.48	0.66 ± 0.82
Mean Load	0.01 ± 0.013	0.009 ± 0.014	0.006 ± 0.008	0.10 ± 0.23^{A}	0.03 ± 0.07^{B}	0.06 ± 0.16^{B}

phosphorus species (Table 4).

For the individual sewersheds, significant seasonality in pollutant loading was observed in two cases. Median TAN loads were significantly higher in spring (0.009 kg/ha) than those of summer (0.002 kg/ha) and fall (0.003 kg/ha) at Blenheim (Fig. 5). Median TSS loads were significantly higher in spring (4.328 kg/ha) and summer (3.484 kg/ha) than the fall (0.854 kg/ha) load at Cooke-Glenmont (Fig. 6). Brezonik and Stadelmann (2002) found significant seasonality in median watershed area-normalized loads of TN, TKN, $NO_{2\text{-}3}$, TP, and TSS in stormwater in Minneapolis-Saint Paul, but significant seasonality was not found in OP loads. This study also found rainfall depth, rainfall intensity, and drainage area to be the most important factors when calculating loads. The sites herein did not experience significant seasonal differences in rainfall depth, but did experience significant seasonal differences in rainfall intensities, which contributed to these differences in pollutant loads.

4.3.2. Annual pollutant loading

No significant differences were seen across the four Columbus sewersheds for annual pollutant loading (Table 5). Loads from nitrogen species are within the range of previous studies of residential watersheds (Page et al., 2015; Line et al., 2002 and2007; Bedan and Clausen, 2009). Annual TKN load has been shown to significantly correlate with cyanobacterial bloom biomass, where cyanobacterial bloom biomass significantly correlated with the annual TKN:NO_3 ratio (Newell et al., 2019).

Atmospheric deposition alone contributes a mean of 0.14 ± 0.10 kg/ha/yr towards the annual TP load (Pease et al., 2018). Annual TP loads generally agree with previous studies of residential watersheds, which have reported loads within 1.5 kg/ha/yr of the Columbus sewersheds (Page et al., 2015; Line et al., 2002 and2007; Bedan and Clausen, 2009). Annual OP loads from all Columbus sewersheds were within 0.5 kg/ha/yr of that reported by Page et al. (2002).

Annual TSS loads from Columbus sewersheds were 2.9–5.7 times less than one study (Line et al., 2007), but 3 to 10.6 times greater than others (Page et al., 2002; Bedan and Clausen, 2009). Another study reported an annual TSS load within the range of those from the Columbus sewersheds (Line et al., 2002).

In general, Columbus sewershed nitrogen and phosphorus annual loads were similar to other residential runoff studies, but TSS values varied among these studies. A possible explanation for these similarities is the continuity in land use. Residential areas experience similar natural and anthropogenic nutrient fluxes. A possible explanation for the TSS disagreements is the discontinuity in residential land attributes and differences in climate. Different soil types, rainfall intensities, or surface slope within residential sewersheds may cause TSS annual loads to vary.

4.4. Comparison to agricultural runoff

Urban runoff causes eutrophication in some lakes and rivers (McDonald and Lathrop, 2016; Xu et al., 2010), but agricultural runoff is the major contributor in others, such as the Western Lake Erie basin (Wilson et al., 2019). Understanding how residential runoff relates to agricultural runoff could lead to better allocation of resources and improved management strategies in watersheds with both urban and rural sources of nutrients.

Monitoring of 40 agricultural fields in Ohio revealed nearly 60% of surface runoff and nutrient load occurred during the spring and winter (Williams et al., 2018). Pease et al. (2018) studied phosphorus discharge at 38 edge-of-field research sites in Ohio, and found mean spring TP and OP loads were significantly higher than those of summer and fall (Table 6). Agricultural runoff TP concentrations were 2.4–3.3 times higher than Columbus mean TP concentrations, and TP loads were 5.5–13.9 times higher than Columbus mean TP loads. Agricultural runoff OP concentrations were 3.1–4.7 times higher than Columbus mean OP concentrations, and OP loads were 3.3–10 times higher than Columbus mean OP loads.Whereas loading from agricultural fields in Pease et al. (2018) was greater than Columbus residential runoff, some agricultural studies have shown annual nutrient and sediment load exports at a rate similar to the Columbus residential sewersheds (TN: 9.8–14.0 kg/ha/yr, Dodd et al., 1992; Beaulac and Reckhow, 1982. TP: 0.94–0.99 kg/ha/yr, Beaulac and Reckhow, 1982; Dodd et al., 1992. TSS: 1604–1958 kg/ha/yr, Aryal and Reba, 2017). Thus, while agricultural runoff can have significantly higher nutrient and sediment loads than those observed in Columbus, some agricultural watersheds have similar loads to Columbus residential sewersheds.

Annual loading in both agricultural and residential runoff depends on natural events, human activity, and land management. Agricultural runoff has been the center of attention in some watersheds (Scavia et al., 2017), but residential and urban runoff can have the same substantial negative impact on water quality in other watersheds (Brezonik and Stadelmann, 2002). In residential watersheds with degraded water quality, efforts should be focused on improving SCM design to prevent nutrient and sediment runoff during seasons that are sensitive for the eutrophication of receiving bodies of water.

4.5. Suggestions for SCM improvement

The seasonal nature of nutrient production from the four sewersheds suggests that SCM maintenance and management strategies could be optimized to mitigate the deleterious effects of seasonal nutrient export on receiving water bodies. SCMs aim to treat stormwater at its source using technologies relying on natural processes to mimic pre-development watershed function (Miles and Band, 2015). Cities across the world, from Chinese "sponge cities" to Columbus, Ohio, USA, are adopting a combination of these strategies to (1) prevent flooding of structures and promote public safety, (2) treat various pollutants and reduce runoff volume from frequently-occurring rainfall events, and (3) mitigate the impacts of urban areas on receiving bodies of water (Nguyen et al., 2019; Sanson and Onderak, 2019).

Infiltration-based SCMs, such as bioretention practices, have been shown to be highly effective at filtering out particulate-based pollutants in runoff (Hunt et al., 2012). Intensive maintenance activities, such as media/vegetation replacement, ensuring forebays and outlets are clear of obstructions, etc., could be implemented in late winter months in preparation for the highly seasonal nature of particulate-bound nitrogen and phosphorous compounds. Locations with higher TSS concentrations (and thus a higher presence of particulate-bound pollutants) following winter deposition could consider implementing additional street-sweeping in the early spring months to collect sediment before it is transported through the sewer network. Delayed or reduced application of fertilizers may also lessen the elevated spring nutrient concentrations that feed algal blooms in the warm summer months. Adopting the use of alternative deicing compounds may decrease the occurrence of sodic soils following the winter months and subsequently lessen TSS conveyance in the spring months.

The design and operation of SCMs may provide other opportunities to address nutrient seasonality. Real time, computerized control of SCMs can vary the retention rate of stormwater, allowing for more treatment of pollutants during the spring and greater infiltration during the summer (Kerkez et al., 2016). More simply, utilizing an adjustable internal water storage (IWS) zones could add flexibility to SCM design and allow stormwater management strategies to address different treatment objectives throughout the year. IWS zones are commonly created by raising the elevation of underdrain in SCMs such as bioretention practices to provide opportunities for increased nitrogen removal via denitrification (Hunt et al., 2012). By instead incorporating a series of valves into drainage networks, designers could provide increased opportunities for prolonged runoff retention and nutrient removal in the nutrient-laden spring months through the creation of an IWS zone, which could then be removed to accommodate more intense rain events in the summer months. Implementing design features and management strategies which can allow SCM function to adapt to the varied nutrient challenges that occur throughout the year may mitigate the export of nutrients from urban areas and lessen the impact on receiving water bodies.

5. Summary and conclusions

The seasonal nature of nutrient export from four residential sewersheds in Columbus, OH, USA was investigated over a period of 30 months. Significant seasonality was found in pollutant concentrations, but seldom in pollutant loads because runoff volume varied in such a way as to offset concentration differences and significant seasonality in rainfall intensity. Concentrations of nitrogen compounds were significantly higher in the spring than in the summer or fall, most likely due to a combination of fertilizer application, atmospheric deposition, and increased particulate-bound organic nitrogen. TP concentrations were significantly higher in spring and fall than summer at three of the four sewersheds. OP, which was found to depend on the amount of woody vegetation and leaf detritus in a sewershed, comprised the majority of the TP concentration. Results from this study demonstrated that urban runoff from residential sewersheds delivered nutrients to receiving streams during seasons that drive algal growth. TSS concentrations were significantly higher in the spring and summer than the fall, potentially associated with deicing salt application and lack of plant development in early spring and significantly higher peak rainfall intensities in the summer months. Nutrient and sediment concentrations were often much lower than in agricultural studies, but annual loads were comparable to some agricultural studies. Results from this study suggest the design and maintenance of stormwater control measures that account for seasonality of nutrient export from urban residential areas could help to mitigate the seasonal impacts of nutrient pollution on receiving water bodies (i.e., eutrophication). Further study of the seasonality of nutrient and sediment loading is needed in regions that have significant differences in rainfall depth throughout the year because "hot moment" nutrient and sediment loading can fuel eutrophication.

Credit author statement

Joseph Smith performed conceptualization, writing – original draft, visualization, investigation, and formal analysis. **Ryan Winston** performed conceptualization, methodology, formal analysis, writing – review & editing, methodology, supervision. **R. Andrew Tirpak** performed writing – review & editing. **David Wituszynski** performed investigation and writing – review & editing. **Kathryn Boening** performed investigation. **Jay Martin** performed methodology, resources, writing – review & editing, supervision, project administration, funding acquisition.

Declaration of competing interest

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

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